Michigan Technological University

Michigan Technological University
Digital Commons @ Michigan Tech

Dissertations, Master's Theses and Master's Reports

2019

CHARACTERIZATION OF HYDRAULIC INTERACTIONS BETWEEN TORQUE CONVERTER AND TRANSMISSION DURING TRANSIENT EVENTS

Mark Woodland
Michigan Technological University, mtwoodla@mtu.edu

Copyright 2019 Mark Woodland

Recommended Citation
Woodland, Mark, "CHARACTERIZATION OF HYDRAULIC INTERACTIONS BETWEEN TORQUE CONVERTER AND TRANSMISSION DURING TRANSIENT EVENTS", Open Access Master's Thesis, Michigan Technological University, 2019.
https://doi.org/10.37099/mtu.dc.etdr/843

Follow this and additional works at: https://digitalcommons.mtu.edu/etdr

Part of the Automotive Engineering Commons

www.manaraa.com

CHARACTERIZATION OF HYDRAULIC INTERACTIONS BETWEEN TORQUE CONVERTER AND TRANSMISSION DURING TRANSIENT EVENTS

By

Mark T. Woodland

A THESIS

Submitted in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

In Mechanical Engineering

MICHIGAN TECHNOLOGICAL UNIVERSITY

2019

© 2019 Mark T. Woodland

www.manaraa.com

المنارة للاستشارات
www.manaraa.com

This thesis has been approved in partial fulfillment of the requirements for the Degree of MASTER OF SCIENCE in Mechanical Engineering.

Department of Mechanical Engineering-Engineering Mechanics

Thesis Co-Advisor: *Jason Blough*

Thesis Co-Advisor: *Darrell Robinette*

Committee Member: *Carl Anderson*

Committee Member: *Chuck Van Karsen*

Department Chair: *William W. Predebon*

www.manaraa.com

المنارة للاستشارات
www.manaraa.com

Table of Contents

List of Figures vii

List of Tables xviii

Preface xix

Acknowledgements xx

Abstract xxi

1 Introduction 1

1.1 Objectives 1

1.2 Torque Converter Basics 2

1.3 Transmission Basics 6

1.4 Literature Review 7

1.4.1 Torque Converter Experimentation 8

1.4.2 Torque Converter Simulation 10

1.4.3 Wet Friction Clutch Development 11

1.4.4 Transmission Development 11

1.4.5 Transmission Simulation 12

2 Experimental Setup 13

2.1 Test Cell 13

2.1.1 Data Acquisition 14

2.1.2 Dyno Controller 15

2.2 Transmission Instrumentation 18

2.3 Transmission Controller 20

2.3.1 Universal Solenoid Driver II 20

2.3.2 Next Gen Transmission Controller 23

www.manaraa.com

2.4 Torque Converter Instrumentation 26
2.4.1 Impeller and Cover 27
2.4.2 Stator 29
2.4.3 Turbine and Clutch Plate 31

3 Methods 34

3.1 Steady State Testing and Analysis 34

3.2 Transient Testing 34
3.2.1 Trigger Offset Module 35
3.2.2 Test Scripting 37
3.2.3 Data Acquisition Parameters 37
3.2.4 Channel Offsetting 38
3.2.5 Testing Procedure 39

3.3 Transient Data Post Processing 41
3.3.1 Signal Dropout Removal 41
3.3.2 Uniform Resampling 42
3.3.3 Channel Identification 44
3.3.4 Channel Organization 46

3.4 Back Drive Test Development 48

3.5 Gear Shifting 50
3.5.1 Transmission Power Flow 50
3.5.2 Calibration Strategy 51
3.5.3 AmeSIM Transmission Model 54
3.5.4 Dyno Torque Management 59

3.6 Torque Converter Clutch Controls 61

4 Results 62

4.1 Steady State 63

www.manaraa.com

4.1.1 Torque Converter Performance Validation 63
4.1.2 Zero Load Pressure 64
4.1.3 TCC Control and Charge Pressure 72
4.1.4 Torque Converter Clutch Capacity and Friction Material Coefficient 74
4.1.5 Clutch Pressures and Forces 76
4.2 Transient 84
4.2.1 Back Drive 84
4.2.2 Gear Shift 96
5 Summary and Conclusions 113
5.1 Steady State Results Summary 113
5.2 Transient Results Summary 113
6 Recommendations 116
6.1 Testing Recommendations 116
6.2 Instrumentation Recommendations 116
7 References 118
A Copyright Permission 122
A.1 Edward De Jesus Rivera Dissertation Reference Permission 122
A.2 SAE Copyright agreement for Transient Testing in Methods Section 123

www.manaraa.com

B Main Test Stand Drawing 124

C Channel Calibration List 125

D Siemens Test Lab Guide 127

E Test Cell Startup and Operation Procedure 133

F USDB II Operation Guide 138

G SOL Commander Guide 142

H Pressure Transducer Specifications 148

H.1 Kulite XCEL-072 148

H.2 Kulite LE-160 149

I Torque Converter Instrumentation Photos 150

J Telemetry Setup Procedure 173

K Torque Converter Clutch Pressures 178

K.1 Raw Data for 6th Gear 178

K.2 5th Gear TCC Pressure Graphics 179

K.2.1 TCC Released 179

K.2.2 TCC Applied 180

K.2.3 TCC Slip 181

K.3 Raw Data for 5th Gear 182

L Back Drive Pressure Results 183

L.1 Impeller Results 183

L.2 Stator Results 187

www.manaraa.com

L.3 Turbine Results 191

M Back Drive CFD Comparison 200

M.1 Impeller +45 Nm CFD Comparison 200

M.2 Impeller -45 Nm CFD Comparison 201

M.3 Stator +45 Nm CFD Comparison 202

M.4 Stator -45 Nm CFD Comparison 203

M.5 Turbine +45Nm CFD Comparison 204

M.6 Turbine -45 Nm CFD Comparison 205

N Back Drive FFT Color Maps 206

N.1 Impeller Color Maps 206

N.2 Stator Color Maps 209

N.3 Turbine Color Maps 213

O Key Analysis Tools 221

O.1 Telemetry Average Pressure 222

O.2 Telemetry Stitcher 225

O.3 Dropout Resample 228

O.4 Telemetry Organizer 228

O.5 Telemetry Calibration 234

O.6 Tach to RPM 235

O.7 Clutch Capacity 236

O.8 Resultant Force 242

O.9 Shape Graphing 243

www.manaraa.com

O.10 Text Graphing 245

www.manaraa.com

List of Figures

Figure 1-1. Torque converter components 2

Figure 1-2 Torque converter power flow torque multiplication (Left), rigid connection (Right) 3

Figure 1-3. Torque converter performance example 5

Figure 1-4. Concept of clutch application timing with respect to impeller and turbine speed 5

Figure 1-5. Transmission cross section and power flow 6

Figure 1-6. Normally low solenoid driver (left), Normally high solenoid driver (right) 7

Figure 2-1. Transmission test cell layout 13

Figure 2-2. Test cell measurement and communication layout 14

Figure 2-3. Dyno control VI status screen 16

Figure 2-4. Dyno controller manual mode 17

Figure 2-5. Dyno controller experimental mode 18

Figure 2-6. Transmission instrumentation 19

Figure 2-7. USD II and Next Gen solenoid drivers in tower instrumentation rack 21

Figure 2-8. USD II control software main screen 21

Figure 2-9. Solenoid parameters window 22

Figure 2-10. Individual solenoid control window 24

www.manaraa.com

Figure 2-11. Solenoid shift schedule window 25

Figure 2-12. Shift profile and trigger activation window 26

Figure 2-13. Example multiplexed data stream for 7 channels [41].....27

Figure 2-14. Transmitter A instrumentation locations [19].....28

Figure 2-15. Transmitter A hardware for power supply and transmitter [24].....28

Figure 2-16. Transmitter B instrumentation locations [19].....29

Figure 2-17. Transmitter B induction coils and transmitter hardware [24] 30

Figure 2-18. Signal slot for transmitter B cut in impeller shell [24].....30

Figure 2-19. Transmitter C instrumentation locations [19].....31

Figure 2-20 Transmitter C induction coils [24].....32

Figure 2-21. Transmitter C induction coils and transmitter connections [24].....32

Figure 2-22. Hardware for power and signal connections to transmitter B & C [24] 33

Figure 2-23. Signal slot for transmitter C cut in cover [24].....33

Figure 3-1. Test cell measurement and communications with transient capabilities 35

Figure 3-2. Trigger Offset Module (TOM).....36

Figure 3-3. Phase error based on 11.5 kHz sampling frequency 38

Figure 3-4. Channel offset procedure.....39

Figure 3-5. Testing procedure flow diagram.....40

www.manaraa.com

Figure 3-6. Raw data trace with dropouts (top), dropout removed trace (bottom) 42

Figure 3-7. IR Telemetrics signal evolution diagram [44] 43

Figure 3-8. Telemetry sampling procedure [44] 44

Figure 3-9. Channel groups (top), individual channel breakdown (bottom) 45

Figure 3-10. Data removal from start and end of channel 46

Figure 3-11. Channel 1 from each run stitched into a time trace 46

Figure 3-12. Example of all channels for transmitter A after post processing 47

Figure 3-13. FFT colormap of channel 2 from transmitter A 48

Figure 3-14. Dyno operation between positive and negative torque 49

Figure 3-15. Back drive speed ratios 49

Figure 3-16. Stick diagram of transmission under study 50

Figure 3-17. Power-on upshift calibration strategy for constant input torque 52

Figure 3-18. Power-on downshift calibration strategy for constant input torque . 53

Figure 3-19. Transmission 1-D model layout 54

Figure 3-20. Current command conversion to pressure 55

Figure 3-21. Solenoid pressure conversion to friction clutch torque capacity 56

Figure 3-22. Example current command profile for a normally low solenoid 57

Figure 3-23. Example current command profile for a normally high solenoid 57

www.manaraa.com

Figure 3-24. Example model results of a downshift from 6th to 5th gear 58

Figure 3-25. Upshift calibration strategy with torque management 59

Figure 3-26. Downshift calibration strategy with torque management.....60

Figure 4-1. Torque converter performance validation.....63

Figure 4-2. Zero load transmission pressure values for impeller and cover: top to bottom- TCC Released, TCC Applied, TCC Slipping.....65

Figure 4-3. Zero load transmission pressure values for stator: top to bottom- TCC Released, TCC Applied, TCC Slipping 66

Figure 4-4. Zero load transmission pressure values for turbine and TCC: top to bottom- TCC Released, TCC Applied, TCC Slipping.....67

Figure 4-5. Line (top) and TCC control (bottom) pressures.....68

Figure 4-6. Centripetal pressure for each impeller and cover channel 69

Figure 4-7. Calculation error for each channel compared to test results 71

Figure 4-8. Impeller and cover centripetal pressures across multiple TCC control pressures.....73

Figure 4-9. Stator centripetal pressures across multiple TCC control pressures.73

Figure 4-10. Turbine and TCC centripetal pressures across multiple TCC control pressures.....74

Figure 4-11. Torque converter clutch capacity 75

Figure 4-12. Pressure profile across TCC 76

Figure 4-13. Force profile across TCC 77

www.manaraa.com

Figure 4-14. Pressure and resultant force acting on TCC example graphic 78

Figure 4-15. Pressure across TCC and resultant force for TCC released 81

Figure 4-16. Pressure across TCC and resultant force for TCC applied 82

Figure 4-17. Pressure across TCC and resultant force for 20 RPM slip 83

Figure 4-18. 45 to -45 Nm test scenario for back drive 84

Figure 4-19. Speed ratio achieved during 45 to -45 Nm test 85

Figure 4-20. Back drive stitched time history for impeller and cover channels ... 86

Figure 4-21. Back drive stitched time history for stator channels..... 86

Figure 4-22. Back drive stitched time history for turbine torus and clutch cavity channels 87

Figure 4-23. Back drive stitched time history for torque converter clutch channels 87

Figure 4-24. Impeller channel 2 pressures during back drive 88

Figure 4-25. Turbine channel 5 pressures during back drive..... 89

Figure 4-26. Stator channel 1 pressures during back drive 89

Figure 4-27. CFD comparison of test vs. steady state values to achieve -45 Nm 91

Figure 4-28. CFD correlation to high speed ratios 92

Figure 4-29. Pressure distribution across stator blade for 45 and -45 Nm..... 92

Figure 4-30. Stator speed identification using pressure data FFT color map 94

www.manaraa.com

Figure 4-31. Hydraulic pump primary frequency 95

Figure 4-32. Multiple frequencies associated with the hydraulic pump 96

Figure 4-33. TCC slipping downshift repeatability verification 98

Figure 4-34. TCC slipping upshift repeatability verification.....99

Figure 4-35. C35R current command profile comparison.....100

Figure 4-36. CB26 current command profile 101

Figure 4-37. Low load, low speed downshift with TCC released- (top to bottom): transmission speeds, transmission torques, clutch pressures, stitched torque converter pressure time history 103

Figure 4-38. Low load, low speed downshift with TCC applied- (top to bottom): transmission speeds, transmission torques, clutch pressures, stitched torque converter pressure time history 104

Figure 4-39. Low load, low speed downshift with TCC slipping 20 RPM- (top to bottom): transmission speeds, transmission torques, clutch pressures, stitched torque converter pressure time history 105

Figure 4-40. Low load, low speed shift with TCC released pressure data comparison 107

Figure 4-41. Low load, low speed shift with TCC applied pressure data comparison 108

Figure 4-42. Low load, low speed shift with TCC slipping pressure data comparison 109

Figure 4-43. FFT of channel 7 measured pressure on the TCC for before, during, and after the shift.....111

www.manaraa.com

Figure 4-44. FFT of channel 6 measured pressure on the TCC for before, during, and after the shift 111

Figure 4-45. FFT of Line pressure for the transmission for before, during, and after the shift 112

Figure D-1. Navigation pane for Test Lab 127

Figure D-2. Navigation bar to select Test Lab window 128

Figure D-3. Channel setup window 128

Figure D-4. Tracking setup window with turbine and output speed windows showing 129

Figure D-5. Acquisition setup window pointing out sampling parameter settings 130

Figure D-6. Measurement window with pressure plot tab open 131

Figure D-7. Exporting data to Matlab in Navigator window 132

Figure F-1. Solenoid driver and power supply mounted in transmission control tower 138

Figure F-2. Control window for USD II software 139

Figure F-3. Solenoid command window for each solenoid 139

Figure F-4. Possible built in operations 140

Figure F-5. Control window light up indicating commands are ready to send to transmission 141

www.manaraa.com

Figure F-6. Sequencer window to create a string of commands to run in a sequence. 141

Figure I-1. Left to right: shaft coupler, transmitter induction coil, head plate, receiver coil on flex plate 150

Figure I-2. Powering induction coil on head plate, receiving induction coil on flex plate 150

Figure I-3. Transmitter coil and head plate placement on transmission housing 151

Figure I-4. Transmitter and hardware for turbine transmitter mounted on clutch plate 151

Figure I-5. Kevlar patch on clutch plate for transmitter 152

Figure I-6. Power and signal pin arrays mounted to shell of turbine 152

Figure I-7. Turbine torus 153

Figure I-8. Stator trailing edge side with receiver induction coil and transmitter hardware mounted in center 153

Figure I-9. Stator leading edge side 154

Figure I-10. Stator laying on top of turbine 154

Figure I-11. Impeller with stator transmitter induction coil 155

Figure I-12. Stator laying on top of impeller 155

Figure I-13. Impeller transmitter hardware mounted to cover. Kevlar patches to allow turbine transmitter signal to escape the torque converter 156

www.manaraa.com

Figure I-14. Turbine transmitter induction coil and Kevlar patches on inside of cover 156

Figure I-15. Impeller torus transducer locations..... 157

Figure I-16. Impeller channel 1 location, leading edge between blades 157

Figure I-17. Impeller channel 2 location, between impeller and turbine..... 158

Figure I-18. Impeller channel 3 location, trailing edge between blades 158

Figure I-19. Impeller channel 4 location, center between blades..... 159

Figure I-20. Cover transducer locations..... 159

Figure I-21. Cover channels 5-7 locations 160

Figure I-22. Stator transducer locations..... 160

Figure I-23. Stator channel 1 location, leading edge/middle/pressure side 161

Figure I-24. Stator channel 2 location, trailing edge/middle/pressure side 161

Figure I-25. Stator channel 3 location, middle of blade/shell/pressure side..... 162

Figure I-26. Stator channel 4 location, leading edge/core/pressure side..... 162

Figure I-27. Stator channel 5 location, trailing edge/shell/pressure side..... 163

Figure I-28. Stator transducer locations..... 163

Figure I-29. Stator channel 6 location, leading edge/middle/suction side 164

Figure I-30. Stator channel 7 location, trailing edge/middle/suction side..... 164

Figure I-31. Turbine transducer locations 165

www.manaraa.com

Figure I-32. Turbine channel 1 location, middle of blade suction side 165

Figure I-33. Turbine channel 2 location, trailing edge pressure side 166

Figure I-34. Turbine channel 3 location, leading edge pressure side 166

Figure I-35. Turbine channel 12 locations, trailing edge suction side 167

Figure I-36. Turbine channel 14 location, leading edge suction side 167

Figure I-37. Turbine channel 15 location, middle blade pressure side 168

Figure I-38. Turbine channel 4 and 13 locations, back of turbine under plate ...168

Figure I-39. Clutch transducer locations 169

Figure I-40. Clutch channel 5 location, outer radius past friction material 169

Figure I-41. Clutch channel 9 location, middle radius 170

Figure I-42. Clutch channel 10 location, outer radius before friction material 170

Figure I-43. Clutch channel 11 location, inner radius 171

Figure I-44. Clutch plate transducer locations 171

Figure I-45. Clutch channel 6 location, middle radius 172

Figure I-46. Clutch channel 7 and 8 locations, inner and outer radius respectively 172

Figure I-1. Power supply for telemetry 173

Figure I-2. Receivers for each transmitter 173

Figure I-3. Digital FV windows- chart display (top), receiver controller (middle), and receiver readout (bottom) 174

www.manaraa.com

Figure I-4. Receiver connected..... 175

Figure I-5. Receiver showing signal strength and recording options 176

Figure I-6. Example of streamed data 177

www.manaraa.com

List of Tables

Table 2-1. Sampling parameters for each measurement type.....15

Table 2-2. Transmission gear ratio including final drive 19

Table 2-3. Transmission measured pressures 20

Table 2-4. Transmitter specifications [41].....27

Table 3-1. Sampling frequency for each type of data.....38

Table 4-1. Summary of tests and operating conditions 62

Table 4-2. Friction coefficient estimates for TCC friction material 76

Table 4-3. CFD parameters and results summary 90

Table 4-4. Steady state speeds required to achieve -45 Nm.....91

Table 4-5. Stator speeds for each speed ratio 93

Table 4-6. Gear shifts completed operating conditions 96

www.manaraa.com

Preface

Multiple objectives were set to be accomplished for this research. First, is developing a test cell that has the capability to run a highly instrumented torque converter and transmission without changing the performance characteristics. A torque converter was instrumented with 29 pressure transducers and placed in a front wheel drive six-speed transmission instrumented to measure clutch and operating pressures. This gives the opportunity to mimic any maneuver that is seen in-vehicle, such as shifting gears.

Second, is developing a procedure for data collection and analysis. The instrumentation was designed for steady state testing, but the need to measure transient events was of interest. The methods that are used are also published through SAE to share the knowledge to others about the capabilities of capturing transient events with multiplexed data. Having this capability opens up the possibilities of what could be studied with the transmission and gives a better insight to where problems can arise.

Third, is creating test procedures that are relevant and that are similar to those in vehicle. The procedures that are covered are baselining the torque converter, gear shifting, and torque converter clutch being released, slipping, and applied. All test results were completed on the same torque converter and transmission. A non-instrumented transmission was used when developing shift and torque converter clutch profiles to avoid damaging the instrumented transmission.

Finally, is presenting the large data sets in a manner that is easy to interpret. By having a summary of the results that is simple improves the odds that additional work will be built off of the results and can be referenced during future development. This became a personal goal of mine to build my experience as well as ensuring that the work completed is stored in a simple and useful manner.

www.manaraa.com

Acknowledgements

Thank you to Ford Motor Company, for without their financial and technical support this project would not have been possible. I would like to specially thank, Steve Frait, Ram Sudarsan Devendran, Jeff Knutson, Soon Park, Mike Leads, and Tom Gochenour for all their time that they put into the project to ensure both the project and my personal success were achieved.

Thank you to all the professors that have impacted my education and taking time from their busy schedules to answer questions and discuss research challenges that I faced. I would also like to thank my committee members, Jason Blough, Darrell Robinette, Carl Anderson, and Chuck Van Karsen, for without their guidance and expertise, I would not be the engineer I am today.

Thank you to IR Telemetrics for providing the instrumented torque converter and technical support. Especially, when developing new procedures and methods when recording transient data.

Thank you to my family and friends for without their support I would not have been able to be successful at graduate school. A special thanks goes out to my girlfriend, Karina, for her unending support, patience, and traveling the graduate school path at Michigan Tech with me.

Finally, I would like to thank Edward De Jesus for his contribution to the project with the test cell development and educating me on torque converter design and operation.

www.manaraa.com

Abstract

A torque converter was instrumented with 29 pressure transducers to measure the torus, clutch plate, and torque converter cavities using telemetry to transfer the data. The torque converter was placed in a six-speed front wheel drive transmission and a test cell was built to drive and load the transmission to mimic in-vehicle performance.

Steady state tests were completed to establish a baseline for pressure performance of the torque converter. The transient events tested include back drive and gear shifting. Back drive showed how the pressure fluctuates across the speed ratios above 1 as well as identifying the stator speed. Gear shifting presented how large the pressure change can be between each gear state. Low speed downshifting, where hydraulic demand can possibly exceed pump capacity, resulted in showing the control over the torque converter clutch was still possible and reliable. These results can be used to improve future calibrations and designs.

www.manaraa.com

المنارة للاستشارات
www.manaraa.com

1 Introduction

Transmissions are complex architectures that transfer power from one location to another and are commonly used in the automotive industry. The constant drive to improve fuel economy causes a large interest in improving transmission efficiency. Transmissions also have an impact on the drive quality that is felt by the driver. Both fuel efficiency and drive quality are controlled by gear shift and torque converter design and calibration.

1.1 Objectives

The objective of this study is to gain an insight on how the torque converter interacts with the transmission through steady state operation and transient events. By understanding what is occurring inside the transmission and torque converter, better calibration techniques can be used to improve fuel efficiency and drive quality. All the measurements are taken using open loop controls, thus eliminating control variation showing only impacts due to the hardware and operation conditions. The information gained can then be applied to future designs.

To achieve this objective a test cell and control strategies had to be developed that was capable of running the transmission through a variety of scenarios. The transmission and torque converter were instrumented and ran through scenarios such as back drive and gear shifting with the torque converter clutch (TCC) applied, released, and slipping. The test scenarios were constructed to mimic, as closely as possible, in-vehicle performance. Data analysis techniques were also developed to handle both steady state and transient event post processing. All the development work and results are presented in the following sections.

www.manaraa.com

1.2 Torque Converter Basics

Torque converters are a turbomachine that transmit power from a driver to a driven component via a fluid interface. There are many different architectures of torque converters for a variety of applications, as seen by [1, 2]. A basic torque converter is made up of three elements, the impeller, turbine, and stator, making up the torus. The addition of a clutch plate allows for the input to be rigidly locked to the output resulting in almost 100% efficiency in power transmission. The torque converter used is this study is a three element, single stage, double phase torque converter as described above [3]. Single stage means the torque converter has a single turbine. The double phase means the torque converter can operate in two modes. The first, is torque multiplication with the stator being fixed. The second, the stator is allowed to freewheel via a one-way clutch. Figure 1-1 illustrates each of the components of the torque converter and the terminology that will be used throughout the rest of this document.

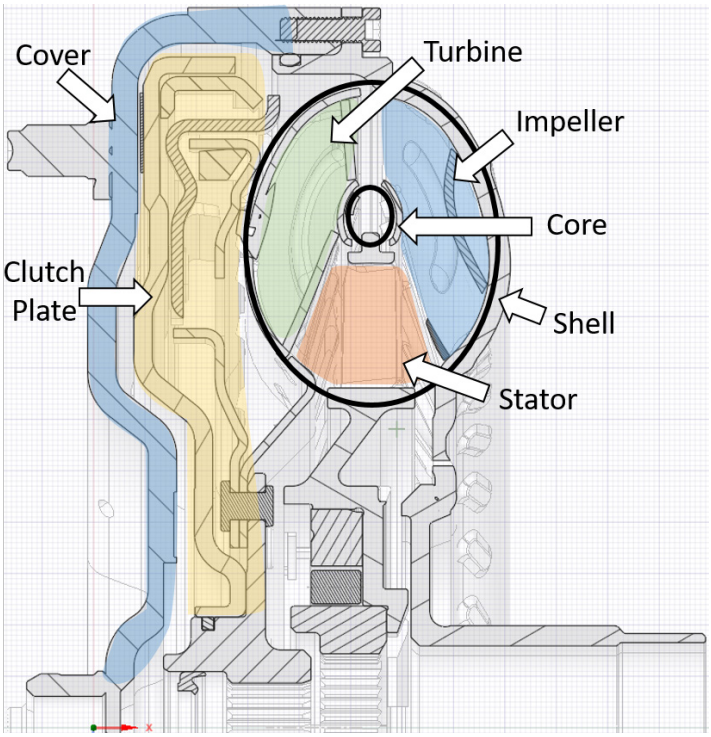


Figure 1-1. Torque converter components

www.manaraa.com

The impeller is attached to the cover that is then mounted to the flex plate and engine. The input power can be transmitted by a fluid or mechanical connection. When power is being transmitted via the fluid the power is transmitted from the impeller to the automatic transmission fluid [ATF] that then rotates the turbine. The flow exits the turbine to the stator which either can cause torque multiplication, during low speed ratios, or free wheel, during high speed ratios. The stator is mounted on a one-way clutch that locks the stator during low speed ratios but will free wheel during high speed ratios. The speed ratio is calculated by Equation 1-1, where N_o is the output speed, N_i is the input speed.

$$SR = \frac{N_o}{N_i} \qquad \text{Equation 1-1}$$

When the power is being transmitted by mechanical coupling, the clutch plate is locked with the cover. This is done by pressurizing the clutch plate to engage the friction material on the clutch with the cover. During mechanical coupling the input and output speeds are the same. Figure 1-2 shows the power flow for fluid and mechanical coupling through the torque converter.

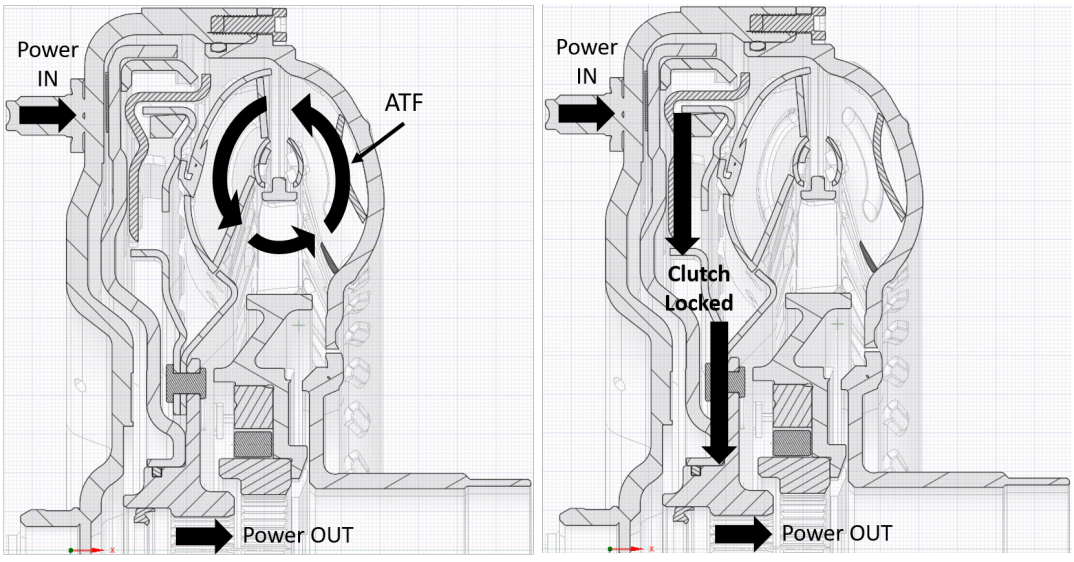


Figure 1-2 Torque converter power flow torque multiplication (Left), mechanical connection (Right)

www.manaraa.com

A torque converter performance is characterized by the K-factor and torque ratio at each speed ratio, as illustrated in Equation 1-2 and Equation 1-3 respectively. The K-factor is determined by the impeller speed N_i, and input torque T_i. The torque ratio is calculated by the output torque T_o divided by the input torque T_i. The efficiency of the torque converter is based on the torque ratio multiplied by the speed ratio, as seen in Equation 1-4.

$$KF = \frac{N_i}{\sqrt{T_i}} \qquad \text{Equation 1-2}$$

$$TR = \frac{T_o}{T_i} \qquad \text{Equation 1-3}$$

$$EFF = TR * SR \qquad \text{Equation 1-4}$$

An example torque converter K-factor, torque ratio, and efficiency curve are shown in Figure 1-3. When the vehicle is not moving the torque converter is operating at stall or a speed ratio of zero. At stall the torque converter is 0% efficient because all the input power is converted to thermal energy and rejected via the ATF. As the torque converter increases in speed ratio so does the efficiency. Once the speed ratio is high enough that the stator begins to free wheel, also called the coupling point, the efficiency increases.

www.manaraa.com

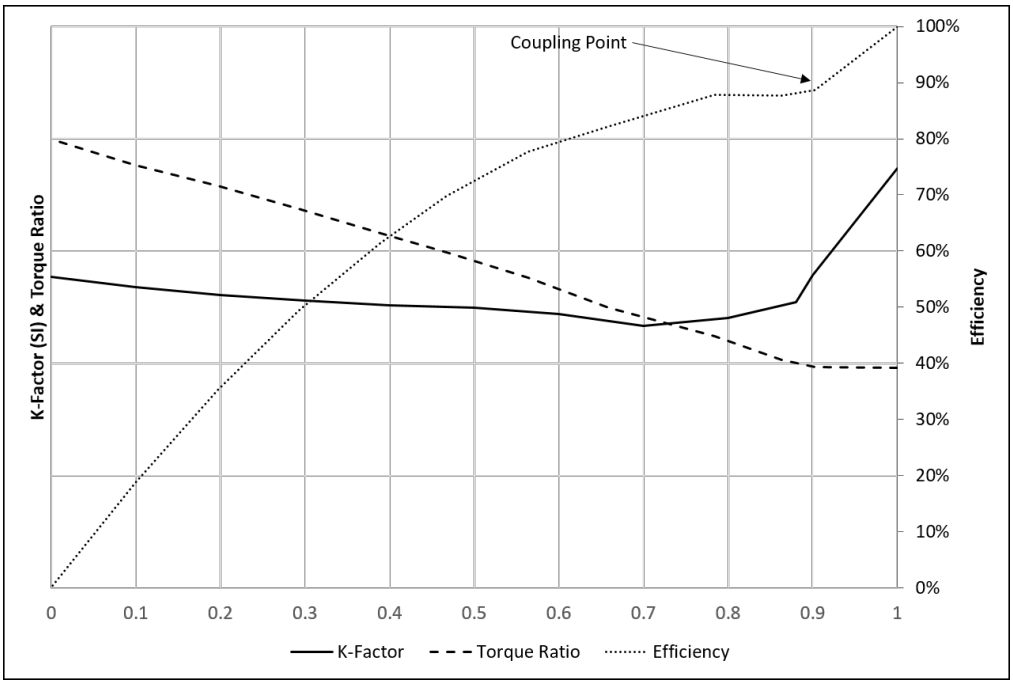


Figure 1-3. Torque converter performance example

When the impeller and turbine speeds converge the clutch plate can be applied and essentially 100% efficiency is achieved. This higher efficiency rate is the motivation to increase the amount of time that the torque converter clutch is applied during operation. Figure 1-4 illustrates how the speeds converge and the larger the speed difference the more energy the clutch has overcome. To large of speed difference can result in glazing or damaging the clutch.

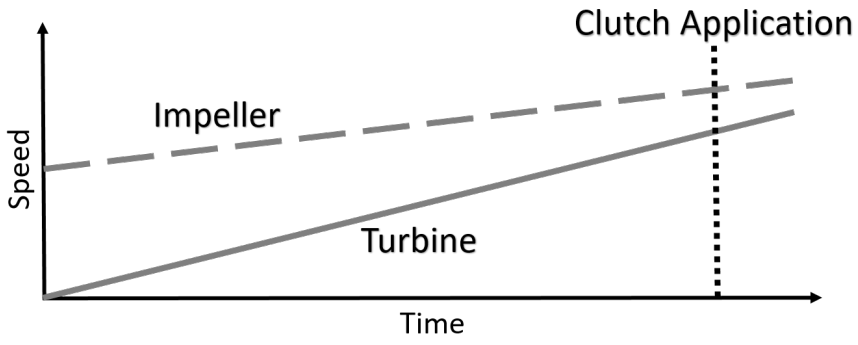


Figure 1-4. Concept of clutch application timing with respect to impeller and turbine speed

www.manaraa.com

1.3 Transmission Basics

The purpose of a transmission is to transmit power from one location to another, which can be accomplished in a variety of methods, such as gears, belts, and clutches [4]. The unit used in this study is a step gear transmission that is an automatic front wheel drive (FWD) 6-speed transmission. The power flow through the transmission under study is illustrated in Figure 1-5. The power from the torque converter is transferred through the transmission by planetary gears, a chain, final drive, and output shafts. The gear ratio is determined by the combination of the clutches and planetary gears.

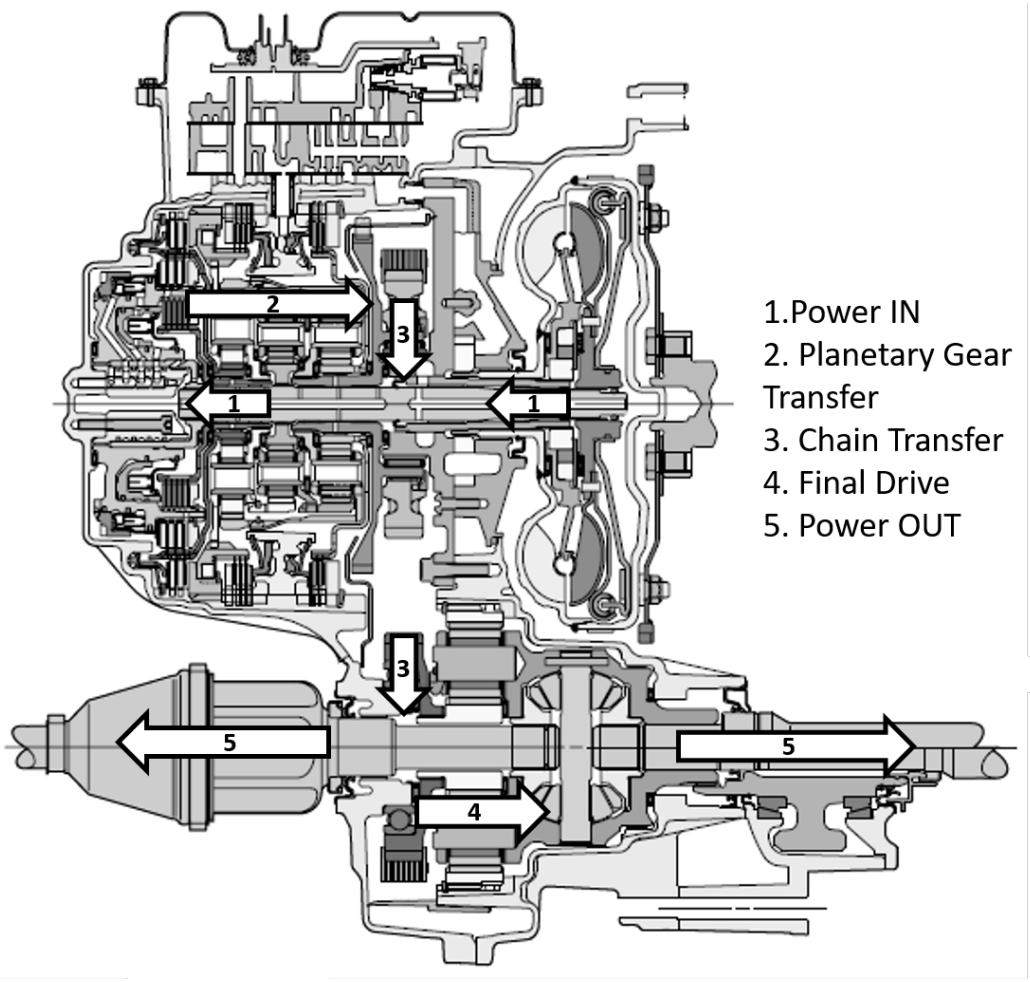


Figure 1-5. Transmission cross section and power flow

www.manaraa.com

The clutches are controlled by solenoid drivers where the pressure is determined by the amount of current sent to the solenoid, as illustrated in Figure 1-6. There are two types of drivers where one is normally low, meaning that when the current is 0 the pressure is also 0. The second driver type is normally high, meaning when the current is 0 the pressures is max. For this research the transmission had to shift gears while under load, so clutch control and shift profiles had to be developed. Gear shift modeling, solenoid pressure profile generation, and dyno management development will be described in the methods section.

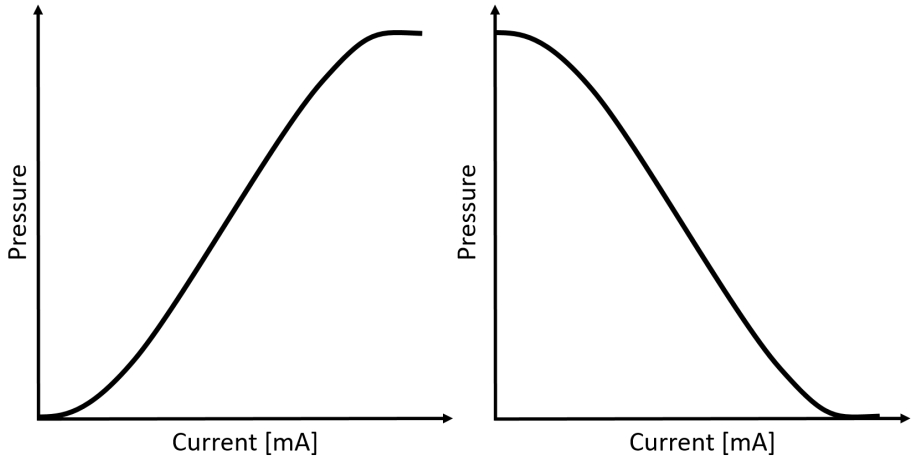


Figure 1-6. Normally low solenoid driver (left), Normally high solenoid driver (right)

1.4 Literature Review

A literature review was conducted to understand past related work and to determine where current research is needed. It was found that there has been extensive instrumentation done on torque converters measuring internal pressures on the torus, but there is a lack of knowledge on pressure measurements on the torque converter clutch. There also has been studies on torque converter and transmission interaction, but none with the torque converter containing specialty instrumentation that can also operate normally in a transmission. This opens up

www.manaraa.com

the possibilities for taking measurements that show how the transmission and torque converter interact. Multiple simulations have been done to predict performance and flow information. This study also allows the ability to improve torque converter simulations by providing a larger amount of data for validation. The following sections are summarizing of the literature review that was used for this study.

1.4.1 Torque Converter Experimentation

Torque converters have been instrumented and studied to improve efficiency and reduce package size. Each component of the torus has been instrumented with pressure transducers to visualize the flow field through the blades. The turbine has been instrumented with pressure transducers and strain gages to observe the loading of the blades [5, 6]. The stator has been instrumented with 72 pressure transducers to measure the profile across the blade. All measurements were static, meaning that the stator was in a fixed position [7].

Flow visualization has also been performed by liquid resin techniques and laser velocimetry [8, 9]. The liquid resin is dotted along the blade and the working fluid is then passed over smearing the resin and showing the flow direction. Laser velocimetry used a Plexiglas torque converter with metallic coated glass particles throughout the working fluid. An argon ion laser was then used to determine the flow velocity during operation. All the above measurements are taken at a speed ratio of 0.8 or lower.

An extensive amount of work has been accomplished in identifying cavitation in torque converters [10-12]. The impeller and stator have both been instrumented with pressure taps to verify the operating conditions that cause cavitation and how cavitation impacts the torque converter performance. A nearfield acoustical technique was also used to identify when cavitation occurred without the need to instrument the torque converter.

www.manaraa.com

1.4.1.1 Transient Torque Converter Testing

Transient testing has been done on torque converters to determine the performance and reverse engineer the design parameters of the torque converter [13]. The transient results were used to validate a nonlinear model to predict torque converter performance. All the transient tests where done with the torque converter clutch released.

Dynamic characterization of the hydrodynamic operation of a torque converter has been tested by having a dynamic input torque [14]. A frequency response function was found to show the attenuation of oscillation when the torque converter is operating as in torque multiplication mode. A second study used the same approach of measuring the frequency response function of the torque converter clutch to improve fuel economy and noise, vibration, and harshness (NVH) [15]. No transient testing involving the torque converter clutch application and release was found.

1.4.1.2 Torque Converter Clutch

The torque converter clutch has been instrumented with thermal couples and pressure transducers to measure the temperature across the friction material [16]. The pressures transducers referenced each side of the friction material during slipping conditions. The friction coefficient and heat rejection rate of the ATF were calculated based on the data collected. The friction coefficient had a large spread due to the limited pressure measurements on the clutch plate. More information on wet clutch development and testing will be described in the following section.

The torque converter clutch operates in three conditions; released, applied, and slipping. Released is used for launching the vehicle from a stop and allows the engine to rotate when the vehicle is stationary. Applied is the most efficient operating condition because the input is mechanically transmitting all the power to

www.manaraa.com

the output, but can have increased NVH issues. Finally, slipping is when the clutch is being applied but is rotating at a slower speed than the input. Slipping the clutch is ideal for transient maneuvers because of the combination of improved efficiency, compared to released, while also having better NVH characteristics over applied. There are many effective strategies to achieve slip control, as seen in [17, 18].

1.4.1.3 Torque Converter Telemetry Instrumentation

Telemetry has previously been used for instrumenting individual torque converter components such as the impeller, stator, turbine and the clutch plate [5, 10, 11, 16]. The torque converter that is under study takes all previous instrumentation methods and combines them into a single torque converter with the impeller, stator, turbine, clutch plate, and cover all being instrumented. This torque converter has also been used for previous research for correlating internal pressures to a computational fluid dynamics (CFD) model [19].

1.4.2 Torque Converter Simulation

Numerical 3-D simulations of torque converters have become more accurate as CFD improve and the knowledge of torque converters continuously grows. The models are validated by comparing the K-factor and TR to experimental data of that torque converter. The pressure and flow profiles are then assumed to be correct [20]. Other simulation studies have looked at blade passing and drive excitations and the correlations to drivetrain NVH [21, 22]. Flow fields and clutch lockup times have also been simulated to reduce clutch application time [23].

A previous study conducted by Edward De Jesus correlated a CFD model with experimental data from the instrumented torque converter used in this study. The model predicted K-factor and TR within 6% of experimental. The pressure profiles across the blades were also found and compared to the pressure measurements that were taken throughout the torque converter. The model pressures were within

www.manaraa.com

20% of the experimental results [24]. As experimentation on torque converters continue, the accuracy of models can also improve allowing for faster new development and improved prototyping.

1.4.3 Wet Friction Clutch Development

A wet clutch is when the friction material is bathed in a fluid, such as torque converters and step transmissions that are lubricated by ATF. A large variety of clutches have been developed for the use in automotive applications [25]. A single surface friction material clutch is used in the torque converter and multi disk clutches are used in the transmission under study. A major consideration during clutch design and testing is the thermal capacity before failure. By understanding the amount of slip time and energy absorption the clutch can withstand, and the limits are not exceeded, the clutch can have extended life [26].

Multiple studies have been conducted that investigated friction material characteristics during slip, clutch life cycle, and fluid interaction on friction performance [27-30]. All these studies isolate the friction material with the clutch or clutch pack to conduct the study. This is useful for initial research but understanding how the clutch performs with other components is of interest for this research.

1.4.4 Transmission Development

Transmissions have been under study for many years to improve efficiency and improve shift quality. Automatic transmissions have been developed from 4, 5, and 6-speed transmission to the more recent 8, 9 and 10-speed transmissions [31-33]. Methods have been developed to include the impact that transmissions have on engine operations. This was done by building upon Environmental Protection Agency (EPA) test cell capabilities to incorporate an engine transmission package to see the true fuel efficiency and emissions [34].

www.manaraa.com

1.4.5 Transmission Simulation

Multiple simulations have been developed to predict transmission performance to reduce the amount of test and development time. Automatic transmission hydraulics are a complicated system that are made up of solenoid valves, pressure regulators, pressure control valves, and clutch actuator systems. Having numerous components results in a nonlinear system to predict dynamic characteristics. Studies have shown that models can be developed to predict steady state and dynamic characteristics by validating through experimental comparison [35, 36].

Basic models have also been developed to improve shift quality and estimate transmission response. Some of the methods from [4, 37-40] are used for understanding shifting techniques and development. Shifting will be described in further detail in the methods section.

www.manaraa.com

2 Experimental Setup

This research had the opportunity of starting with an empty test cell, so a goal was set to develop a test cell that has the capability to operate numerous models of transmissions. The following sections explain the development of the test cell, dynamometer controller, data acquisition, transmission instrumentation, transmission controller, and torque converter instrumentation.

2.1 Test Cell

A test cell was built to operate the 375 Nm input torque capacity FWD 6-speed transmission. A General Electric 380 kW DC dynamometer was used to drive the transmission with a General Electric 540 kW AC dynamometer as the transmission output absorber. The differential in the transmission is welded to allow the absorbing dyno to control the output speed and torque. Figure 2-1 shows the layout of the test with the input dyno on the left, transmission in the middle, and output dyno on the right. The instrumentation will be described in a later section.

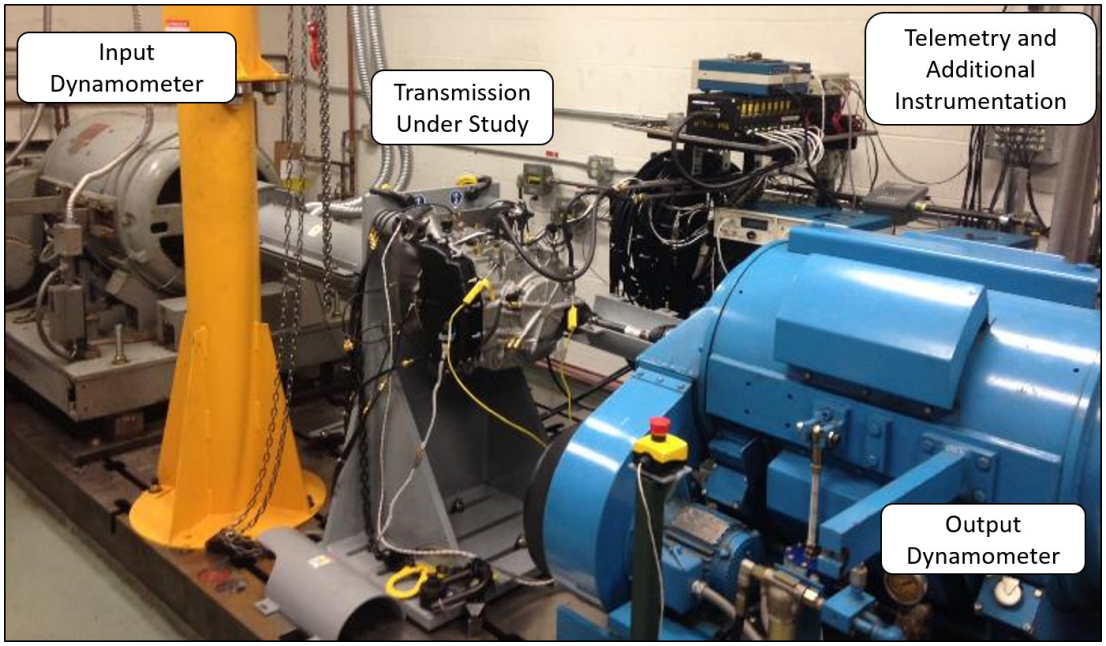


Figure 2-1. Transmission test cell layout

www.manaraa.com

The test stand hardware was designed by a previous graduate student with the main drawing in Appendix B [24]. The test stand is designed so that only the head plate and shafting connections have to be customized to the transmission. A transmission installation, from drain to refill, can be accomplished in 3 hours.

2.1.1 Data Acquisition

The test cell has the capability to record a variety of measurements including pressures, temperatures, speeds, and torques. Figure 2-2 illustrates how each component is connected and where each measurement is recorded. In Figure 2-2 the shaded boxes represent physical hardware, while the white boxes are measurements and controls. Each of the lines represent the flow path of information for physical, electrical, and trigger connections by solid, long dashed, and short dashed lines respectively. The Universal data acquisition (DAQ), in the diagram, records all the measurements. Note, in later sections additions will be made to the layout to allow for transient measurements.

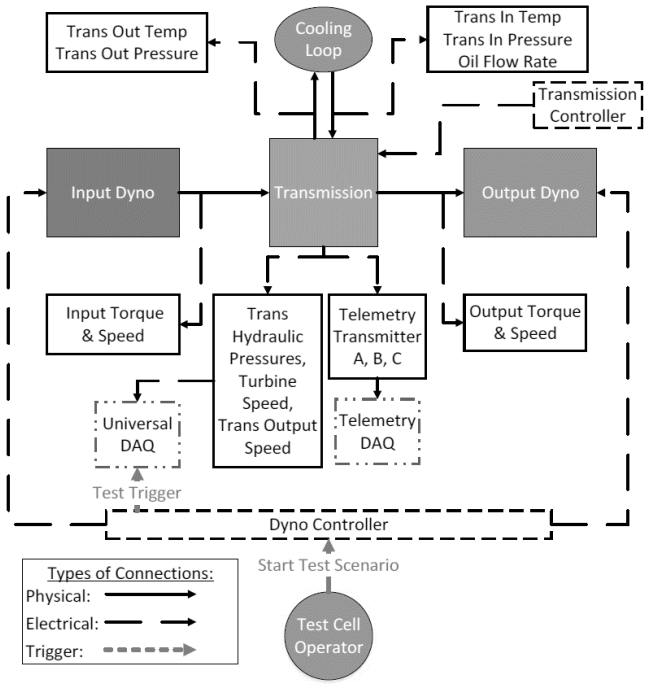


Figure 2-2. Test cell measurement and communication layout

www.manaraa.com

A Scadas III was used for data acquisition, referred to as the Universal DAQ. Each of the channel's calibrations can be found in Appendix C. The data was recorded using the parameters in Table 2-1. The speeds are sampled at a higher frequency because the measurements are a pulse train and the faster the signal is recorded the higher the accuracy. DAQ parameters dealing with transient measurements will be discussed in further detail in later sections. A detailed guide on how to use the DAQ software can be referenced in Appendix D.

Table 2-1. Sampling parameters for each measurement type

Channel Type	Sampling Rate
Speed	51,200 Hz
Torque	6,400 Hz
Pressure	6,400 Hz
Flow	6,400 Hz
Temperature	10 Hz

2.1.2 Dyno Controller

The drive and absorbing dynamometers are controlled by a DYN-LOC IV and an AC2000 IGBT Digital Adjustable Speed Drive controller respectively. A custom LabVIEW Virtual Instruments (VI) is used to communicate to the dyno controllers. The VI has three control windows, one for the test cell status, one for manual operation mode, and one for experiment operation mode. The status screen contains both dynamometer's speed and torque, the temperature and pressure of the inlet and outlet of the transmission, and the flow rate of the oil through the cooling loop. Figure 2-3 shows the layout for the status screen.

www.manaraa.com

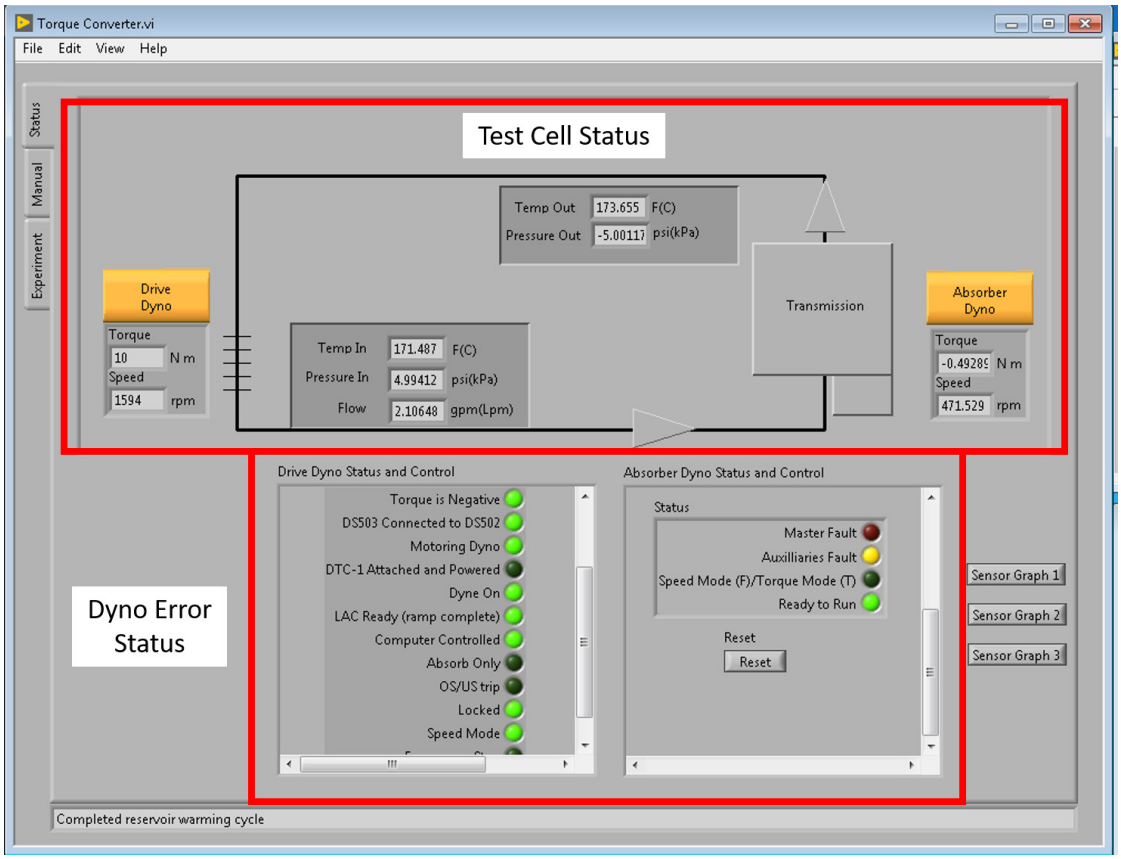


Figure 2-3. Dyno control VI status screen

The dynamometers can be controlled in manual or experimental mode. In manual mode, each dyno can be placed in speed or torque control. The user then inputs a speed or torque value and presses commit. Dyno data can be recorded manually by activating the start/stop button or by setting a time limit that automatically stops the recording. The manual tab also contains the error status of the dynos to show any current errors. Figure 2-4 shows the layout of the manual control tab.

www.manaraa.com

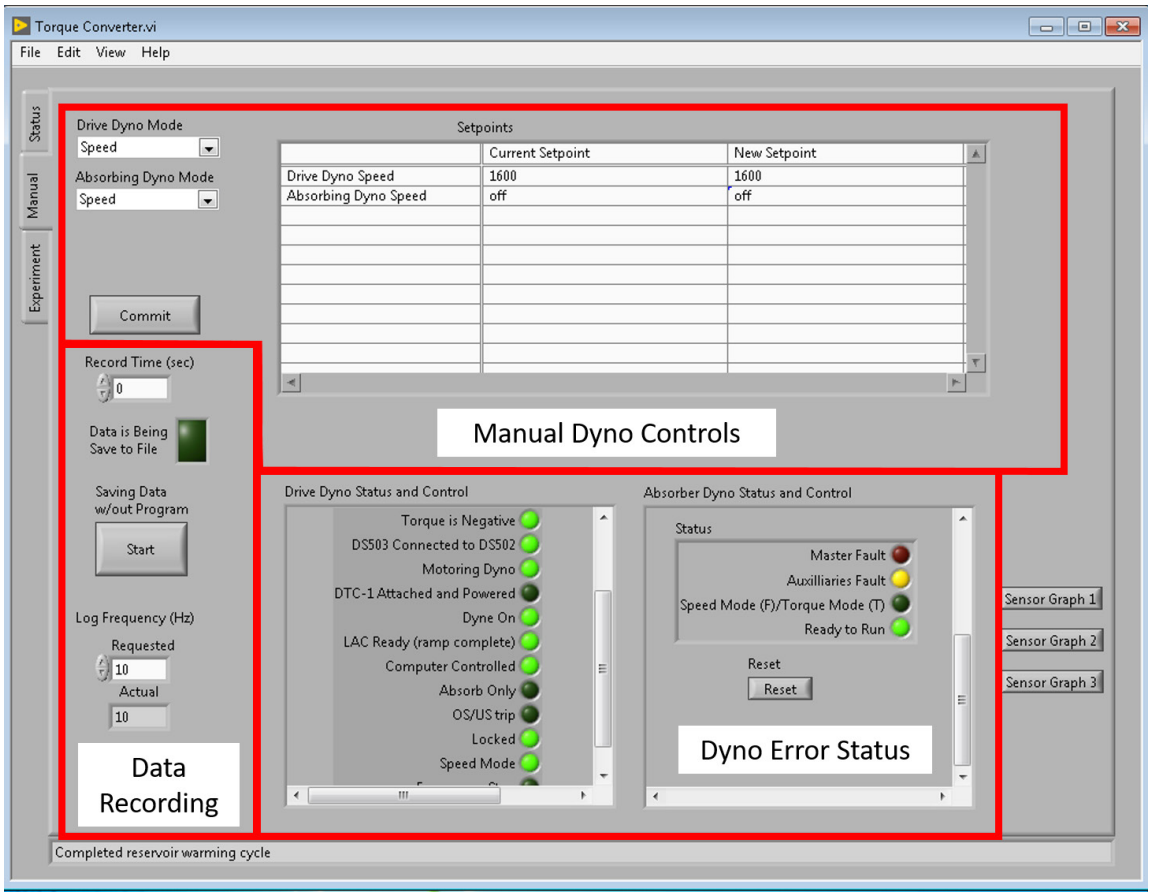


Figure 2-4. Dyno controller manual mode

The experimental mode automates the operation of the dyno commands. The user writes a script, prior to the test run, by defining speed or torque mode for each dyno, the control speed/torque command, and how long to hold conditions before proceeding. Each step can also issue a trigger and record data. Manual record and dyno status operate the same in manual mode. When running programs, the data is saved to a predefined file location and can automatically increment the test file name by selecting the “Auto-increment Filename”. There is also warm up and cool down cycles built in by assigning a script to each button. Figure 2-5 shows the layout of the experimental control tab. This is a brief summary of the dyno software controller capabilities. For a detailed step by step guide reference Appendix E.

www.manaraa.com

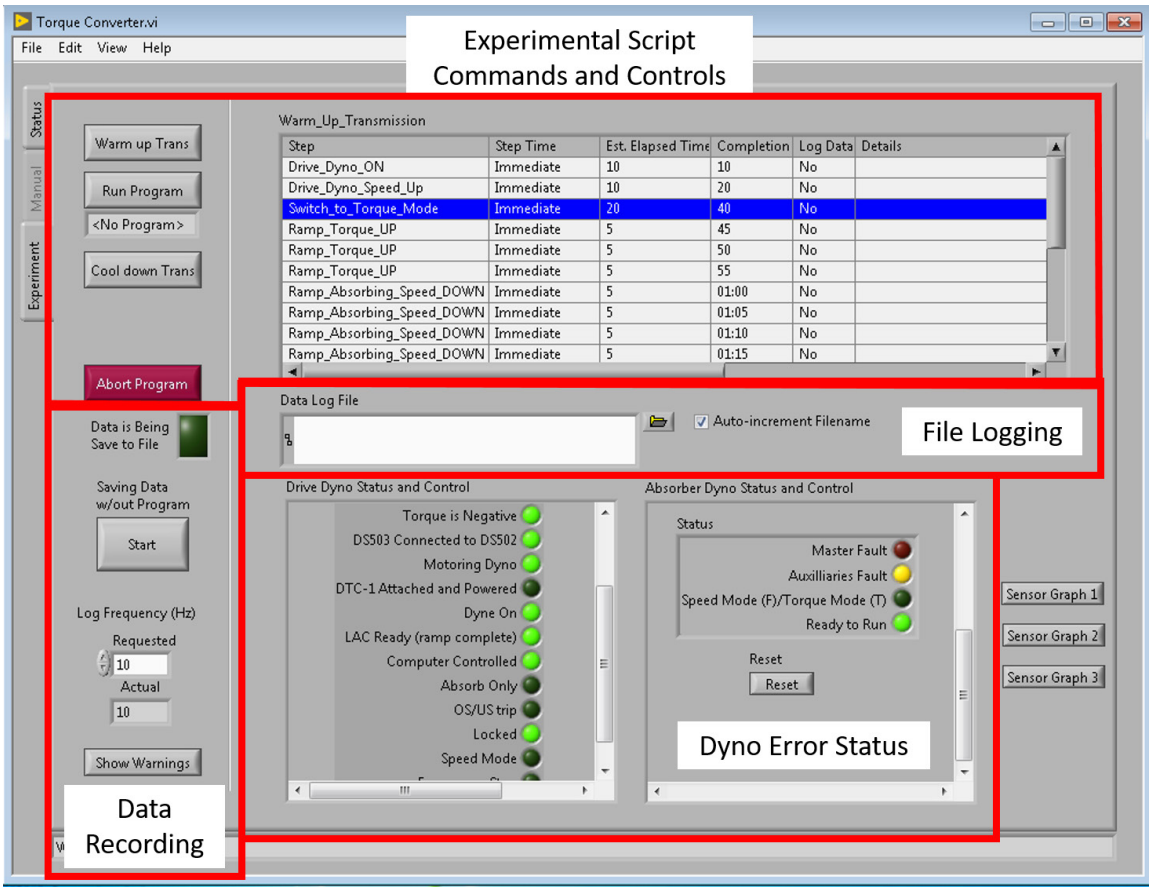


Figure 2-5. Dyno controller experimental mode

The transmission was operated by first starting the input dyno in speed mode with the output dyno turned off. This allows the transmission to pressurize the hydraulics before applying any load. Once the transmission is spinning the input and output can be changed to torque and speed mode respectively. Torque and speed mode was selected because it mimics how a vehicle operates with the driver requesting a certain vehicle speed via the throttle. Then the engine provides a torque based on that throttle and load from the transmission.

2.2 Transmission Instrumentation

The 6-speed FWD transmission has the gear ratios specified in Table 2-2. The majority of testing was completed using 5th and 6th gear to reduce the amount of

www.manaraa.com

output torque that had to be absorbed. The turbine shaft in the transmission and the hardware used to connect the transmission output shaft to the dyno are the weakest points in the system. A limit of 450 Nm on the output dyno provides a safety factor of 2 for both components. The 450 Nm was used as on operation limit when running tests.

Table 2-2. Transmission gear ratio including final drive

Gear State	Gear Ratio
1st	15.38
2nd	9.95
3rd	6.41
4th	4.85
5th	3.36
6th	2.50
Rev	-9.88

Pressure transducers were added to the solenoid body and transaxle case to measure clutch, control, and line pressures, illustrated in Figure 2-6. The channels that are recorded from the transmission instrumentation are listed in Table 2-3, but the channels of interest are Line, TCC Apply, TCC Release, and all clutch pressures. The other pressures were used for monitoring purposes. All pressures in the transmission are measured downstream of their respective pressure regulators.

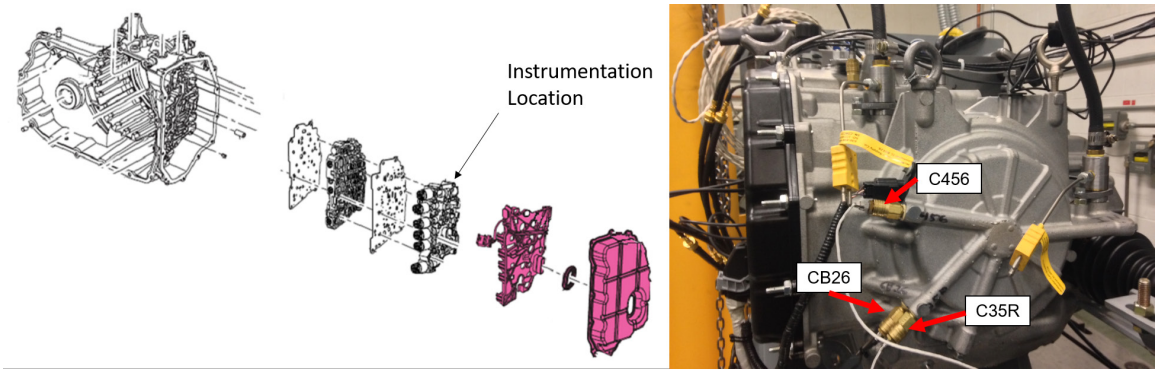


Figure 2-6. Transmission instrumentation

www.manaraa.com

Table 2-3. Transmission measured pressures

Operation Pressures	Clutch Pressures
Transmission Inlet Oil Pressure	CB1234
Transmission Outlet	C35R
Line	CB26
Variable Bleed Solenoid TCC	C456
Variable Bleed Solenoid Line	CBLR
Solenoid Feed	
TCC Apply	
TCC Release	

2.3 Transmission Controller

A solenoid is an electrically controlled valve that controls fluid flow through the transmission for the purpose of clutch application and torque converter pressurization. To control the transmission a solenoid controller was required. A commercial solenoid controller was used at the beginning of the study, but additional functionality was required later, so a Next Gen controller was developed. Both control systems will be described to document their capabilities.

2.3.1 Universal Solenoid Driver II

The Universal Solenoid Driver (USD) II is a commercial solenoid controller that sends current to each of the solenoids. The USD II was used at the beginning of the research. A 12-volt power supply powers the USD II. Figure 2-7 shows the USD II and power supply mounted in the control tower. The male BNC connectors on the front of the USB II are the current outputs to each individual solenoid.

www.manaraa.com

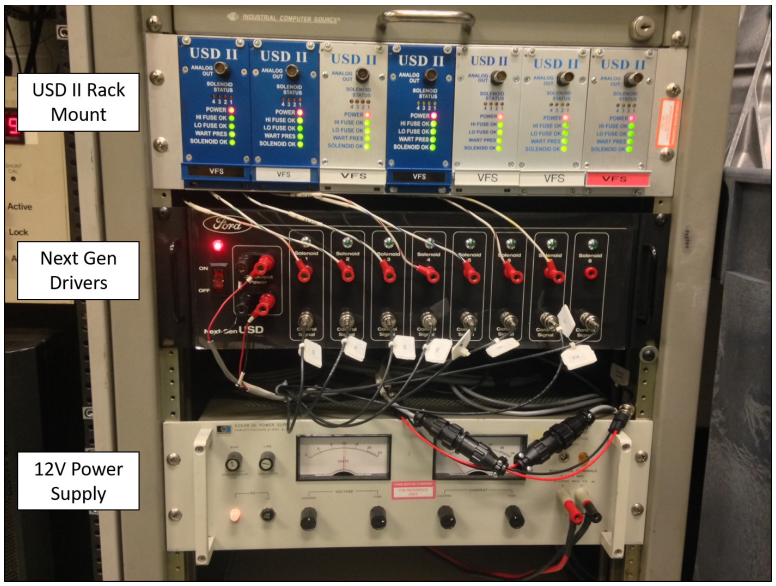


Figure 2-7. USD II and Next Gen solenoid drivers in tower instrumentation rack

The software used to control the drivers allows the user to manually operate each driver or run scripts for automation. In the software each driver has a separate control where the current command can be set between 0 to 255 counts (0 to 1000 mA). Figure 2-8 is a screenshot of the software, where the boxes on the left are the controls for each driver and on the right are the command buttons.

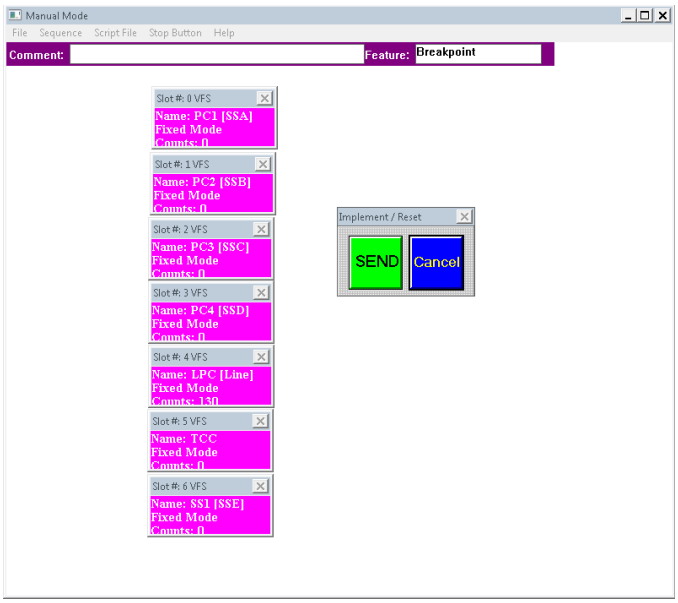


Figure 2-8. USD II control software main screen

www.manaraa.com

To open the solenoid parameters window, double click on one of the driver boxes. In the parameters window, the controls of interest are: mode selection, duty cycle, and frequency. The mode selection allows the user to select between a fixed current command to a built in operation, such a sweeps and steps. The duty cycle is where the 0 to 255 counts is used to command the desired current. A duty cycle is used to achieve the current level by changing the percentage the duty cycle is on. The frequency, set to 66.66 Hz, is not a parameter that changes. Figure 2-9 is a snapshot of the solenoid parameter window. If additional information about operating the USD II controller is needed, reference Appendix F.

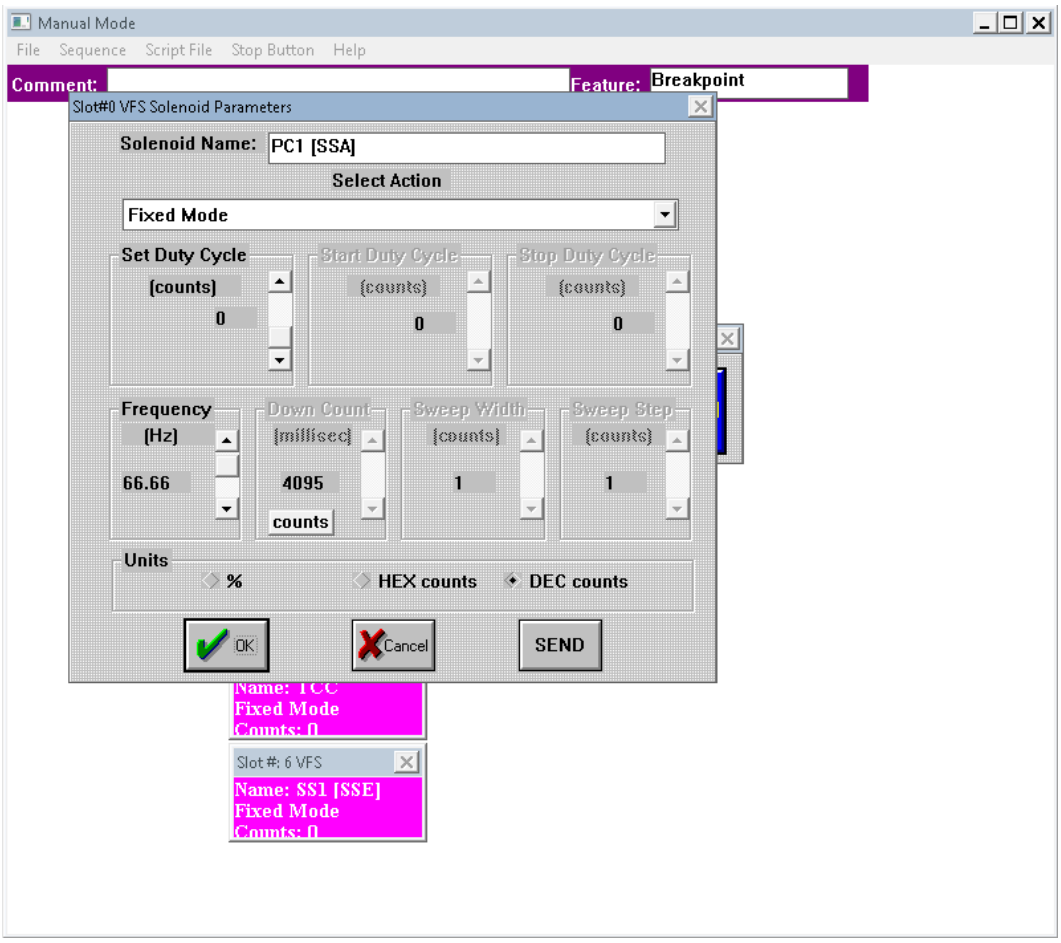


Figure 2-9. Solenoid parameters window

www.manaraa.com

2.3.2 Next Gen Transmission Controller

The USD II is a useful solenoid controller when the transmission is kept in a fixed gear, but having the capability to shift gears under load was of interest. Although, the USD II does have the capability to run scripts the software is time consuming to create new profiles and a more versatile software was necessary. The Next Gen transmission controller includes all the functionality of the USD II, but also allows for gear shifting and trigger activation.

The Next Gen solenoid driver and LabVIEW VI, called SOL Commander, was developed by Ford. SOL commander continued to undergo development throughout the project by both Ford and the MTU team. SOL Commander sends a command to the Next Gen solenoid driver box via a National Instruments card. An equivalent amount of current is then sent to the solenoid. The Next Gen driver is powered by the 12-volt power supply and both can be seen in Figure 2-7. The amount of current being sent to the solenoids was measured from BNC outputs on the driver.

Sol Commander started with the ability to control each solenoid separately to active a fixed gear, same as the USD II. Each solenoid can have a different high and low value and sweep between those values for a specified amount of time and repeat the sweep the predefined number of times. This is useful for solenoid control development, but for this research the sweep function was only used for TCC application and release. Figure 2-10 shows the layout of the solenoid control tab. The graph in the middle shows how the selected solenoid is operating. The stacked plots on the right show what each solenoid is doing based on the shift schedule that is loaded. The light and value indicators next to each of the graphs show which solenoid is active and the current command value. The commands can be implemented without sending to the transmission and this is done by selecting the ENGAGE/DISENGAGE button.

www.manaraa.com

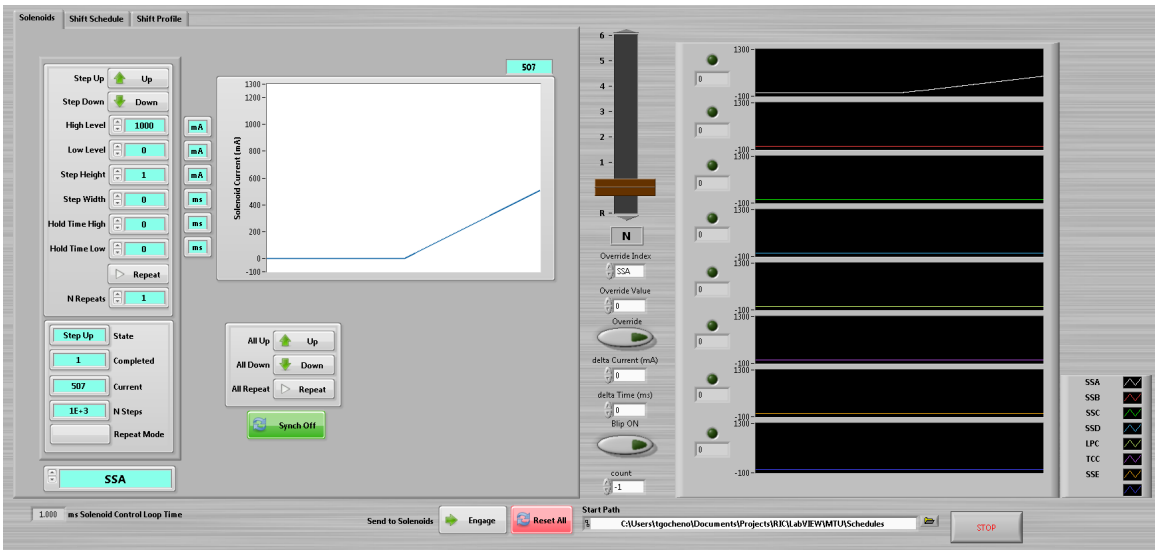


Figure 2-10. Individual solenoid control window

The second tab in the Sol Commander is the *Shift Schedule* selector and modifier. In the shift schedule window, a schedule can be made to select which solenoids are active for each gear. This schedule can be saved and reloaded for future use. The shifting lever, in the center, determines the gear state and selects which column of solenoids to activate. Loading the solenoid schedule is done prior to spinning the transmission. Figure 2-11 is an example of how a shift schedule will appear in the shift schedule tab. Both the solenoids and shift schedule tabs were developed and provided by Ford.

www.manaraa.com

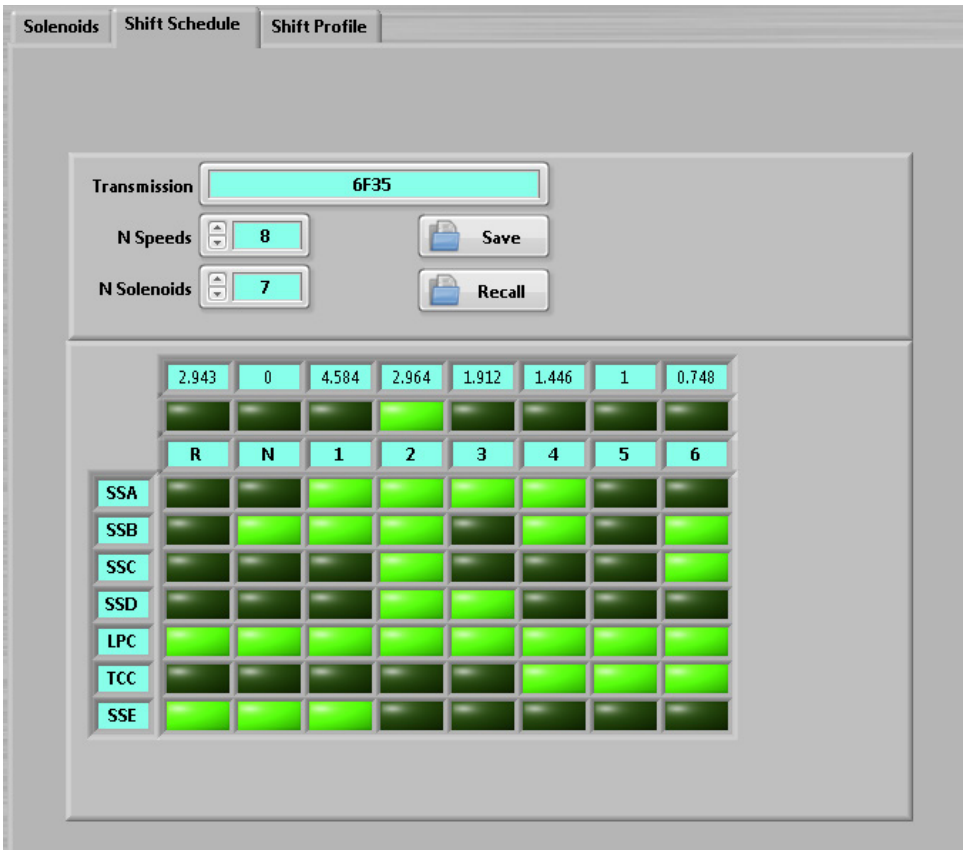


Figure 2-11. Solenoid shift schedule window

The additional capability to load solenoid profiles and activate based on a trigger were required to complete the research. These were additions made to the SOL Commander by the MTU team. An additional tab was added called *Shift Profile.* Under shift profile, a stack plot was added to show a profile of each solenoid. These profiles can be loaded for each gear having different profiles for upshifts and downshifts. Once profiles are loaded for each gear, the set can be saved as a group and reloaded for future use.

With the profiles loaded, they can be activated manually by moving the shifting lever or by using the trigger activation. The user specifies if an upshift or downshift should occur once the trigger is activated. The trigger activation is armed by pressing *Activate on Trigger,* which then disables majority of the controls, except the ability to cancel. This is a built in safety feature to ensure no unwanted changes

www.manaraa.com

are made while the SOL Commander waits for the trigger. Once the trigger is activated, the shift profiles run and hold the last value until a new command occurs. Figure 2-12 shows the layout of the shift profile tab. For a detailed operation guide of SOL Commander reference Appendix G.

Figure 2-12. Shift profile and trigger activation window

2.4 Torque Converter Instrumentation

The torque converter was instrumented with 29 pressure transducers, 7 on the cover and impeller, 7 on the stator, and 15 on the turbine and clutch. Transducers were spread over multiple blades to reduce the impact the wiring and transducers has on the flow characteristics. Two types of pressure transducers were used on the torque converter. The Kulite XCEL-072 and Kulite LE-160 were used and can handle operating temperature up to 235°C and a maximum Full Scale Output (FSO) hysteresis of ±0.5%. For the transducer's specifications reference Appendix H. Only three transmitters were used for all 29 transducers due to packaging limitations inside the torque converter. Each transmitter transmits multiplexed data for approximately 1 second for each transducer. Table 2-4 summarizes the specifications for each of the transmitters.

www.manaraa.com

Table 2-4. Transmitter specifications [41]

Transmitter	Number of Channels	Time Per Channel [sec]	Torque Converter Instrumentation Locations
A	7	1	Impeller and Cover
B	7	1.013	Stator
C	15	1.006	Turbine and Clutch Plate

An example of how the multiplexed data appears is shown in Figure 2-13. The instrumentation was completed by IR Telemetrics located in Hancock, MI. Telemetry was used to transmit the data allowing the torque converter to operate normally in the transmission, which will be described in the following sections.

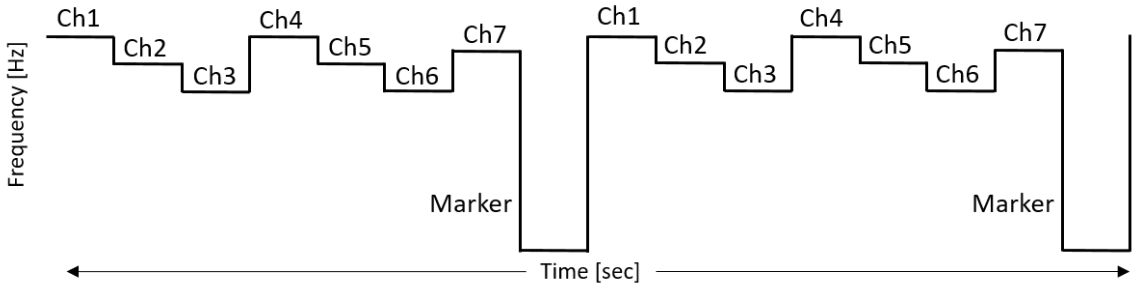


Figure 2-13. Example multiplexed data stream for 7 channels [41]

2.4.1 Impeller and Cover

Transmitter A includes 7 pressure transducers: 3 on the cover, 3 between the impeller blades, and 1 between the impeller and turbine. Figure 2-14 illustrates the instrumentation locations on the impeller and cover. The channel names with square boxes are measuring the clutch cavity while those with a chamfered box are measuring the impeller.

www.manaraa.com

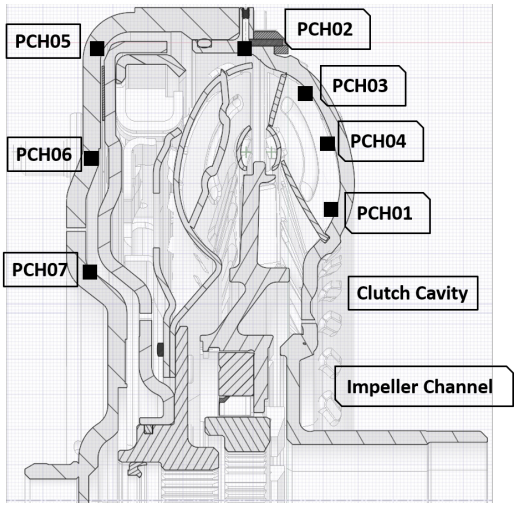


Figure 2-14. Transmitter A instrumentation locations [19]

Instrumentation hardware for transmitter A is located on the outside of the cover. This makes it the most reliable signal because the antennas in the bell house of the transmission can pick up the signal easily. Figure 2-15 shows the hardware located on the outside of the torque converter cover.

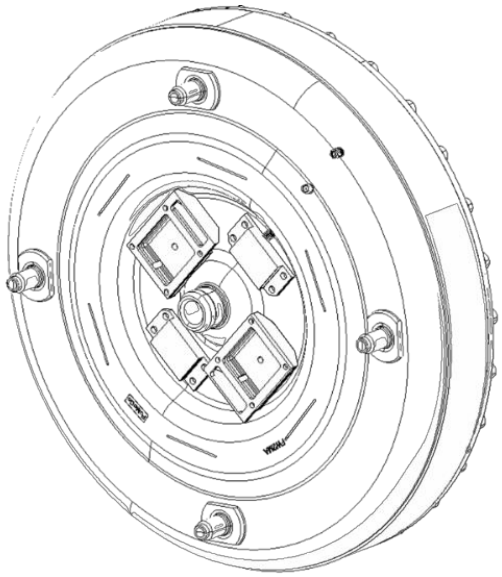


Figure 2-15. Transmitter A hardware for power supply and transmitter [24]

www.manaraa.com

2.4.2 Stator

Transmitter C includes 7 pressure transducers which are all located on the stator blades. Figure 2-16 illustrates the instrumentation locations on the stator. Three radial locations were measured across the blade. Channels near the core, blade middle, and shell are represented by square, dashed, and chamfered boxes respectively. Measurements were also taken on the pressure and suction side of the blade represented by solid and hollow circles respectively.

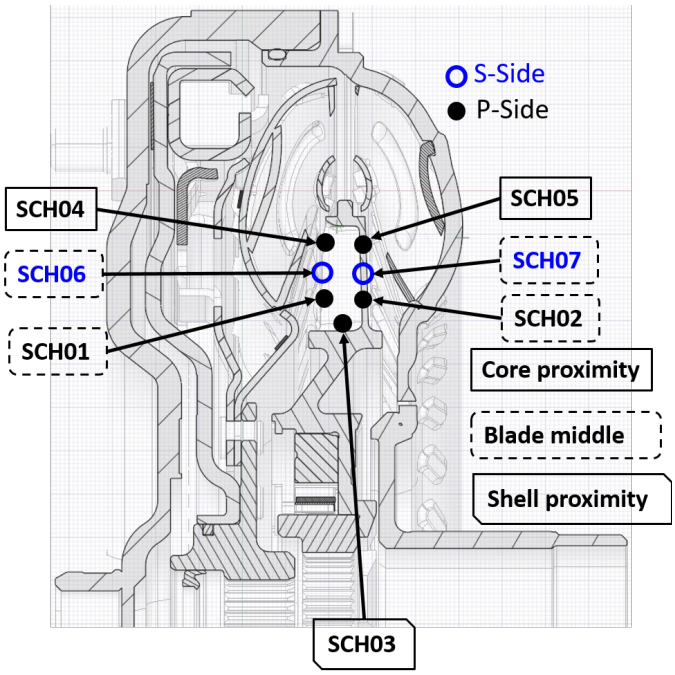


Figure 2-16. Transmitter B instrumentation locations [19]

All the transmitters are powered via induction coils which allows for a wireless power supply. This allows each component to spin normally without any wire interference. Transmitter B's induction coil is mounted below the stator blades, as seen in Figure 2-17.

www.manaraa.com

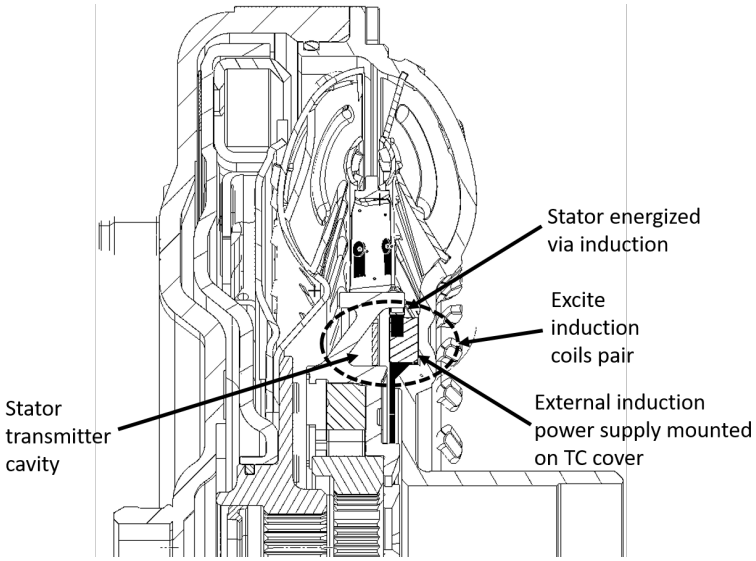


Figure 2-17. Transmitter B induction coils and transmitter hardware [24]

For the signal to be transmitted from the inside of the torque converter, multiple reradiating slots were cut into the impeller shell, as seen in Figure 2-18. The slot is covered by Kevlar sheets on both sides allowing for signal to transmit through without ATF leakage.

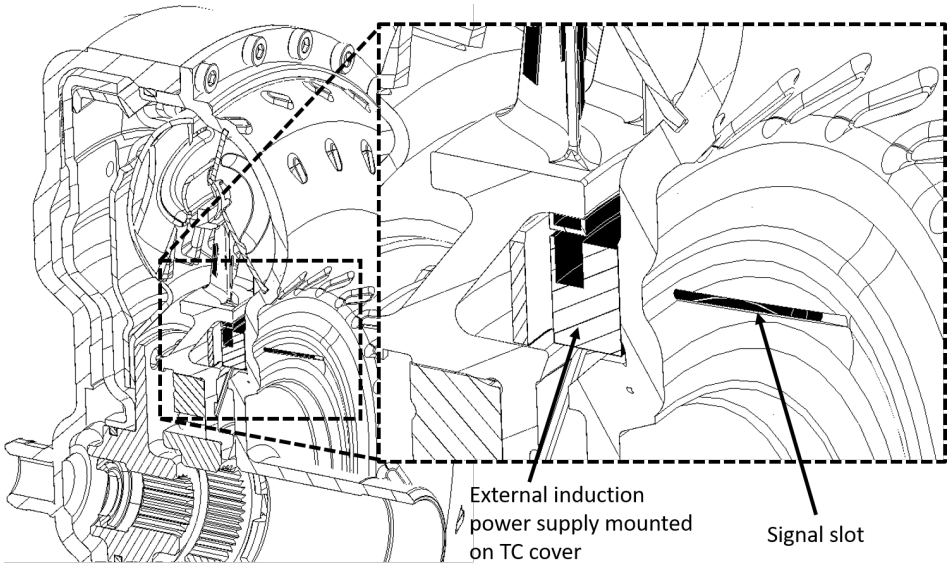


Figure 2-18. Signal slot for transmitter B cut in impeller shell [24]

www.manaraa.com

2.4.3 Turbine and Clutch Plate

Transmitter C includes 15 transducers, 6 on the turbine blades and 9 on the clutch plate/cavities. Figure 2-19 illustrates the instrumentation locations on the turbine and clutch plate. The transducers on the turbine blade are represented by chamfered boxes and solid and hollow triangles for pressure and suction sides of the blade respectively. The transducers measuring the clutch plate and cavities are represented by square and dashed boxes respectively.

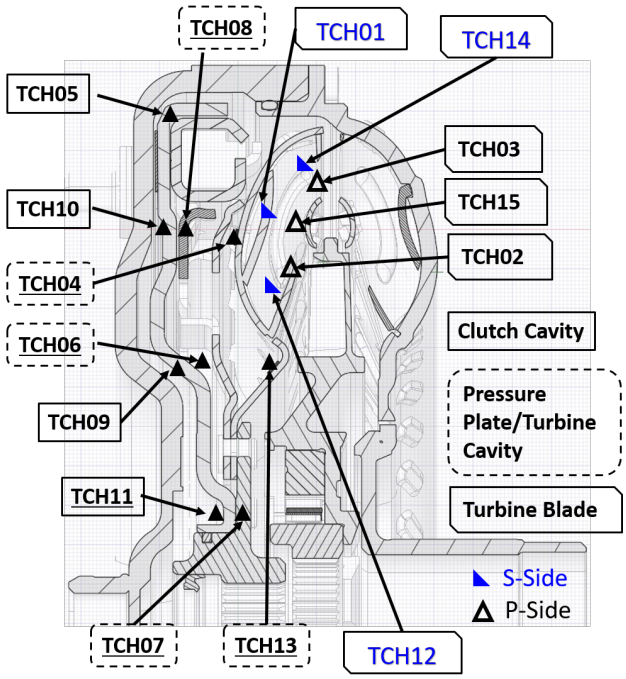


Figure 2-19. Transmitter C instrumentation locations [19]

Instrumentation of the turbine and clutch plate was the most complicated due to their location and functionality. Figure 2-20 shows the transmitters and induction coils mounted to the clutch plate. The instrumentation on the clutch plate is powered directly from the induction coil mounted to the plate, but the turbine required pin connections to transmit the power and signals.

www.manaraa.com

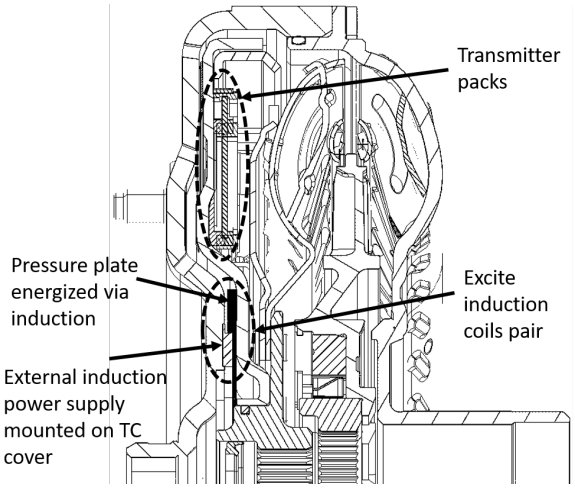


Figure 2-20 Transmitter C induction coils [24]

Figure 2-21 shows the pin connections used to transmit power and communication with the turbine. These pins are designed to float allowing the clutch plate to move axially giving the ability to apply and disengage the clutch normally.

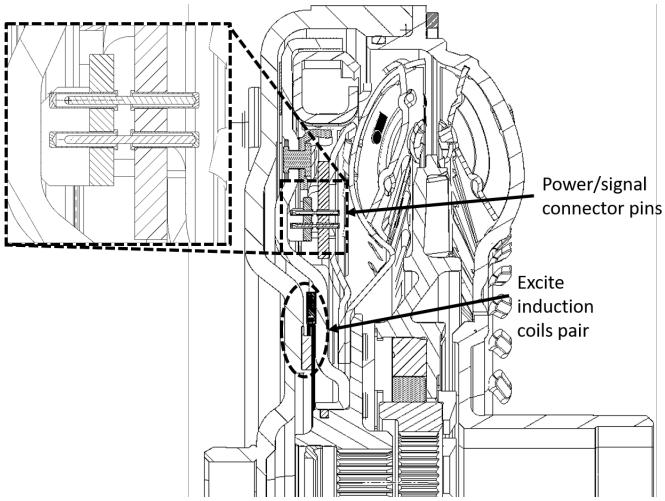


Figure 2-21. Transmitter C induction coils and transmitter connections [24]

Two connector pin arrays were used to have redundancy, ensuring that power and communication will always be active. Figure 2-22 shows the pin arrays mounted to the shell of the turbine.

www.manaraa.com

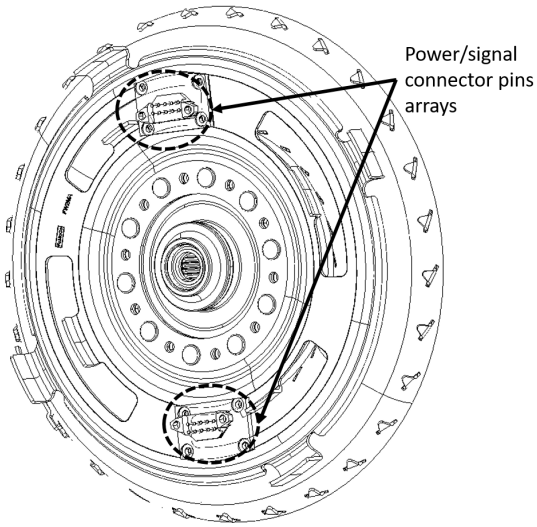


Figure 2-22. Hardware for power and signal connections to transmitter B & C [24]

To transmit the data, slits had to be cut on the clutch plate and cover. Only one slit was required on the clutch plate because the transmitters are rigidly mounted to the plate. Multiple slits were cut around the cover providing a better opportunity for the signal to escape the torque converter and reach an antenna mounted to the transmission. All the slits are covered with the same Kevlar patches as on the impeller shell. Figure 2-23 shows the slit location on the clutch plate and cover. Photos of all the physical transducer locations and telemetry hardware can be found in Appendix I.

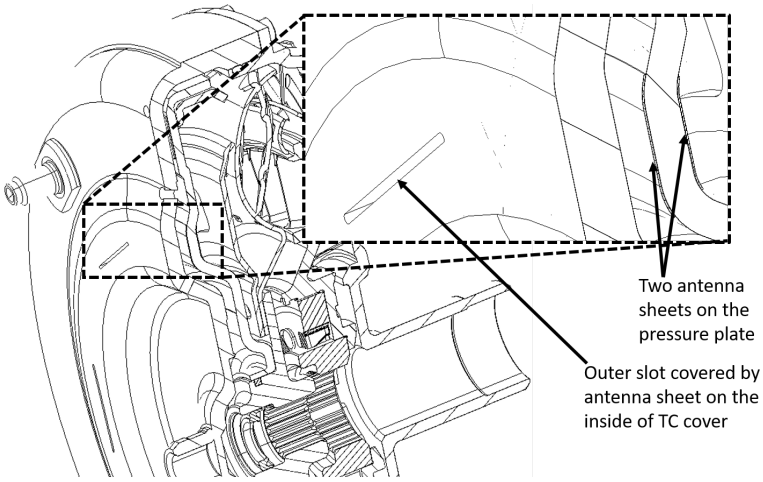


Figure 2-23. Signal slot for transmitter C cut in cover [24]

www.manaraa.com

3 Methods

Multiple procedures were developed throughout this study to improve test cell functionality and accuracy of mimicking in vehicle operation. The procedures are broken into steady state and transient testing. The following sections describes how each method was used and how the data is analyzed.

3.1 Steady State Testing and Analysis

Steady state testing was implemented first in the test cell to better understand the operation of the transmission and torque converter. The instrumentation in the torque converter is also ideal for steady state testing because of the multiplexed data. This is because when running at steady state the conditions are assumed to be constant and only one cycle through the channels are required to get the pressure measurements. The software, provided by IR Telemetrics, also outputs a document with the steady state pressure values for each channel. With the pressure values broken up by channel, the analysis becomes trivial. The steady state tests were used as a datum for TCC pressures, but the measurements of real interest were transient maneuvers.

3.2 Transient Testing

To be able to take transient measurements with the multiplexed pressure data, a method to repeat the transient event, shift the telemetry recording time, and the ability to sync the operational and pressure data was required. The following sections described the procedure and hardware that was developed to achieve transient testing.

www.manaraa.com

3.2.1 Trigger Offset Module

The hardware and electronics that must be able to communicate to achieve transient maneuvers include the transmission, dynamometer controls, telemetry system, and universal DAQ. Figure 3-1 shows the flow of information between all the above components with the solid, long dashed, and red short dashed lines representing physical, electrical, and trigger connections respectively. Note that the trigger offset module (TOM) and the delayed trigger communications are the additions to the test cell from the previous layout that allows the test cell to acquire transient data. Without these components, the test cell would only be capable of collecting steady state data.

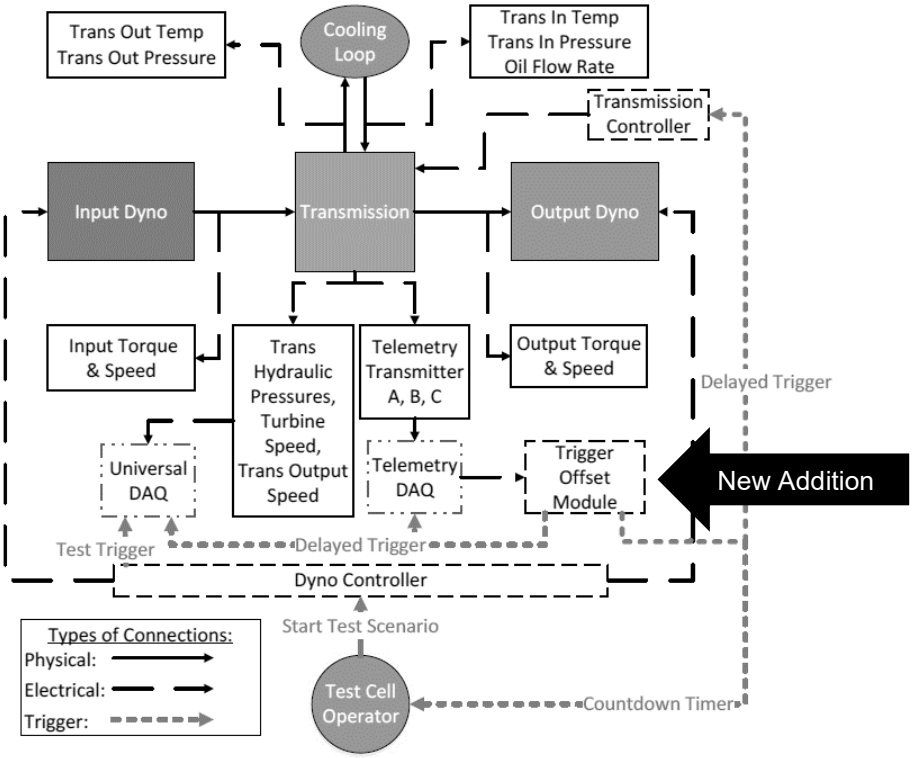


Figure 3-1. Test cell measurement and communications with transient capabilities

www.manaraa.com

The TOM consists of an Arduino Mega 2560, a liquid crystal display (LCD), keypad, and three BNC jacks. The module is shown in Figure 3-2 with each of the components labeled. The signal from transmitter A is fed into the input BNC jack where the Arduino monitors the signal for a marker. When a marker is identified a countdown is displayed on the LCD for the predefined time that was inputted through the keypad (ex. 1 sec, 2sec, 3sec). When the countdown completes, a trigger is sent to the telemetry DAQ and transmission controller.

Figure 3-2. Trigger Offset Module (TOM)

www.manaraa.com

3.2.2 Test Scripting

A test script allows the transient event to be repeated by commanding either dynamometer, transmission, or a combination of the two to complete a maneuver. Manual operation can be done for very basic maneuvers, but is not recommended because the possibility for repeatability error increases. The test script can vary from a basic script, such as only sweeping input speed, to a complicated script, where the input and output dynamometers change speed or torque with the transmission shifting gears.

3.2.3 Data Acquisition Parameters

When working with triggered transient events, extra consideration and understanding is necessary to preserve the integrity and quality of the measurement. Ideally, the event channel sampling should be 180 samples per cycle of the highest frequency of interest [42]. As the frequency of importance increases towards Nyquist, the phase error will increase. The phase error in transient acquisition is related to the sensing of the trigger event since an event cannot be identified until the delta-t after it occurred. Phase errors due to triggering will cause an offset between each of the channels in post processing. If timing between channels is important the triggering error must be minimized. The acquisition of channels which are not transient in nature can be sampled at a reduced rate to improve data storage efficiency. Table 3-1 describes the parameters used for testing. The maximum error that can be seen due to trigger accuracy at 51.2 kHz is 20 microseconds. This is doubled to 40 microseconds due to the use of two triggers per transient event. A maximum 40 microsecond delay with the slowest telemetry sampling frequency of 11.5 kHz results in the phase error shown in Figure 3-3. Frequencies of interest in this study are below 100 Hz where the phase error is minimal thus no significant errors due to triggering are anticipated.

www.manaraa.com

Table 3-1. Sampling frequency for each type of data

Transient Event Data	51.2 kHz
Monitoring Data	6.4 kHz
Telemetry Data	11.5-32 kHz

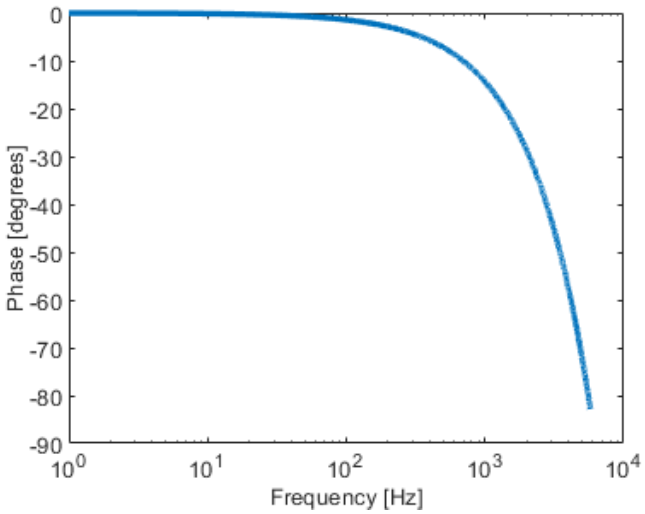


Figure 3-3. Phase error based on 11.5 kHz sampling frequency

3.2.4 Channel Offsetting

Channel offsetting is the process of shifting the start time when the telemetry records data with respect to the start of the transient event. This gives the ability to change which channel is the first in the data set. The test is repeated 16 times to capture the transient maneuver on all the channels. 16 tests are required because transmitter C has 15 channels plus 1 marker. Transmitter A and B only require 8 repetitions of the test due to 7 channels plus 1 marker. Figure 3-4 illustrates a transient maneuver of sweeping input speed and how each test run is offset by 1 channel. By changing which channel the maneuver begins on, different channels will observe different portions of the transient event. The transient event can be any length of time because the telemetry will continue to repeat recording until the end of the test. A transient event of 0.5 or 30 seconds will require the same number of test runs to capture the total event on every channel.

www.manaraa.com

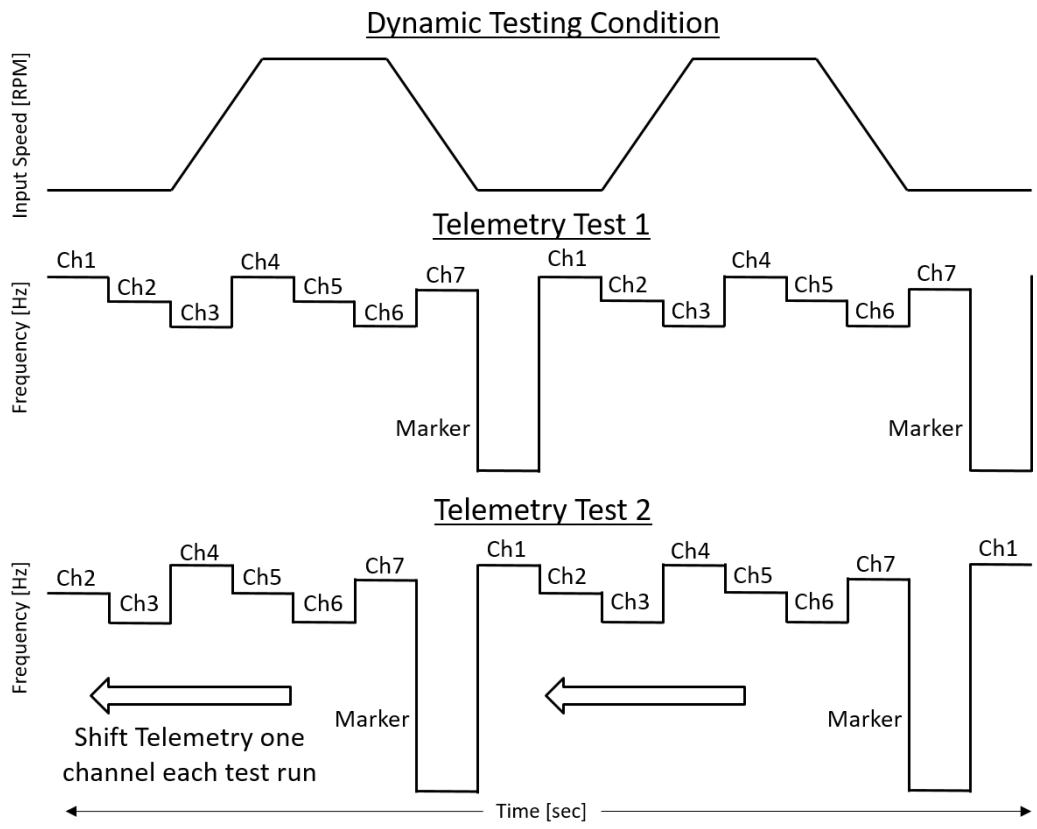


Figure 3-4. Channel offset procedure

3.2.5 Testing Procedure

To collect a data set, a six step process occurs for each test run. Before running, the test script must be ready to start and the TOM must have the required trigger delay for that run. The six step process is broken down into a flow chart shown in Figure 3-5. The first step is to sync the three transmitters by power cycling the system. All three transmitters run off a single power supply allowing for all three transmitters to be turned on simultaneously. To fully discharge the transmitters a two-minute power off cycle is required, which is due to capacitors throughout the system. This causes the transmitters to start on the same channel every time. If this step is skipped, the telemetry data will start on a random channel and capturing the transient event on every channel will not be possible.

www.manaraa.com

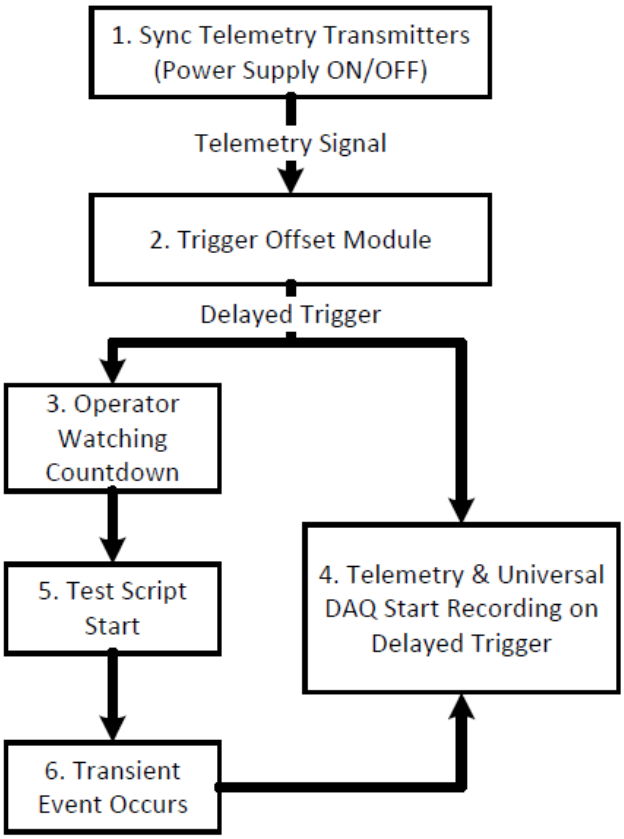


Figure 3-5. Testing procedure flow diagram

Once the transmitters are synched and powered back on, one telemetry signal is monitored by the TOM looking for the first marker. The telemetry signal used in this case was transmitter A because it contained the fewest number of dropouts, reducing the possibility of false markers.

When a marker occurs, the TOM will countdown the predefined delay time. Once the countdown is complete, triggers are sent to the telemetry receivers and universal DAQ to begin recording for a specified amount of time. The operator also starts the test script from watching the LCD on the TOM upon completion of the countdown. The test script will begin to run and initiate the transient event, which is then captured on the telemetry receiver and universal DAQ. This process is then repeated the 16 times to fully capture the transient event by shifting the TOM delay time by 1 sec per run.

www.manaraa.com

3.3 Transient Data Post Processing

Once a full set of test runs have been completed the data must go through multiple processing steps to create a useable time history. This process involves dropout removal, uniform resampling, channel identification, and a channel stitching process.

3.3.1 Signal Dropout Removal

Dropouts are the loss of signal in the telemetry data which results in a false recorded signal. These dropouts are caused by the transmitted signal having to pass through the reradiating slots through the clutch plate and cover. Transmitter A has the least amount of dropouts because the transmitted signal is on the outside of the cover. The dropouts are one to three data points in length averaging 0.1 milliseconds of signal loss.

To remove dropouts, all data points outside of 3 standard deviations of the local mean were identified. A 3 standard deviation range was chosen because statistically 99.7% of the possible mean values will fall in this range [43]. No issues were found with using this technique for the transition between channels. Once the dropouts were identified, they were removed and replaced with the local mean. Figure 3-6 is an example of transmitter B's raw data stream and the dropout removal processed data.

www.manaraa.com

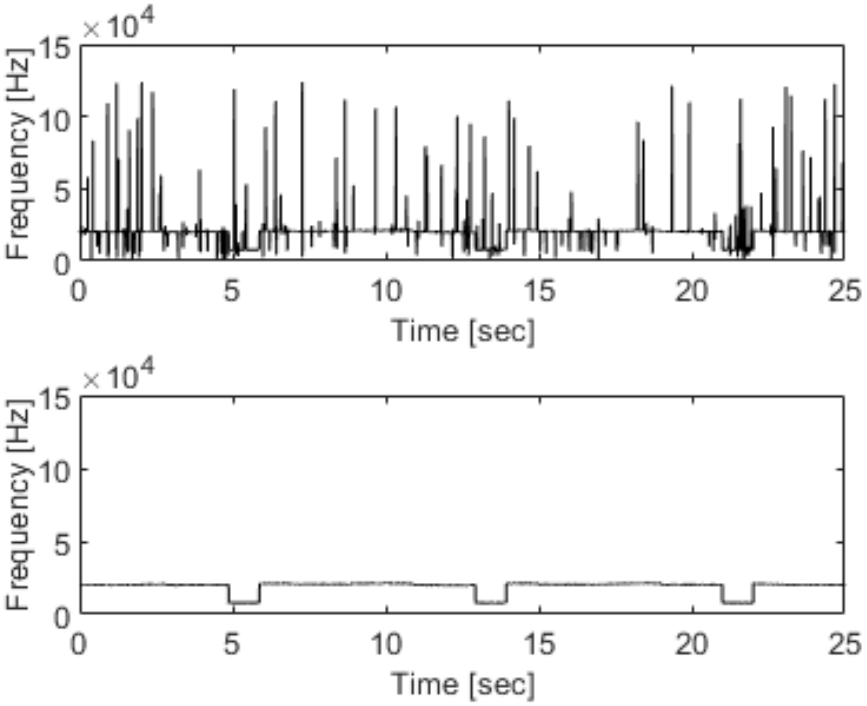


Figure 3-6. Raw data trace with dropouts (top), dropout removed trace (bottom)

3.3.2 Uniform Resampling

The instrumented torque converter was developed by IR Telemetrics with their patented telemetric signal evolution process. Figure 3-7 illustrates how the signal is measured by the transducer, converted to a pulse width modulated (PWM) signal, and transmitted as a microwave signal. The square wave frequency is then recorded and reconstructed back to the original signal.

www.manaraa.com

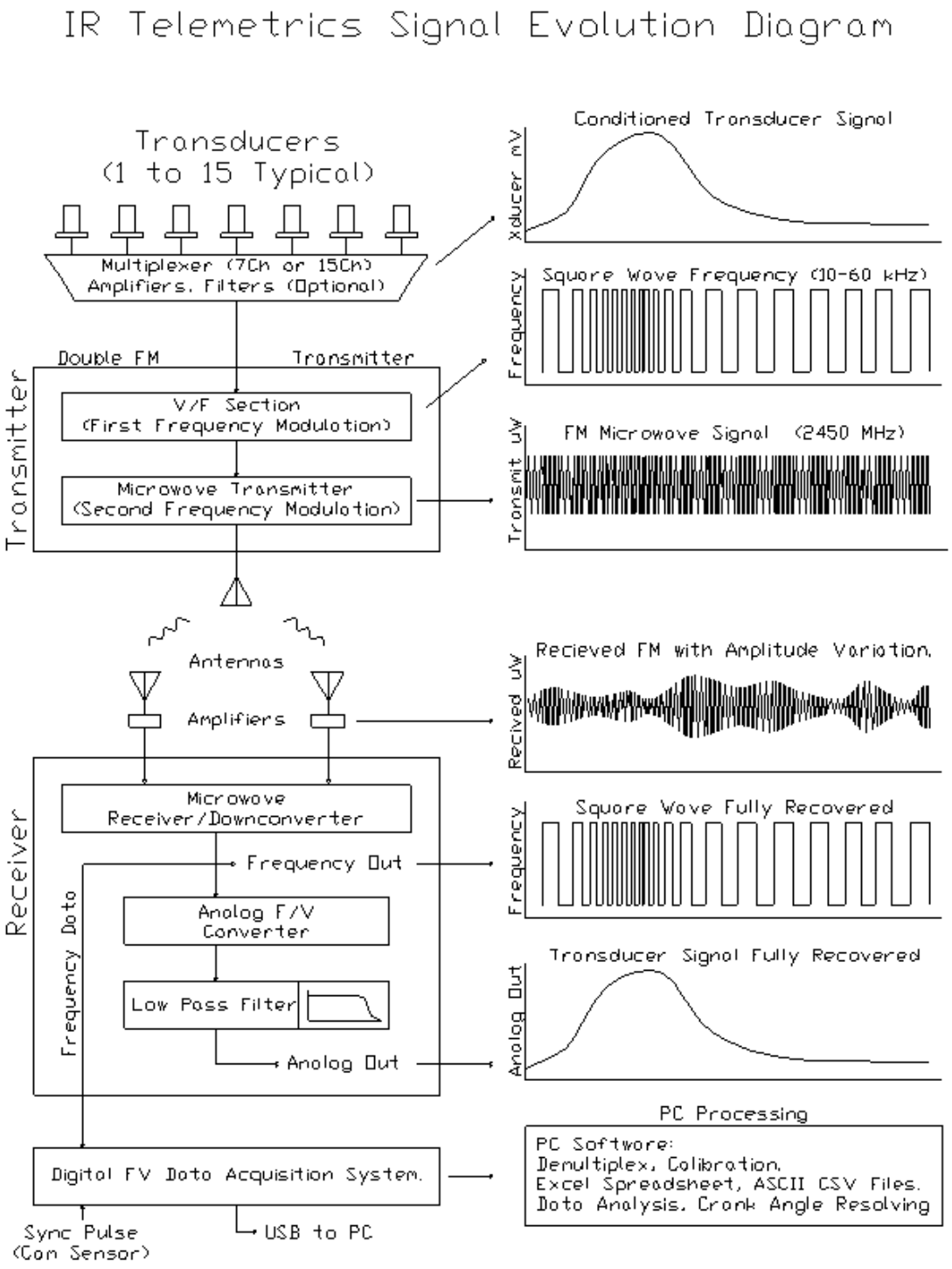


Figure 3-7. IR Telemetrics signal evolution diagram [44]

www.manaraa.com

The reconstructed signal does not have a uniform sampling rate because a sample is taken on every rising edge of the square wave. The frequency of the square wave is directly proportional to the measured pressure, so as the pressure increases so does the frequency. Figure 3-8 is an example of where the samples are taken on the square wave, represented by stars, and shows how the sampling rate varies with frequency.

The data was resampled to a constant sampling frequency of 52 kHz by using a cubic spline interpolation. A uniform time vector was made and a value was interpolated at each new time interval. The uniform resampling allows for easier manipulation of the data for later processing and analysis.

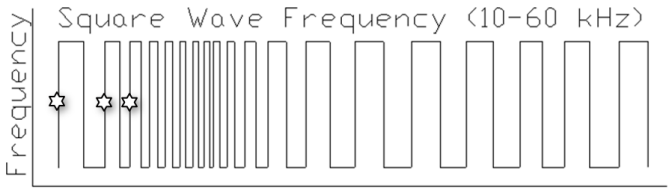


Figure 3-8. Telemetry sampling procedure [44]

3.3.3 Channel Identification

To identify each of the channels, the marker starts and ends are required. The channel length can be calculated by determining the marker length from the marker start and end values for that transmitter. This accounts for the slight time per channel variation between each of the transmitters. The data goes through a two-step process where full channel sets are processed first and then partial channel sets second. The full channel sets are when all 7 or 15 channels were recorded, this is determined by a marker end to marker start. The channel set is then broken into individual channels based on the marker length. Finally, 1% of the data points are removed from the ends of each channel to ensure that no false data is saved from the channel transitions. Figure 3-9 shows the channel sets and how the channels appear after channel identification processing.

www.manaraa.com

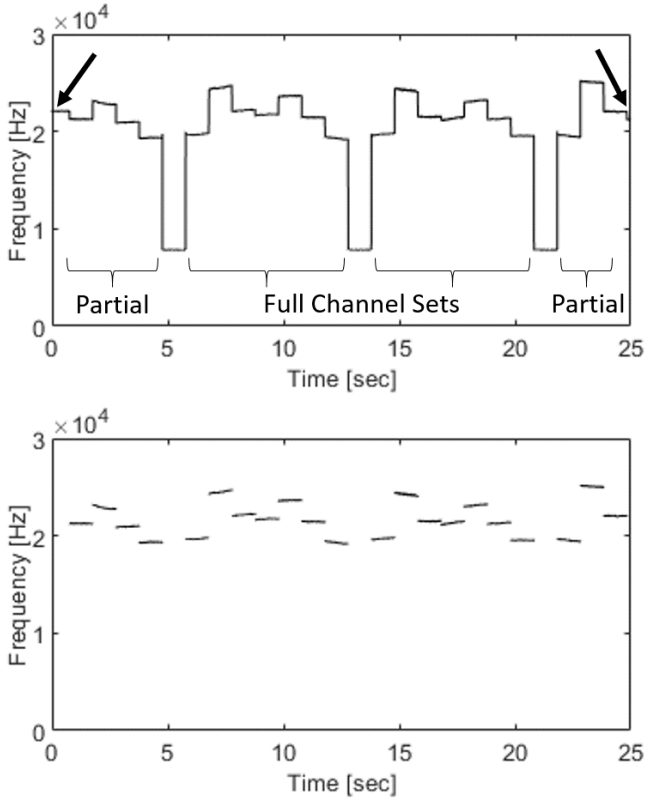


Figure 3-9. Channel groups (top), individual channel breakdown (bottom)

The partial channel sets are only going to occur at the beginning and end of the test run. The partial channel sets go through a similar process as the full sets, but instead of using the marker start and end values, the beginning and end time of the data set are used. The number of complete channels are then calculated using the length of the marker. Then, all the complete channels are split based off of the first and last marker for the beginning and end partial sets respectively. Again, 1% of the data on each of the channels are removed, as illustrated in Figure 3-10.

www.manaraa.com

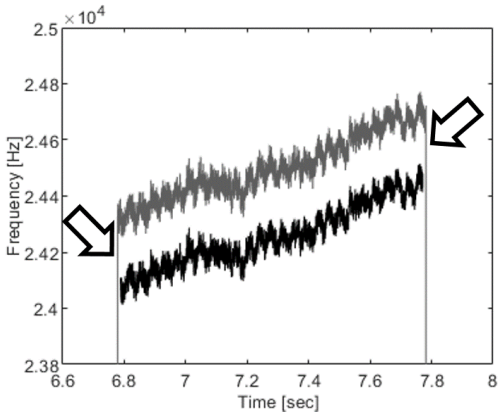


Figure 3-10. Data removal from start and end of channel

3.3.4 Channel Organization

The channel identification process is completed with each test run, which consists of separating all the channels from a test run into their respective channels. For example, all the channel 1's and 2's will be grouped separately into their two respective groups. Once all the channels have been organized into the proper groups, an ordering process is applied. The ordering is determined by the time vectors that are associated with each of the individual channels and organized chronologically. This ordering connects each channel creating a "continuous" time trace. Figure 3-11 shows an example of how channel 1 was pulled from each of the test runs and organized in the proper order.

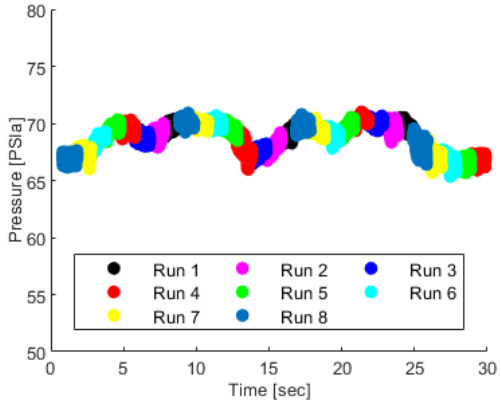


Figure 3-11. Channel 1 from each run stitched into a time trace

www.manaraa.com

The data processing will produce 7 or 15 individual traces depending on the number of channels for that transmitter. Figure 3-12 shows the fully processed data for all 7 channels of transmitter A. It is important to note that each of the channel time histories appear to be continuous, but there are still discontinuities in the data and cannot be treated as one continuous data set. This is mainly a concern if additional post processing on the data is of interest, such as converting to the frequency domain. The time histories can then be synced to the universal DAQ data for further processing and analysis.

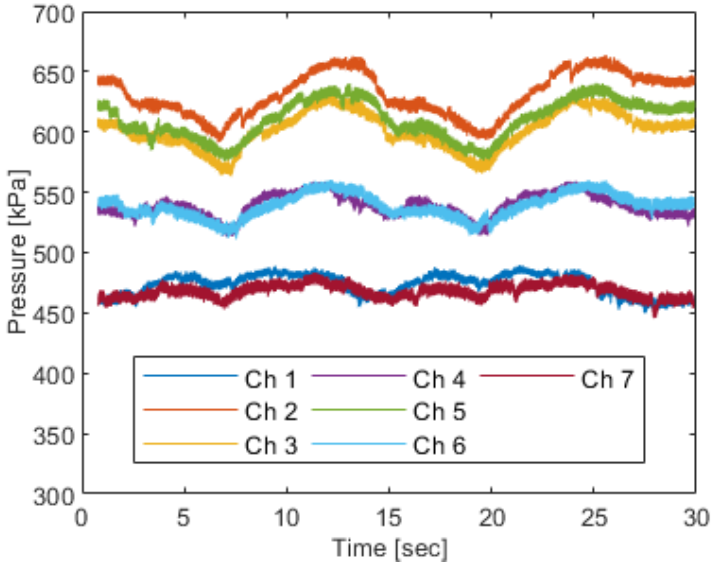


Figure 3-12. Example of all channels for transmitter A after post processing

The data can still be converted to the frequency domain as long as data blocks from the original 1 second recording are used and do not span across runs. Figure 3-11 illustrates the blocks of data that can be used for converting to the frequency domain. Figure 3-13 is an example Fast Fourier Transform (FFT) colormap that was created using channel 2 from transmitter A.

www.manaraa.com

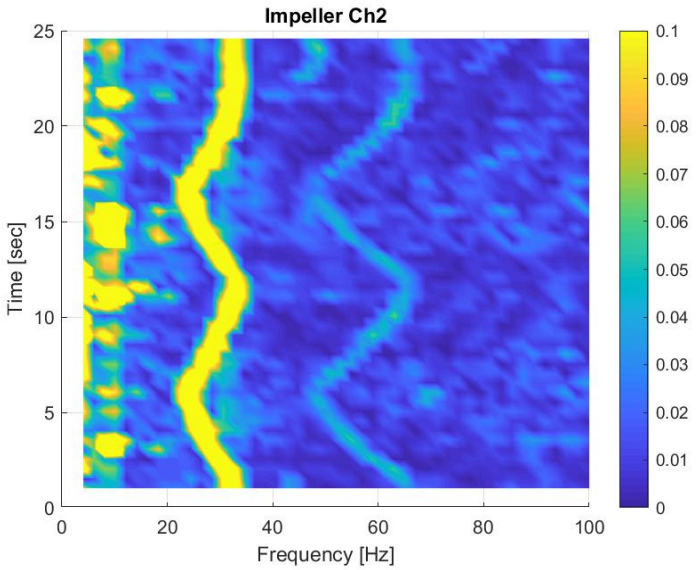


Figure 3-13. FFT colormap of channel 2 from transmitter A

3.4 Back Drive Test Development

Back driving occurs when the power flow in the transmission is reversed where the output is driving the input. This can occur when cruising down a hill without applying the brakes or throttle. The vehicle speed increases down the hill due to the weight of the vehicle instead of power generated by the engine. The engine is at idle speed but since the output of the transmission is going faster than the input a back drive condition occurs. During back drive an open torque converter can see speed ratios larger than 1, while a locked torque converter will drive the input engine speed up.

To create a back drive condition in the test cell, the drive dyno was set to torque mode and the absorbing dyno to speed mode. The absorbing dyno was set to a constant output speed, while the drive dyno oscillated between a positive and negative torque representing engine driving the transmission and transmission driving the engine respectively. The drive dyno did not have the capability to operate at a constant negative torque due to being a DC dyno. Figure 3-14 is an

www.manaraa.com

example of a positive 45 to -45 Nm test where the dashed lines represent the input and output torque and the solid lines representing the impeller and turbine speed. All the back drive tests were completed in 5th gear.

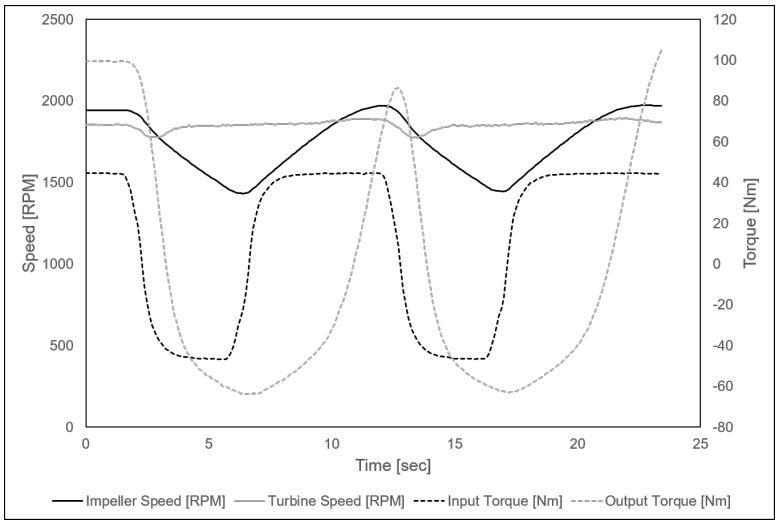


Figure 3-14. Dyno operation between positive and negative torque

Using this back drive method, speed ratios between 0.96 and 1.3 can be achieved. Figure 3-15 shows the speed ratios that are achieved from the test scenario shown in Figure 3-14. By creating test scripts, as described earlier, the speed ratios can be reproduced repeatability.

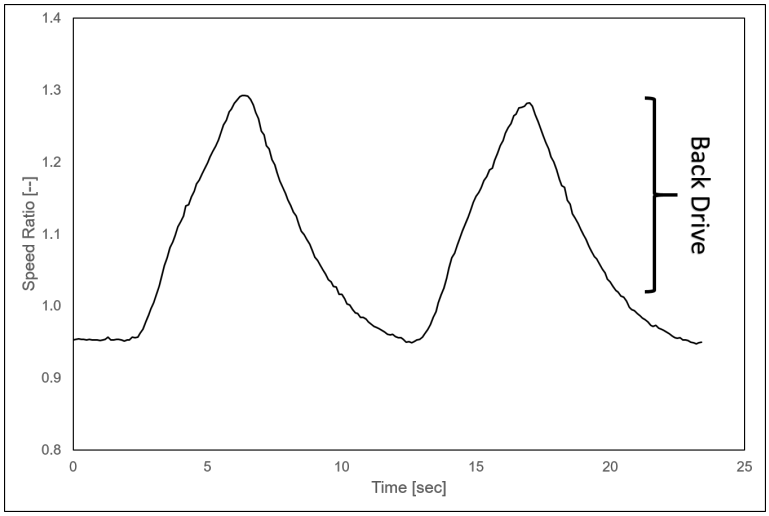


Figure 3-15. Back drive speed ratios

www.manaraa.com

3.5 Gear Shifting

3.5.1 Transmission Power Flow

Before calibrating for a gear shift an understanding of the layout and power flow of the transmission is required. Figure 3-16 is a stick diagram of the 6 speed transmission understudy. There are three planetary gear sets and six clutches. The power flow starts on the left from the turbine shaft as the input of the transmission. Depending on the combination of clutches the power will be transmitted across the three planetary gear sets creating different gear ratios. The output is a chain drive to the final drive ending on the left of Figure 3-16. By visualizing the transmission power flow, an understanding between oncoming and off-going clutches for calibration becomes clearer.

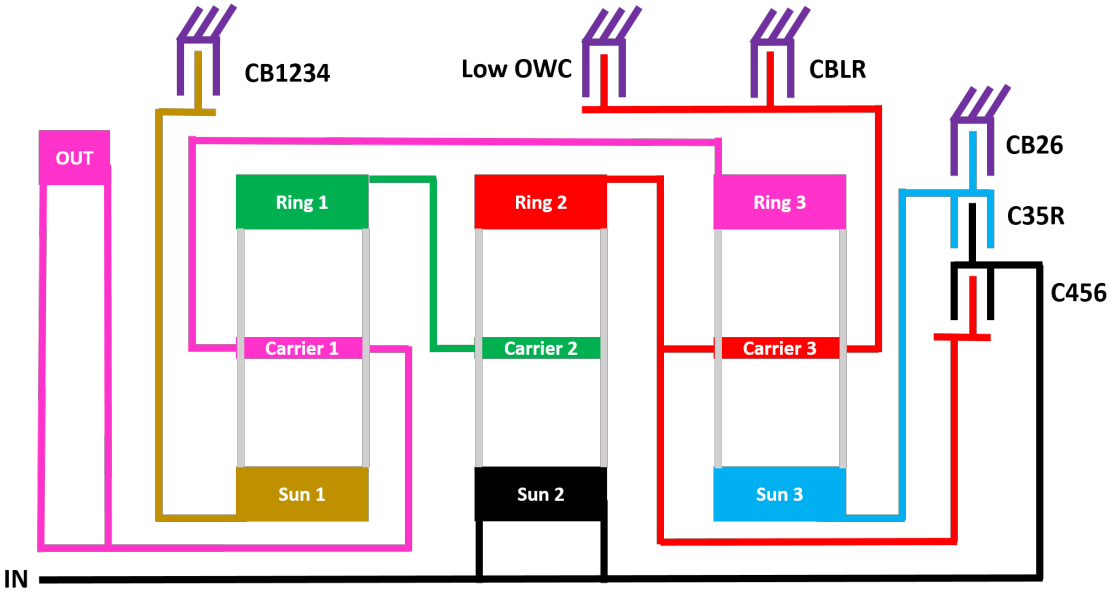


Figure 3-16. Stick diagram of transmission under study

www.manaraa.com

3.5.2 Calibration Strategy

The work done with gear shift calibration was to mimic previous vehicle shift maneuvers as closely as possible. It is important to note that the calibrations used for these tests where modified to accommodate the test cell and were not developed by a transmission calibration engineer. This results in calibrations that are good for representing the hydraulic interaction during a shift but may not be vehicle quality shifts.

The combination of clutches that are on and off determines the gear ratio of the planetary gear sets. The simplest strategy to transition from one gear to the next is by having one off-going clutch and one oncoming clutch. Off-going and oncoming mean that a clutch is losing or gaining capacity to hold torque, which is controlled by the clutch pressure. There are four shifts types that can occur in an automatic transmission: power-on upshift, power-on downshift, power-off upshift, and power-off downshift [4]. Power-on means that the input driver is applying power to the transmission, while power-off is low or no throttle conditions where there is no power to the transmission. This study only looked at power-on upshifts and downshifts. Each shifting strategy uses similar principles but there are some slight differences.

During a shift there are two phases that occur, torque and inertia phase. Torque phase is when the torque is being transferred from one clutch to another without having an input speed change. Inertia phase is when the input speed changes from the starting gear speed to the ending gear speed. During inertia phase, the inertia of the input is playing a role in the final amount of transitional torque that the on-coming clutch must carry.

For this study the input torque and output speed were held constant. Having a constant output speed is not abnormal during a gear shift because of the large vehicle mass, but ideally the input torque would have additional torque

www.manaraa.com

management to get a constant output torque. Having a constant input torque was done to simplify the maneuver and reduce calibration time, but still retained the key hydraulic information of interest. An example of a typical power-on upshift calibration strategy, used for this study, is shown Figure 3-17. During the torque phase the off-going clutch decreases to zero while the on-coming clutch increases to hold input torque capacity. At the end of torque phase, the end gear state is achieved and the output torque decreases to the end gear state torque value. Once inertia phase begins the input speed decreases causing a large torque fluctuation in the output torque. The oncoming clutch has to increase torque capacity to accommodate the output torque fluctuation until the input speed reaches the end gear speed. At the end of inertia phase, the oncoming torque capacity is reduced because the output torque is reduced.

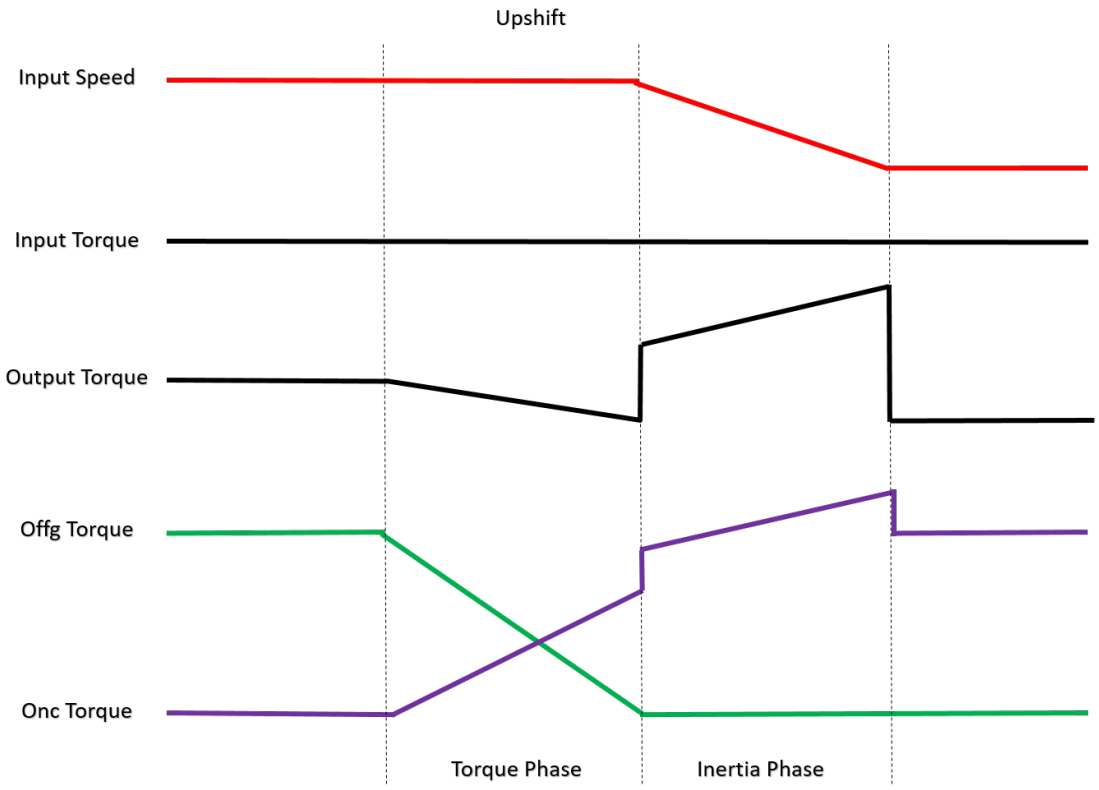


Figure 3-17. Power-on upshift calibration strategy for constant input torque

www.manaraa.com

A power-on downshift is the reversed process of completing a power-on upshift. The downshift first begins with the inertia phase with an input speed increase. Due to a constant input torque, the output torque drops caused by a reduction in off-going clutch torque capacity to allow input speed to increase. At start of torque phase, the input speed has reached the end gear state speed. The off-going clutch torque capacity increases to stop the input speed from increasing. The off-going clutch then reduces torque capacity as the on-coming clutch torque capacity increases. The output torque increases with the oncoming clutch until the end gear has been reached. Figure 3-18 illustrates the calibration strategy for a power-on downshift.

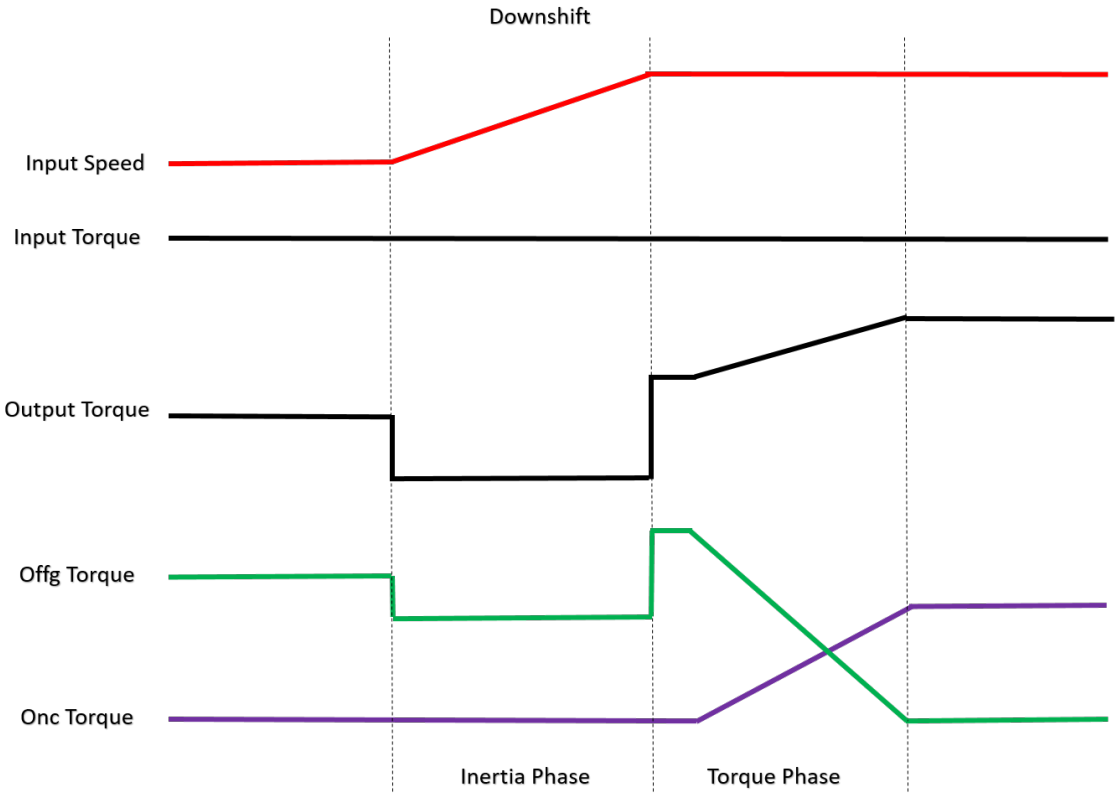


Figure 3-18. Power-on downshift calibration strategy for constant input torque

www.manaraa.com

3.5.3 AmeSIM Transmission Model

A 1-D model of the transmission was built in LMS Amesim to develop shift profiles before attempting with the hardware. The model consists of the transmission inertias, stiffness, damping, planetary gears, and friction clutches. The component connection layout can be seen in Figure 3-19. This model does not contain a torque converter model, so the shift represents what occurs when the TCC is applied. Having the TCC applied is the worst case scenario for torque fluctuation during a gear shift because the large input dyno inertia has a big impact on the torque fluctuation during the inertia phase of the shift. When the torque converter is open, the input and output dynos are not mechanically coupled and free to transition slowly. The model was used to reduce the fluctuation while mimicking the shift calibration profile from the vehicle data.

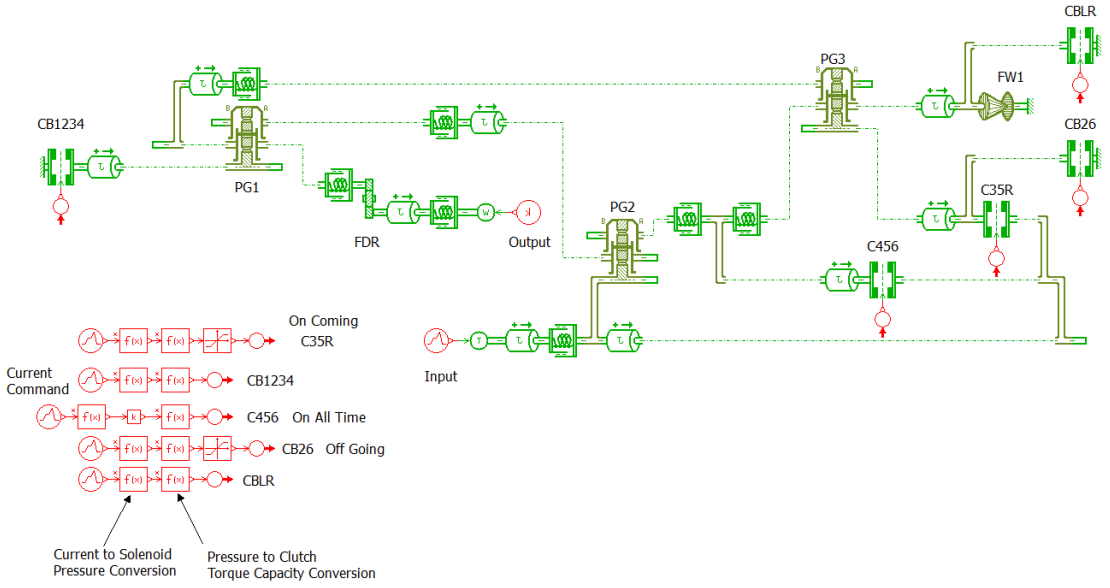


Figure 3-19. Transmission 1-D model layout

www.manaraa.com

3.5.3.1 Shift Model Parameters

The parameters that were used in the model are estimates for mass and stiffness of the transmission components. To control the clutches, a conversion from electrical current command to pressure and then pressure to clutch friction torque was done. Figure 3-20 show the calibration curves that were used for both normally low and high solenoids to convert from a current command to a pressure.

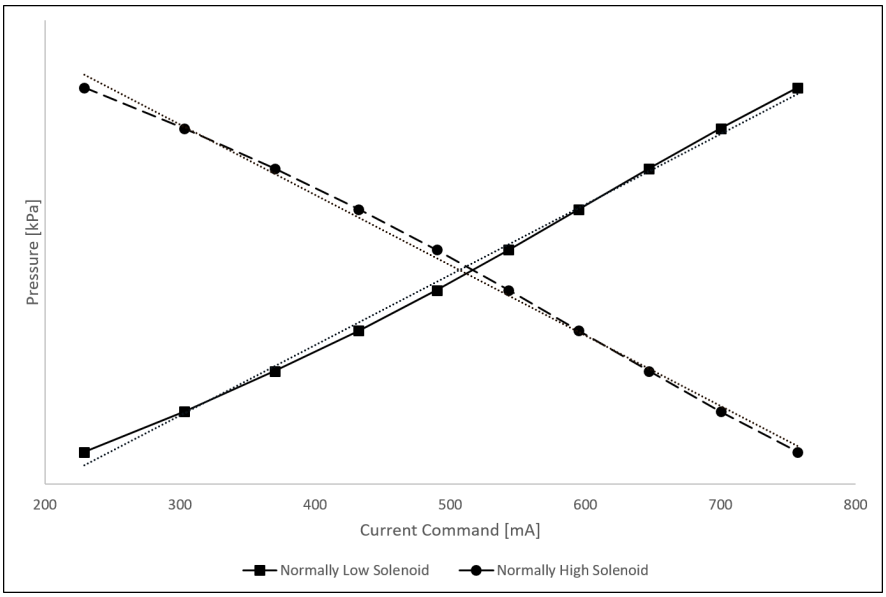


Figure 3-20. Current command conversion to pressure

The pressure is then fed into a calibration curve for each clutch. The calibration curves are dependent on the gear state because each clutch has to hold a different amount of torque based on the gear ratio. Figure 3-21 are the calibration curves for clutches C456 and CB26 for 6th gear.

www.manaraa.com

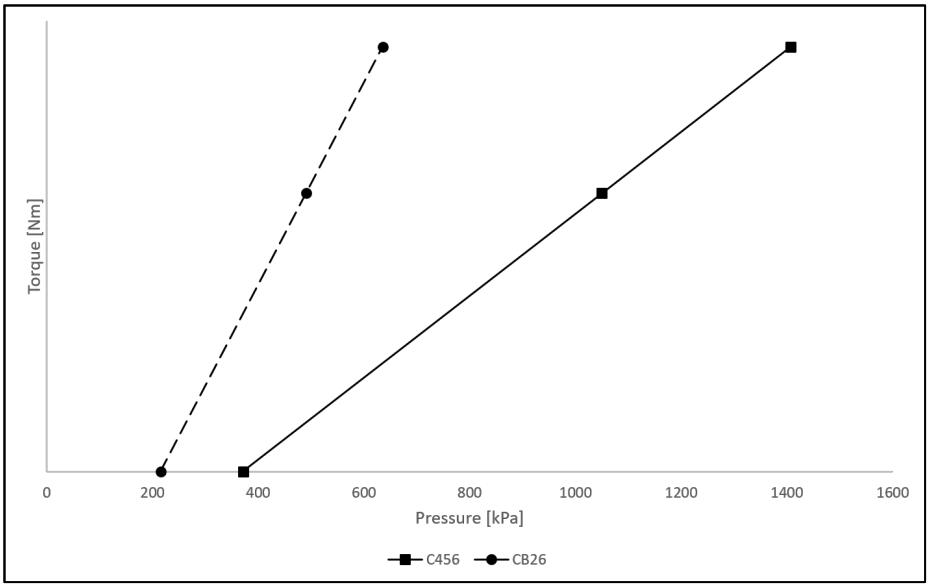


Figure 3-21. Solenoid pressure conversion to friction clutch torque capacity

3.5.3.2 Shift profiles

The starting shifting profiles were taken from vehicle data based off the regulator pressure. Multiple shifts from the data were averaged to get a general shift profile. The pressure was then converted to a current command. A profile was made for each of the clutches. Figure 3-22 and Figure 3-23 are example current command profiles for the oncoming clutch controlled by a normally low or high solenoid respectively. The off-going clutches were calibrated to decrease capacity linearly during the torque phase following the same calibration strategies that were discussed above in Figure 3-17 and Figure 3-18.

www.manaraa.com

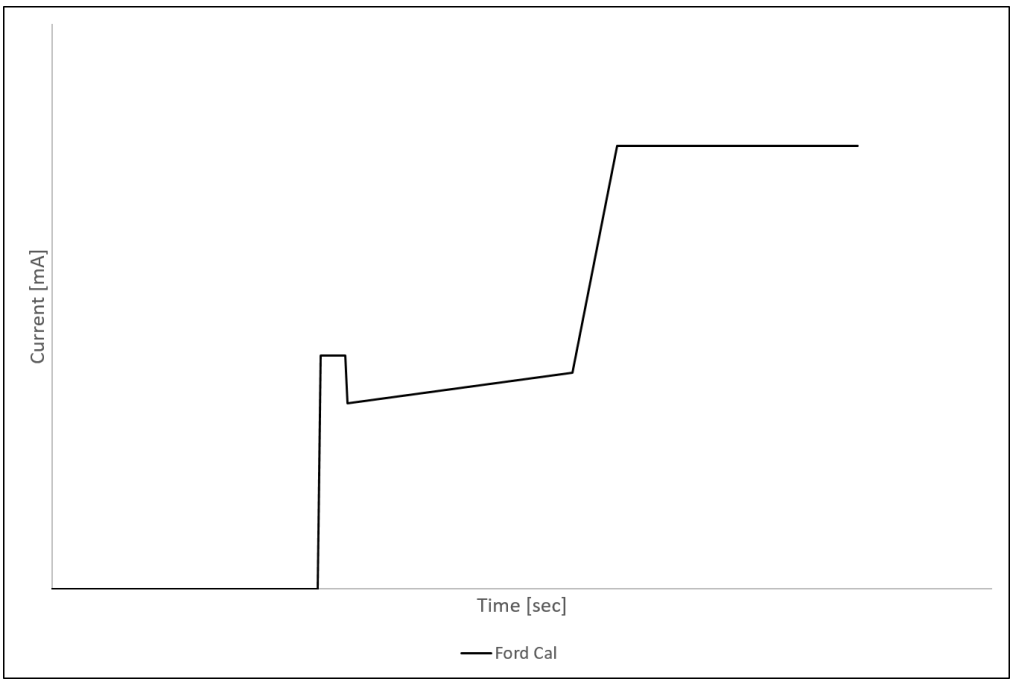


Figure 3-22. Example current command profile for a normally low solenoid

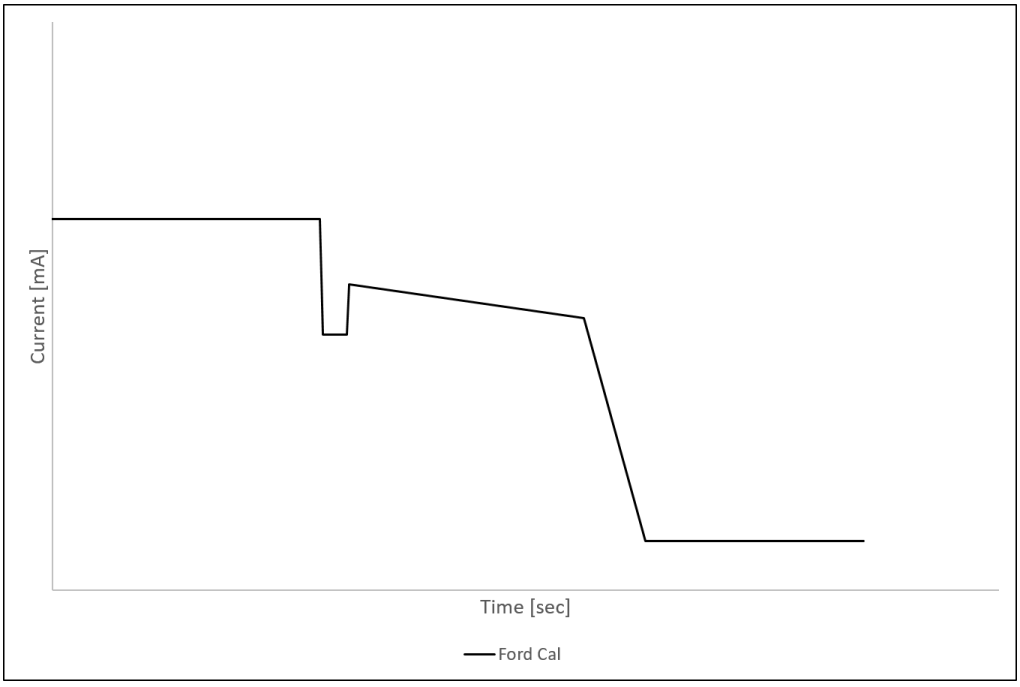


Figure 3-23. Example current command profile for a normally high solenoid

www.manaraa.com

3.5.3.3 Shift Model Results

Both speed and torque for the input and output are taken from the model to verify that the shift is properly calibrated. The output torque is the main concern to ensure that the limit of 450 Nm is not exceeded. The input speed is also of interest to see how long the shift takes. Ideally the transition period for the input speed should take between 0.3-0.6 seconds. Due to the large inertia from the input dyno these times were not met but kept in mind to get the shift as short as possible without damaging the transmission. Figure 3-24 are the results from the model for a downshift.

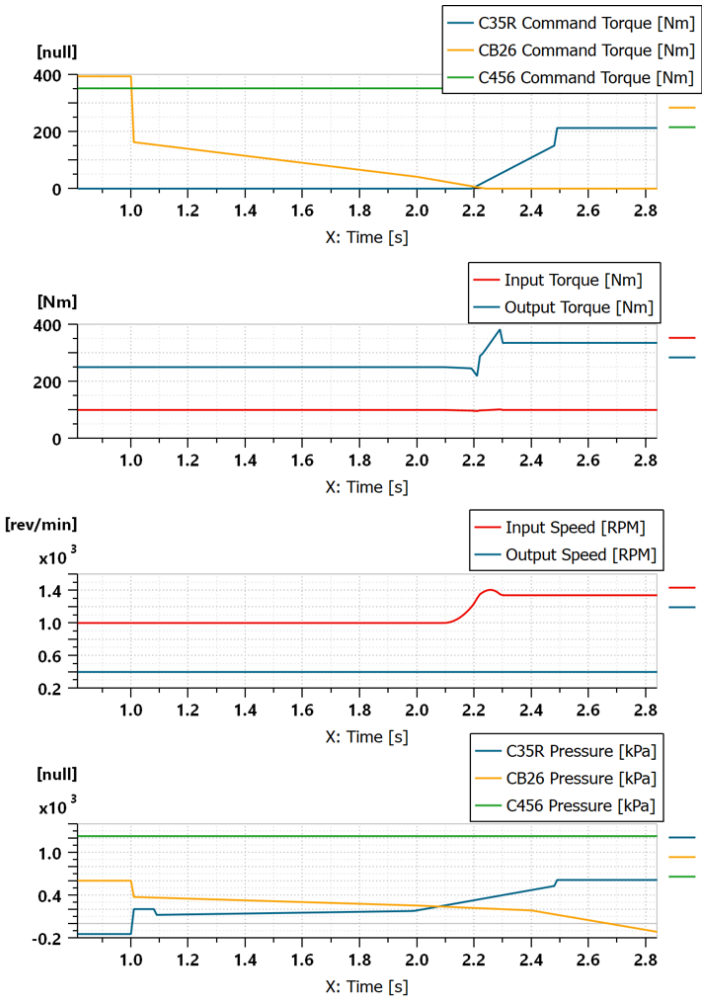


Figure 3-24. Example model results of a downshift from 6th to 5th gear

www.manaraa.com

3.5.4 Dyno Torque Management

Once the shift profile is finalized, the profile is then taken to the test cell to verify the shift is occurring properly. Torque management was also developed to compensate for the large output fluctuation that was seen in the above shift calibration strategy. Torque management is accomplished by writing a script that changes the input dyno torque as the transmission is shifting. The torque management and shift are synced by a trigger that activates the shift once the dyno script has been initiated. With torque management the output torque can be reduced to a smooth transitional torque reduction. Figure 3-25 illustrates the calibration strategy for adding torque management to an upshift. During an upshift the input torque is reduced during the inertia phase to help decrease the input speed. Once inertia phase is over the input torque returns to the starting torque value.

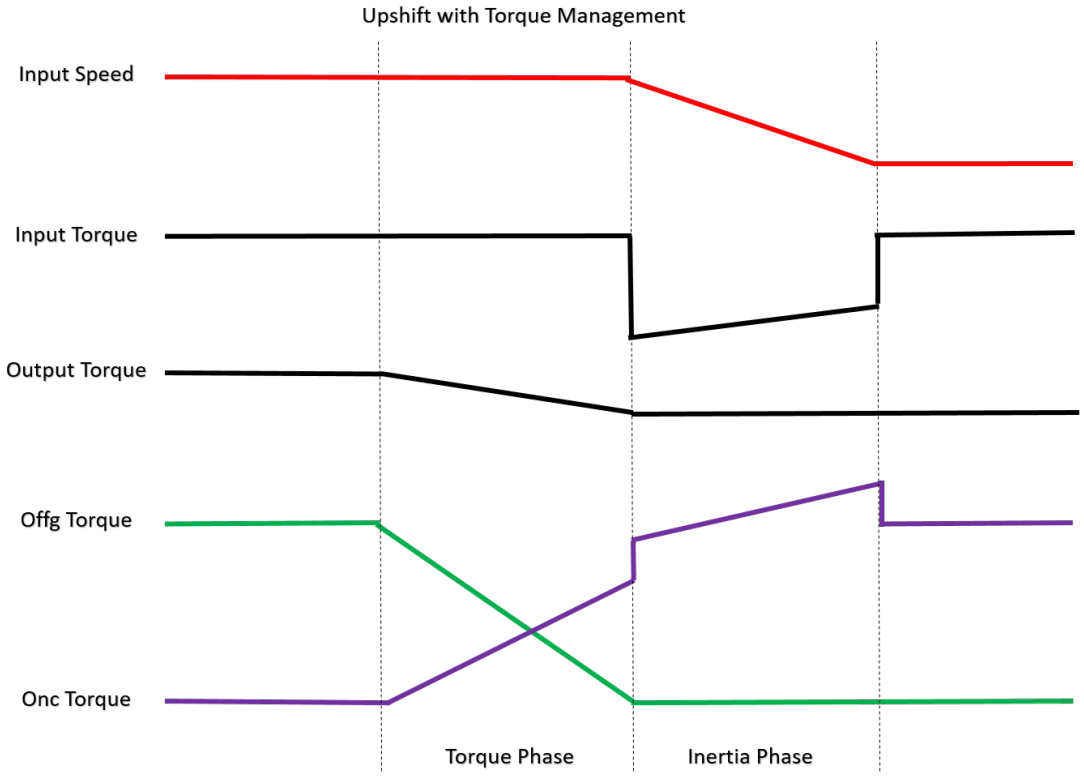


Figure 3-25. Upshift calibration strategy with torque management

www.manaraa.com

A similar torque management strategy is used for downshifts. The difference is during the inertia phase, instead of an input torque reduction there is a torque increase. By increasing the input torque this helps increase the input speed. Once inertia phase is completed, the input torque returns to the starting torque through the torque phase. Note for vehicle shift calibration the ideal output torque is kept constant throughout for drivability and driver comfort. The output torque was not kept constant for the tests because the more complex torque management strategy could not be replicated well due to the slow response of the dynamometers.

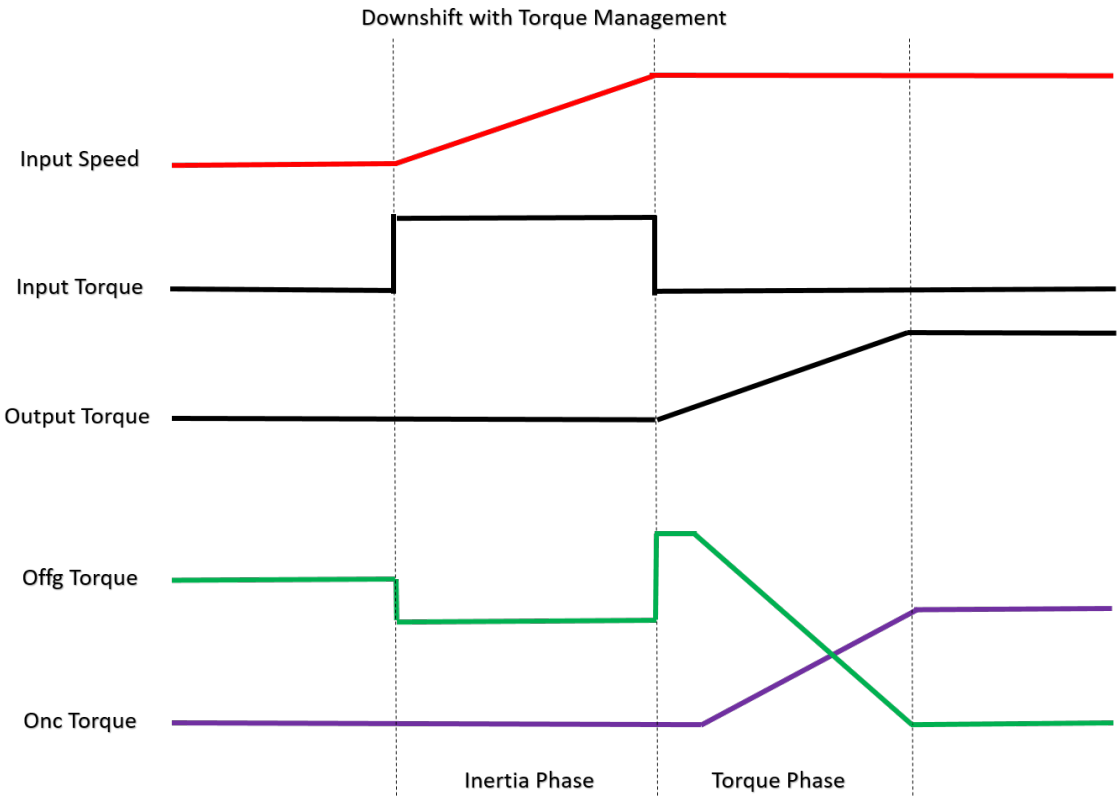


Figure 3-26. Downshift calibration strategy with torque management

www.manaraa.com

3.6 Torque Converter Clutch Controls

The TCC was controlled by using the SOL Commander software. SOL Commander has the capability to do steady state and transient TCC testing. For the scope of this research all TCC testing was done as steady state in released, slipping, or applied. The slipping conditions were determined manually by adjusting the slip between the input and turbine speed until the desired amount of slip was met. The command current needed to get a specific amount of slip under certain load is repeatable and can be used with the transient testing methods that were discussed in previous sections.

www.manaraa.com

4 Results

A variety of test scenarios were completed for this study. A summary of the tests that are presented in the following sections are given in Table 4-1.

Table 4-1. Summary of tests and operating conditions

Test Name	Purpose	Operating Conditions		Transmission Gear State
		Input Dyno [Speed or Torque Mode]	Output Dyno [Speed or Torque Mode]	
Steady State Tests				
Zero Load Pressure	To acquire a baseline pressure for each channel without loading effects, only charge and centripetal pressure.	Speed Mode-500-3000 RPM	Freewheeling	5th
Control and Application Pressure	To ensure that a constant relationship occurs between control pressure at the regulator to the application pressure in the TC	Torque Mode-20-120 Nm	Speed Mode-Constant 400 RPM	6th
TCC Clutch Capacity and Friction Material Coeffcient	To validate the pressure measurements on the TCC compared to preivious work and design requirements	Torque Mode-20-120 Nm	Speed Mode-Constant 400 RPM	6th
Centripetal Pressure	To understand the centripetal impact on the measurements and to see how consistent the centriptal pessure is across a variety of conditions	Torque Mode-30-100 Nm	Speed Mode-100-400 RPM	5th, 6th
Clutch Pressures and Force	To visualize the pressure profile across the TCC and calculate the resultant force acting on the TCC	Torque Mode-30-100 Nm	Speed Mode-100-400 RPM	5th, 6th
Transient Tests				
Back Drive	To understand how an open TC pressures can fluctuate when turbine is driving impeller	Torque Mode-45 to -45 Nm	Speed Mode-Constant 500 RPM	5th
Cruising Speed Power-on Up and Downshifts	Baseline shift events where transmission hyrdualics have enough capacity to feed all systems properly	Torque Mode-30 Nm	Speed Mode-Constant 500 RPM	5th-6th
Low Speed Power-on Up and Downshifts	To observe possible hyrdualic deficiencies and what systems may have reduced capacity	Torque Mode-30 and 100 Nm	Speed Mode-Constant 400 RPM	5th-6th

www.manaraa.com

4.1 Steady State

Steady state testing was conducted to build a base understanding of the systems normal operating conditions. The steady state results provide a datum to compare to the transient tests to see if abnormalities occur and if relations can be connected.

4.1.1 Torque Converter Performance Validation

To validate that the torque converter was operating according to specification a performance test was conducted. Speed ratios were tested from 0.1-0.9 by keeping a constant 75 Nm input torque and changing the output speed with the transmission in 5th gear. Figure 4-1 shows the results for the torque converter performance test. The lower solid curve is the K-factor specifications with the tolerance limits shown by dashed lines with the test data overlaid as the gray line with circle markers. The upper curve is the torque ratio using the same formatting as the K-factor for specification and tolerance limits. Both curves are within the tolerance limits so the torque converter was deemed to be operating properly.

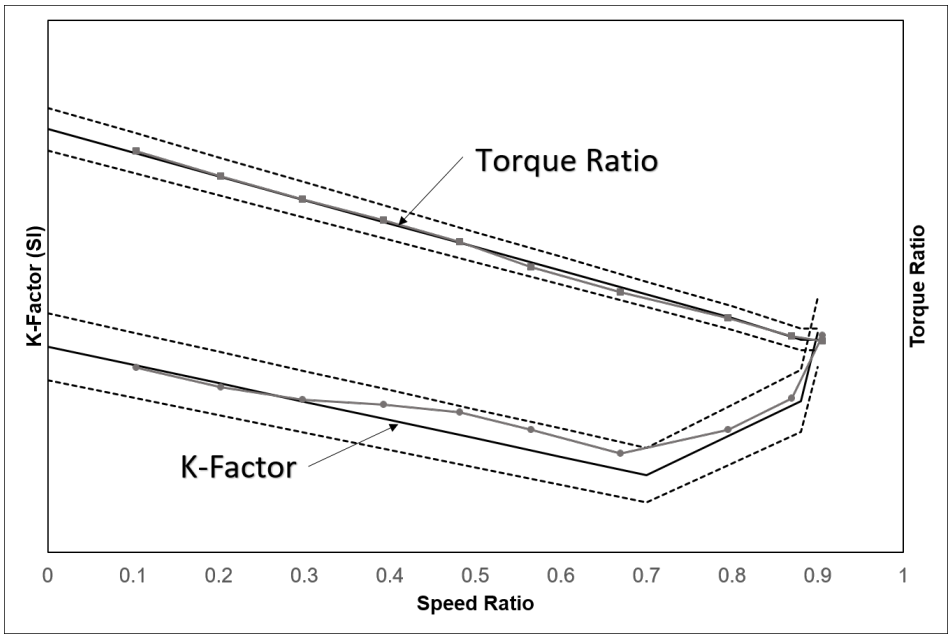


Figure 4-1. Torque converter performance validation

www.manaraa.com

4.1.2 Zero Load Pressure

Determining the pressures of the torque converter when the transmission is in zero load condition provides the baseline for pressure based on charge and centripetal pressure. This baseline can be compared to loaded conditions to compare variations in the pressure. The transmission was placed in neutral with a constant line pressure current command. The input speed was swept from 750-3000 RPM with the output dynamometer freewheeling. Results for TCC released, slipping, and applied can be seen in Figure 4-2, Figure 4-3, and Figure 4-4 for the impeller, stator and turbine respectively. Each figure contains the line and charge pressure where the line pressure is the feed pressure for the whole transmission and the charge pressure is the feed pressure for only the torque converter. As the speed increases so does the pressure which is due to the centripetal pressure change.

www.manaraa.com

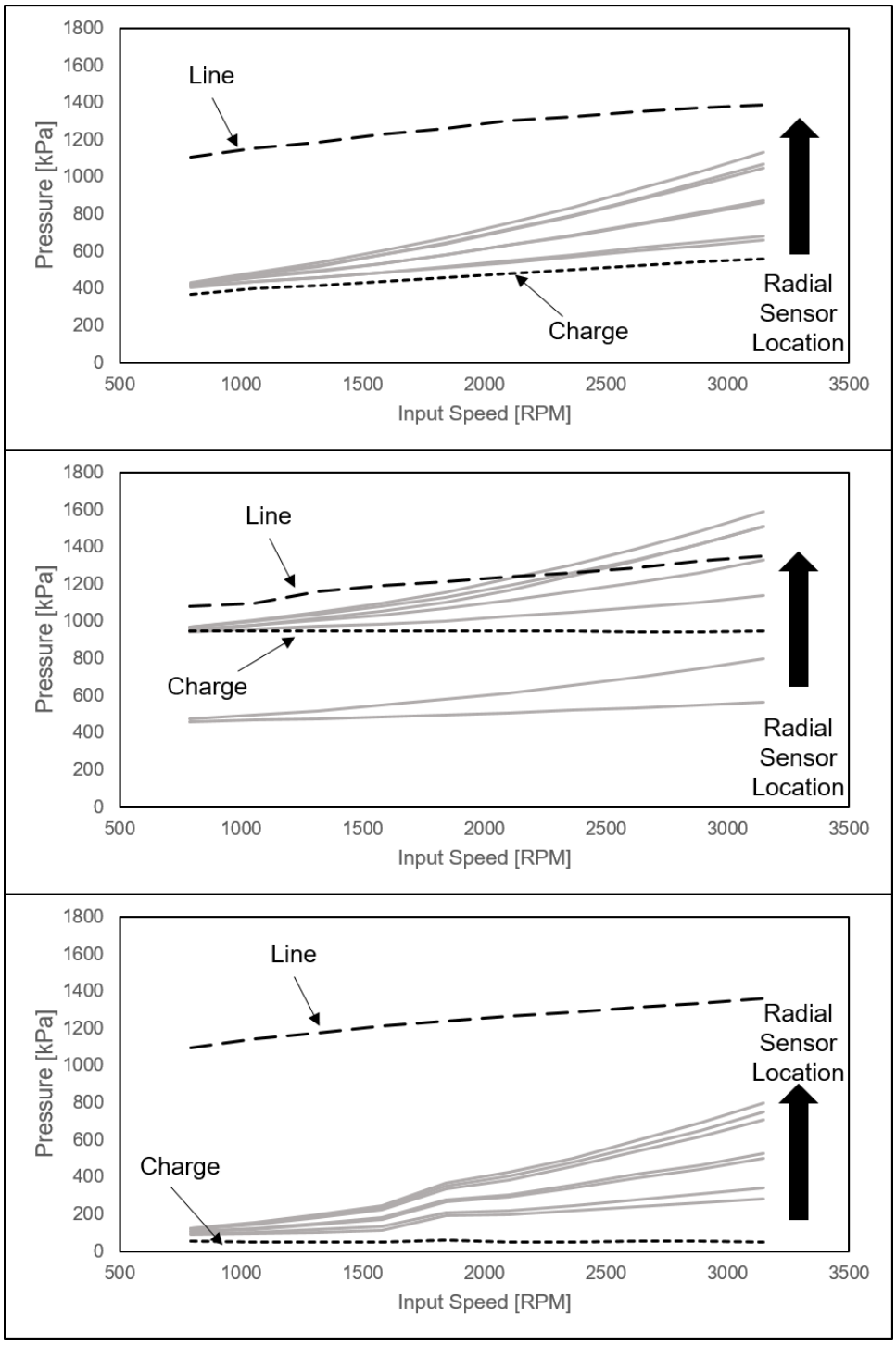


Figure 4-2. Zero load transmission pressure values for impeller and cover: top to bottom- TCC Released, TCC Applied, TCC Slipping

www.manaraa.com

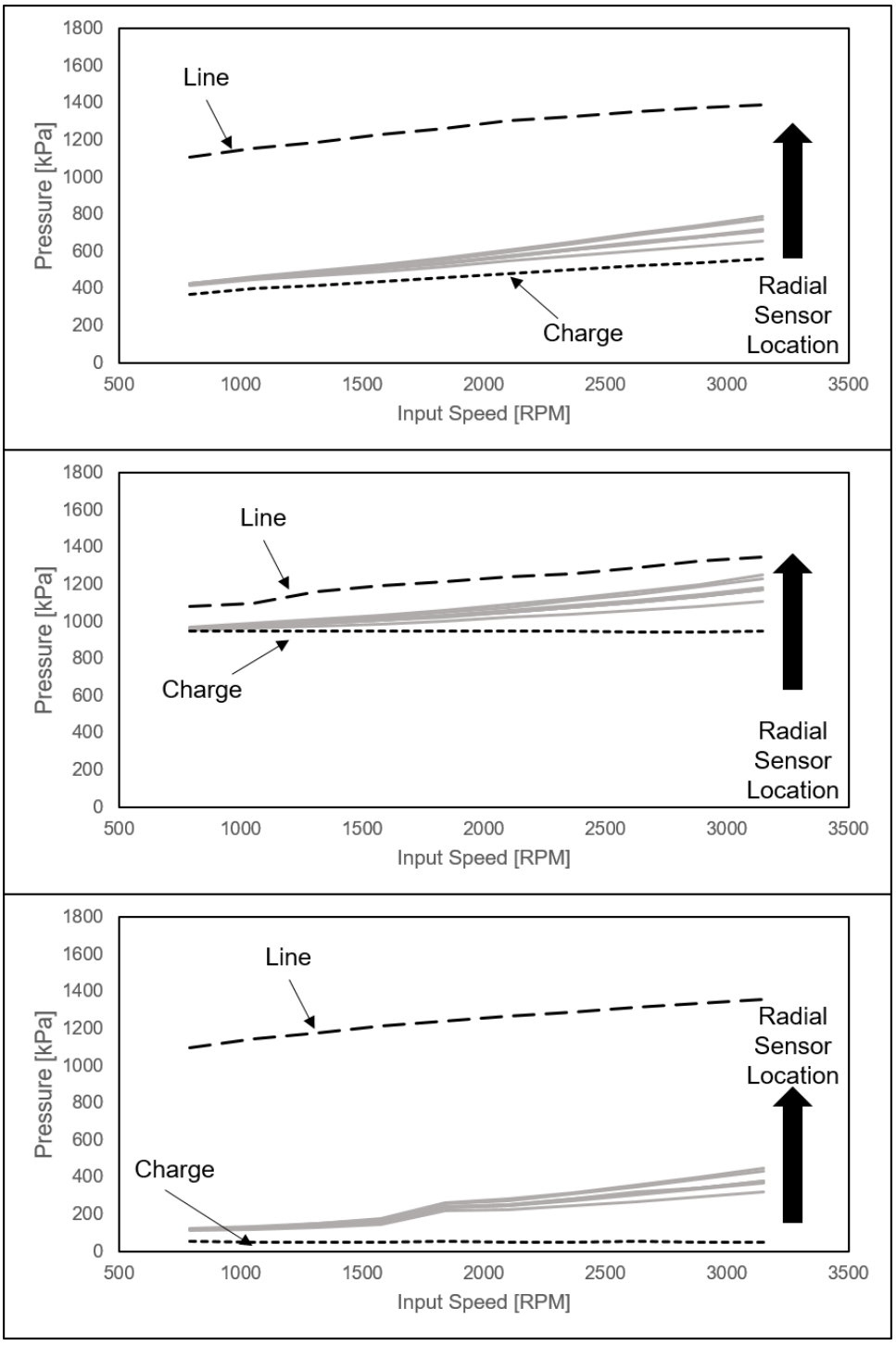


Figure 4-3. Zero load transmission pressure values for stator: top to bottom- TCC Released, TCC Applied, TCC Slipping

www.manaraa.com

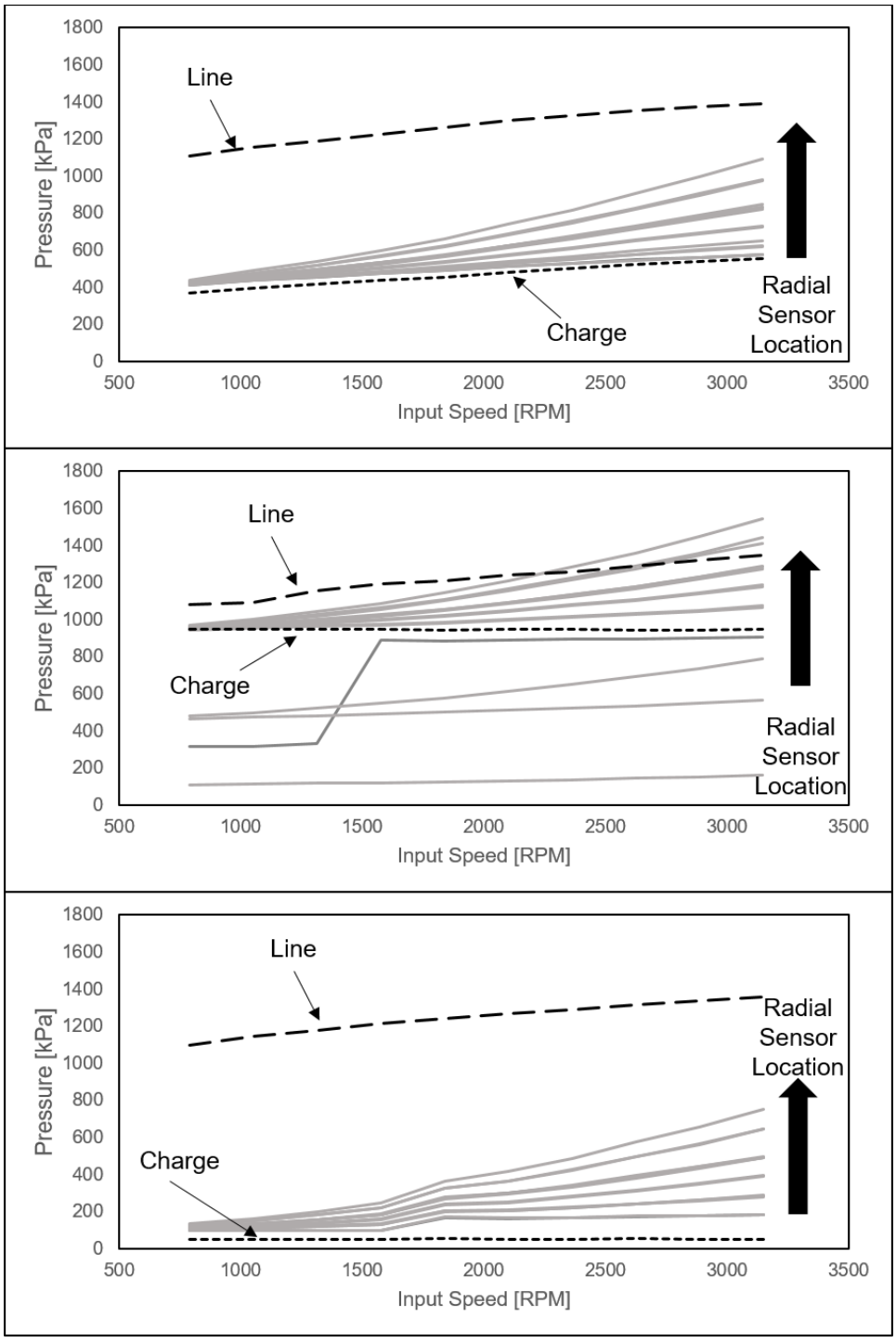


Figure 4-4. Zero load transmission pressure values for turbine and TCC: top to bottom- TCC Released, TCC Applied, TCC Slipping

www.manaraa.com

4.1.2.1 Centripetal Pressure

A test was done to see how the much variation there is in the charge pressure when running a constant current command instead of a constant pressure. This is of interest because the transmission controls are open looped and have no feedback. Without any feedback the pressure would have to be manually adjusted for each test condition. Figure 4-5 shows the results of the pressure change for line and TCC control as a function of speed. The target line pressure was 1172 kPa (170 PSI) and was set for 1500 RPM as majority of the testing will occur between 1000-2000 RPM. At 500 RPM the charge pressure is low and this is due the system not having the capability to pressurize the torque converter. This is not a concern because this is below idle speed of an engine and will not be an area of testing.

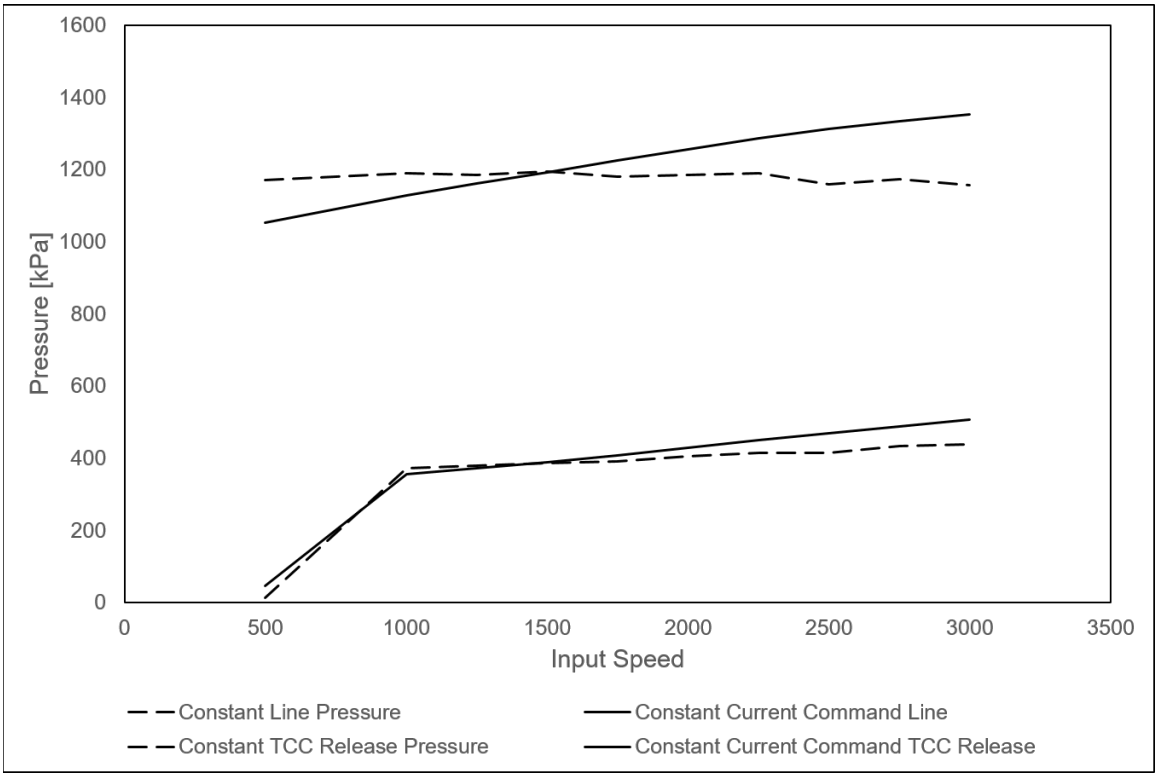


Figure 4-5. Line (top) and TCC control (bottom) pressures

www.manaraa.com

To normalize the data, the charge pressure was removed to show the centripetal component of the pressure. Figure 4-6 is an example of how the centripetal pressures are radially and speed dependent. The larger the radial location and speed the higher the centripetal pressure. This trend follows for all other sensors on the stator, turbine, and TCC.

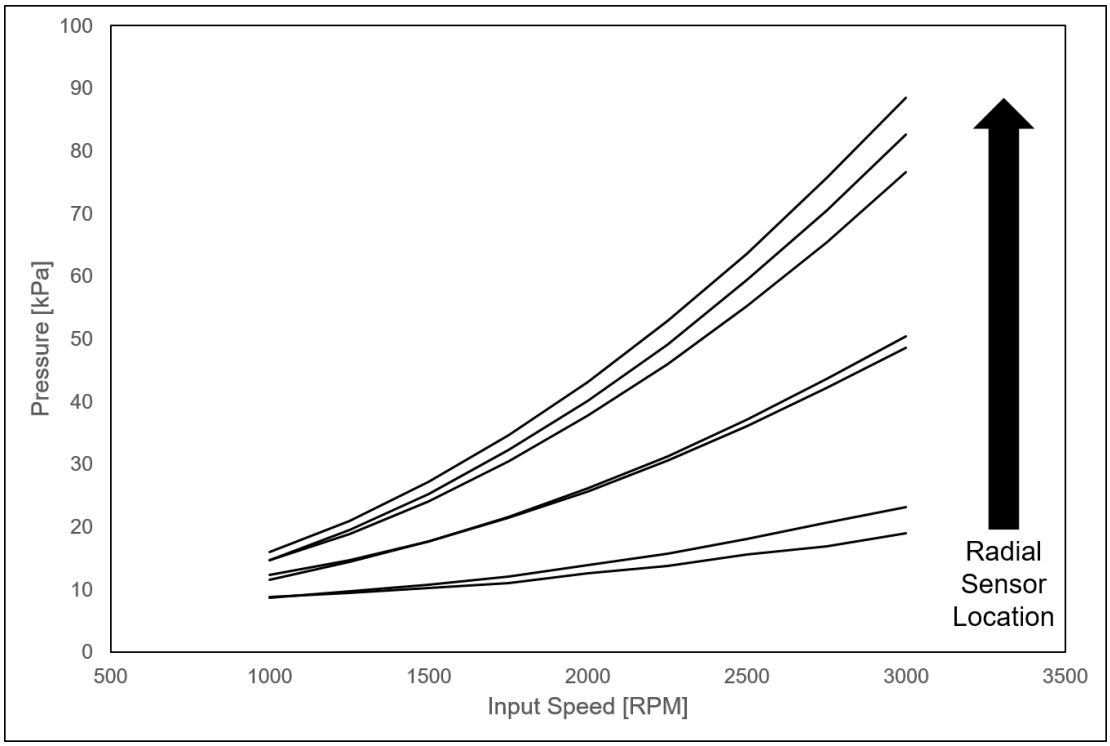


Figure 4-6. Centripetal pressure for each impeller and cover channel

4.1.2.2 Centripetal Pressure Calculation and Accuracy

The centripetal pressure was calculated using Equation 4-1 and Equation 4-2. Equation 4-1 calculates the pressure at each radius based on the oil density ρ, radial location r, oil feed starting radius r_o, charge pressure P_{charge}, and the angular velocity ω. The angular velocity is calculated using Equation 4-2 where N is rotational speed in revolutions per minute. Note that the angular velocity and radial location are squared which is seen in the centripetal pressure results seen in Figure 4-6.

www.manaraa.com

$$P(r) = \frac{1}{2}\rho\omega^2(r^2 - r_o^2) + P_{charge}$$ Equation 4-1

$$\omega = N * \frac{2\pi}{60}$$ Equation 4-2

A pressure was calculated for each instrumented location and compared to the test results. The associated error for each channel can be seen in Figure 4-7. In summary the calculated pressures are within ±15% of measured value. The errors show an underestimate in pressure at lower speeds and overestimate in pressure at higher speeds. This calculation can be used for initial design to give estimate pressures because of how quick results can be calculated. For final designs a more technical model should be used for final pressure values. This equation will be used as a comparison in later analyzes as a design comparison.

It is important to note that these calculations are valid for when the torque converter is operating past the coupling point and not in torque multiplication mode. In torque multiplication there are additional fluid dynamics that contribute to the pressure.

www.manaraa.com

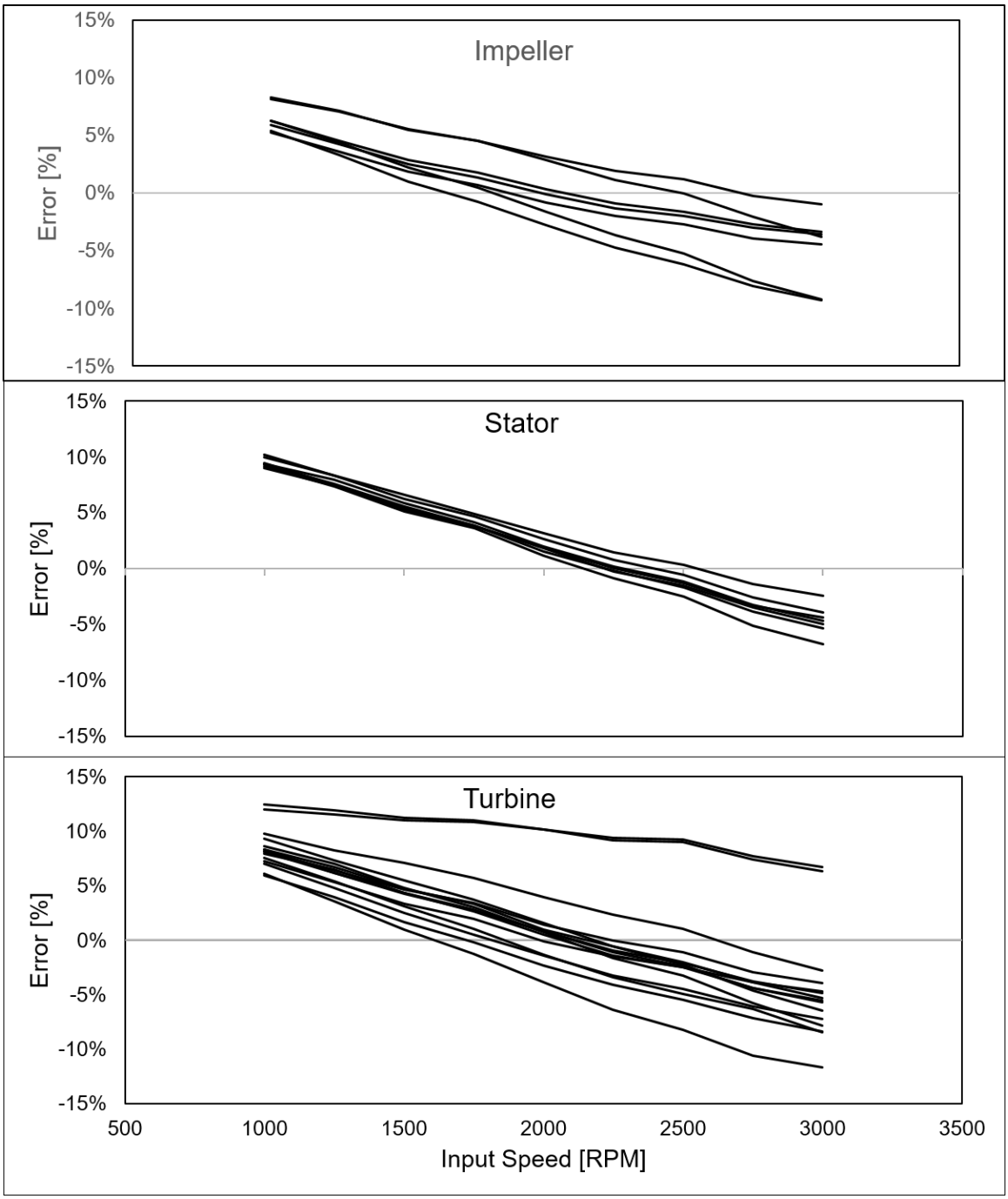


Figure 4-7. Calculation error for each channel compared to test results

www.manaraa.com

4.1.3 TCC Control and Charge Pressure

A study was conducted to characterize the interaction of the TCC control pressure and the pressures seen in the torque converter. This test was completed with the TCC slipping at a constant 20 RPM varying input torque from 20-120 Nm and a constant output speed of 400 RPM in 6th gear. The test showed that the torque converter internal pressure is constant in relationship to the charge pressure at a constant output speed. This was done as a validation study to ensure that the understanding of how the torque converter may vary was recorded. The results for all three transmitters are shown in Figure 4-8, Figure 4-9, and Figure 4-10 are the results of the measured pressure minus the charge pressure for the impeller/cover, stator, and turbine/TCC respectively. The dashed lines are the channels that are in the torus or between the TCC and turbine shell. The solid lines are the channels between the TCC and cover. The results show that the dashed line pressures have a constant centripetal pressure across the range of charge pressures, while the solid line pressures decrease. This is due to the charge pressure is only seen by the dashed line channels because the TCC is applied cutting off the charge pressure from the solid line pressures. Since the charge pressure increases a larger difference is seen when compared to the solid line pressures.

www.manaraa.com

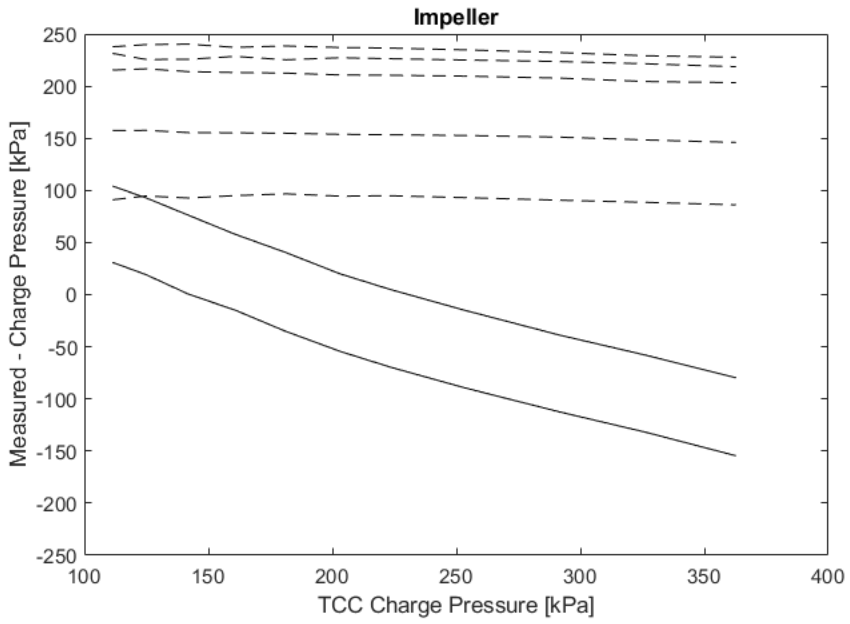


Figure 4-8. Impeller and cover centripetal pressures across multiple TCC control pressures

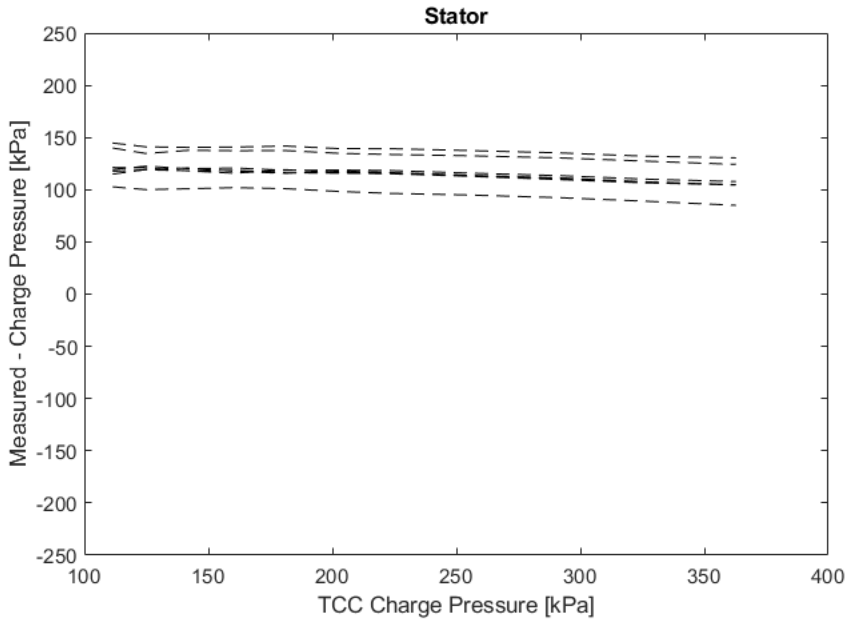


Figure 4-9. Stator centripetal pressures across multiple TCC control pressures

www.manaraa.com

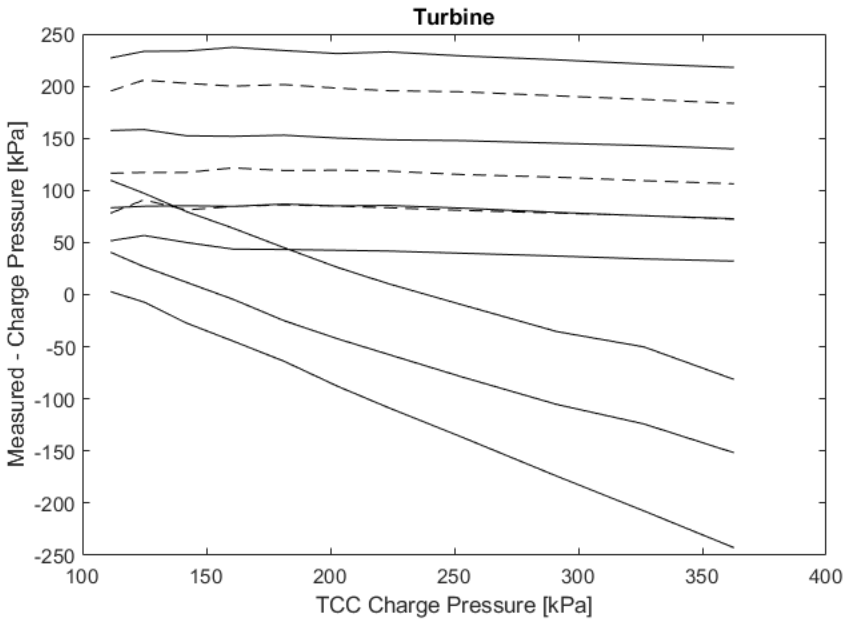


Figure 4-10. Turbine and TCC centripetal pressures across multiple TCC control pressures

4.1.4 Torque Converter Clutch Capacity and Friction Material Coefficient

Testing the TCC capacity and friction material coefficient was of interest to characterize the TCC in comparison to other literature and design parameters. The TCC capacity should have a linear trend, so as the charge pressure increases so does the amount of torque the clutch can transmit. This was tested by sweeping input torque from 20-120Nm with a constant output speed of 400 RPM in 6^{th} gear. The charge pressure was increased until the clutch begins to drive the input speed down. Figure 4-11 shows the results of the clutch capacity test and how there is a linear correlation between charge pressure and clutch capacity.

www.manaraa.com

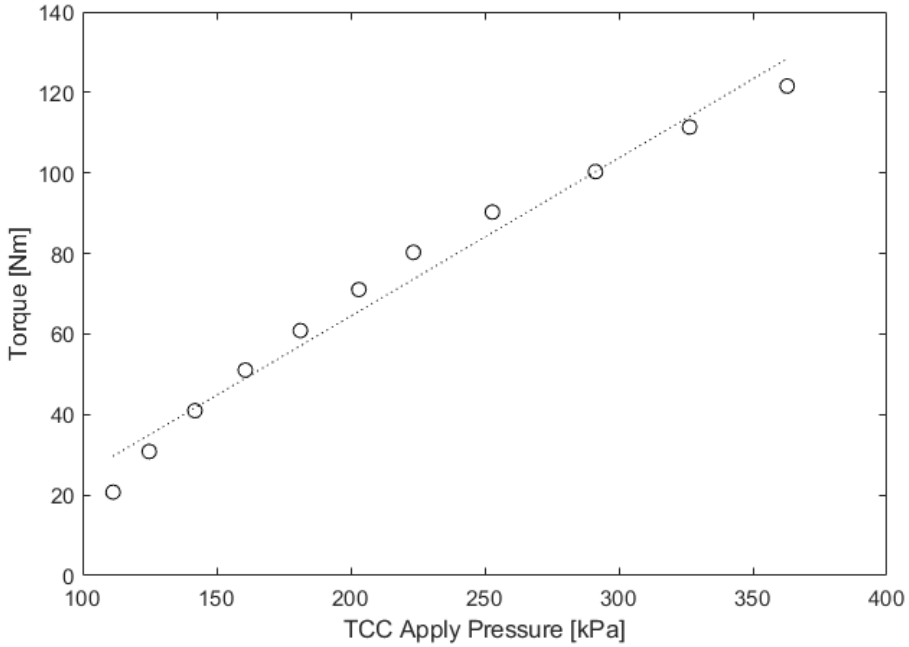


Figure 4-11. Torque converter clutch capacity

This agrees with [4] when slip across a frictional clutch is small there is a linear correlation to the capacity. This can be explained by Equation 4-3 were T is torque capacity, p is pressure across the surface, μ is friction coefficient of friction material, r is radius along the surface, integrated between r_o outer radius and r_i inner radius. There is a linear correlation between torque capacity and pressure.

$$T = \int_{r_i}^{r_o} 2\pi p \mu r^2 \, dr \qquad \text{Equation 4-3}$$

The friction coefficient for the TCC was determined by running three different tests to cover the areas of operation for a TCC. The TCC was tested during slip of 5-10 RPM, when the clutch begins to make contact with the cover and pull the input speed down, and when the clutch is disengaging from the cover and releasing torque capacity. The friction coefficient was calculated by using Equation 4-3 and then averaged for each condition. The friction coefficient for the TCC was found to be an average of 0.19, which is in the range for possible friction coefficients of paper material [45].

www.manaraa.com

Table 4-2. Friction coefficient estimates for TCC friction material

Test Condition	Friction Coefficient
Slip 5-10 RPM	0.0605
Start of Contact with Cover	0.3132
Releasing Contact with Cover	0.2057

4.1.5 Clutch Pressures and Forces

The clutch pressures across the TCC, channels 5-11, were used to determine the resultant force acting on the TCC during slipping and applied conditions. A quadratic curve fit was applied to the pressure measurements on each side of the TCC. The pressures were subtracted between the front and rear of the TCC to get a pressure profile representing the acting pressure across the clutch. An example pressure profile can be seen in Figure 4-12 with the circles representing the pressure measurements with the dotted line being the curve fix to the data. The dashed line is showing the resulting pressure profile across the clutch with the solid lines indicating the location of the friction material. It is assumed that the pressure across the friction material is negligible because only a small amount of ATF can travel across the friction material.

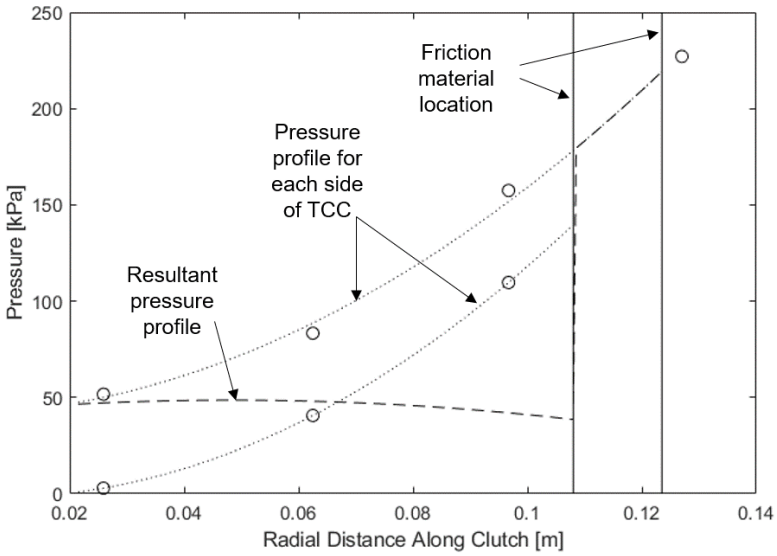


Figure 4-12. Pressure profile across TCC

www.manaraa.com

The force due to pressure is calculated at each radius along the clutch by using Equation 4-4. Equation 4-4 uses all the same parameters as Equation 4-1 above.

$$F(r) = \pi r^2 \left[\rho \omega^2 \left(\frac{r^2}{4} - \frac{r_o^2}{2} \right) + P_{int} \right] \quad \text{Equation 4-4}$$

An example force profile is given in Figure 4-13 with the dashed line showing the force profile and the solid line is where the resultant force is acting. The resultant force is where there is an equal amount of force on each side of the line.

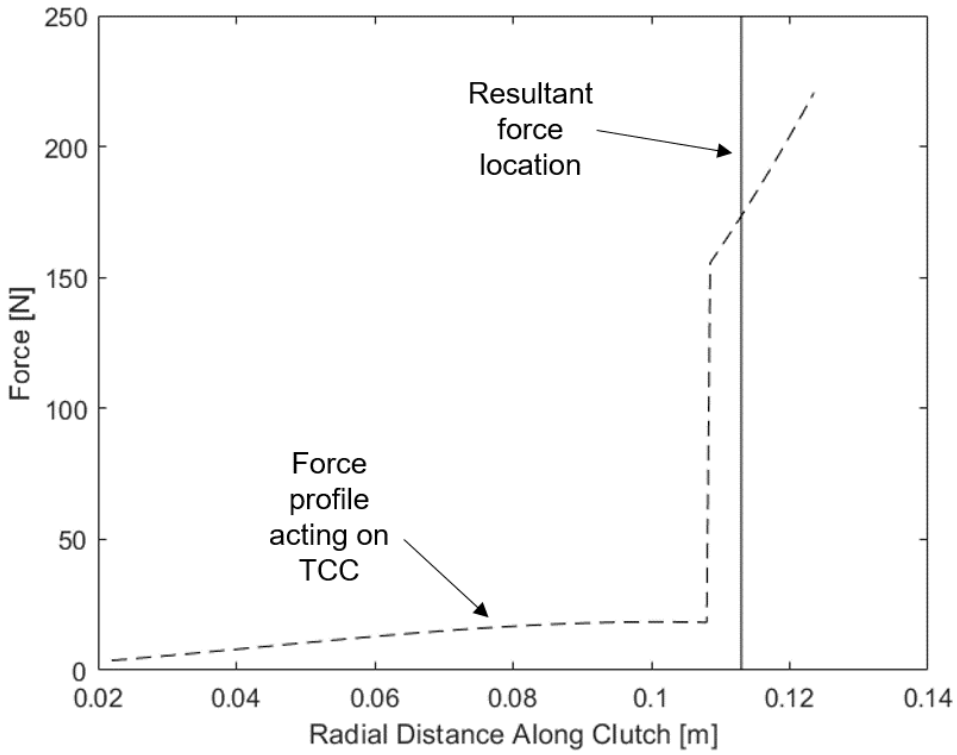


Figure 4-13. Force profile across TCC

The pressure profiles and resultant force were measured at 30 and 100 Nm in 6th gear across 300-500 RPM. The results are illustrated by an example graphic shown in Figure 4-14 with a summary on interpretation listed below.

www.manaraa.com

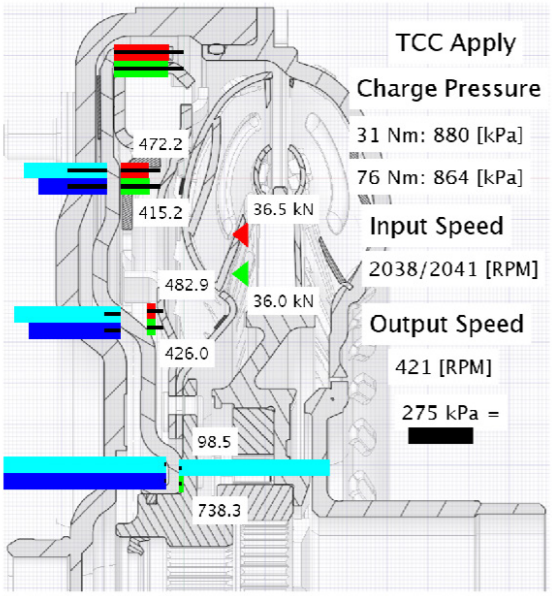


Figure 4-14. Pressure and resultant force acting on TCC example graphic

- Colored Bars
  - All pressures are relative to charge pressure
    - Sensor pressure – charge pressure = ΔP
  - Positive Pressure (+ΔP)
    - Red- 30 Nm input torque (low load)
    - Green- 100 Nm input torque (medium load)
  - Negative Pressure (-ΔP)
    - Cyan- 30 Nm input torque (low load)
    - Blue – 100 Nm input torque (medium load)
  - Text next to color bar
    - Shows value for ΔP between each side of clutch plate
  - Black color bars
    - Calculated pressure at each sensor location based on input speed and charge pressure
  - 275 kPa (40 PSI) reference bar in right bottom corner for scale comparison
- Colored Arrows
  - Shows location of resultant force with magnitude
    - Red- low load
    - Green – medium load
- Text on Right
  - Provides operating conditions of test

www.manaraa.com

Clutch pressures and resultant force were measured for with the TCC released, slipping 20 rpm, and applied. Figure 4-15 show the results for TCC released. Looking at the pressures between the front and back of the clutch, the pressures are equally opposed causing the clutch to be open. This is expected and the resultant forces mean nothing in the case of TCC released because the clutch is not touching the cover.

In the case when the TCC is applied the resultant force location is of importance. When the TCC is applied, the pressures on the front of the clutch have a lower pressure than the charge pressure. Since the TCC is applied the input speed is decreased, compared to the TCC released case, and has less centripetal pressure impact. There is also a large pressure difference across the clutch causing the TCC to be applied. The resultant forces were found to be located towards the center of the TCC with similar magnitudes of application force. This shows that since the charge pressures were the same the input torque has no impact on the resultant force. The results can be seen in Figure 4-16

The area of really interest is when the TCC is slipping because minor changes in operating points and charge pressure can have a large impact on TCC slip. Remember the goal is to apply the clutch as quickly as possible while also maintaining good drive quality with low NVH. By having the TCC slip the clutch can be partially applied through changing operating conditions, such as gear shifting. Figure 4-17 show the results for the TCC slipping 20 RPM. The charge pressure changes from 103.4 kPa (15 PSI) for low loads to 262 kPa (38 PSI) for medium loads to be able to handle the higher torque capacity. This causes a large pressure difference across the clutch for the medium loaded case compared to the low load. For the medium load case the resultant force is located at the center of the clutch, like when the TCC is applied, but the low load case shows that the resultant force is located at a large radius. By using the friction coefficient found from above the torque capacity of the clutch for each force is found to be equal to the 30 and 100

www.manaraa.com

Nm input torque. The thing of interest is that if the resultant force is located a larger radius and moves when a larger torque occurs there will be a delay for the transition and slip control may fluctuate. Further analysis is required to understand the possible impacts.

Additional cases were completed in 5th gear showing similar results as in 6th gear drawing the same conclusions. The 5th gear results can be seen in Appendix K along with the raw data values for each case.

www.manaraa.com

Figure 4-15. Pressure across TCC and resultant force for TCC released

www.manaraa.com

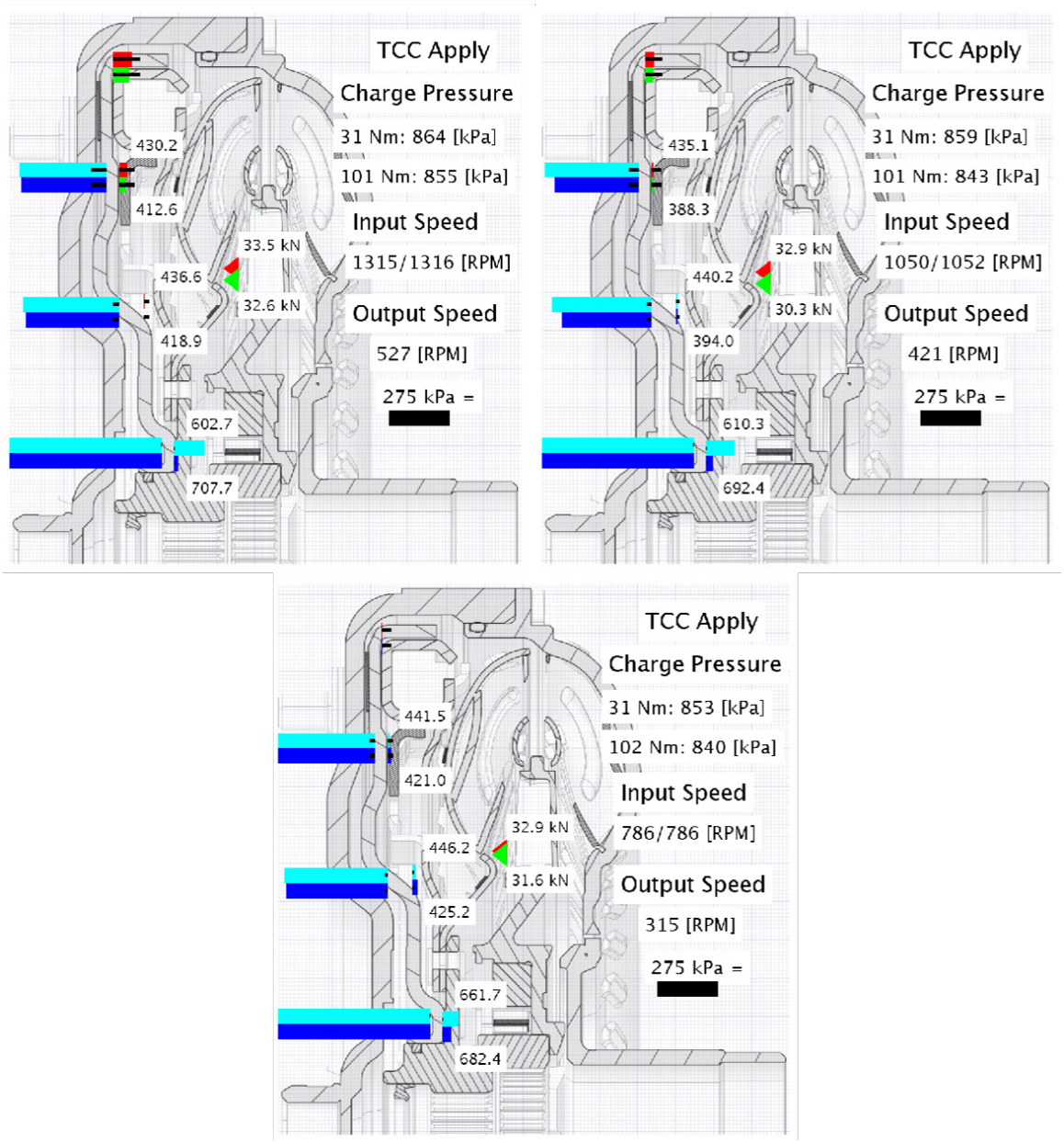


Figure 4-16. Pressure across TCC and resultant force for TCC applied

www.manaraa.com

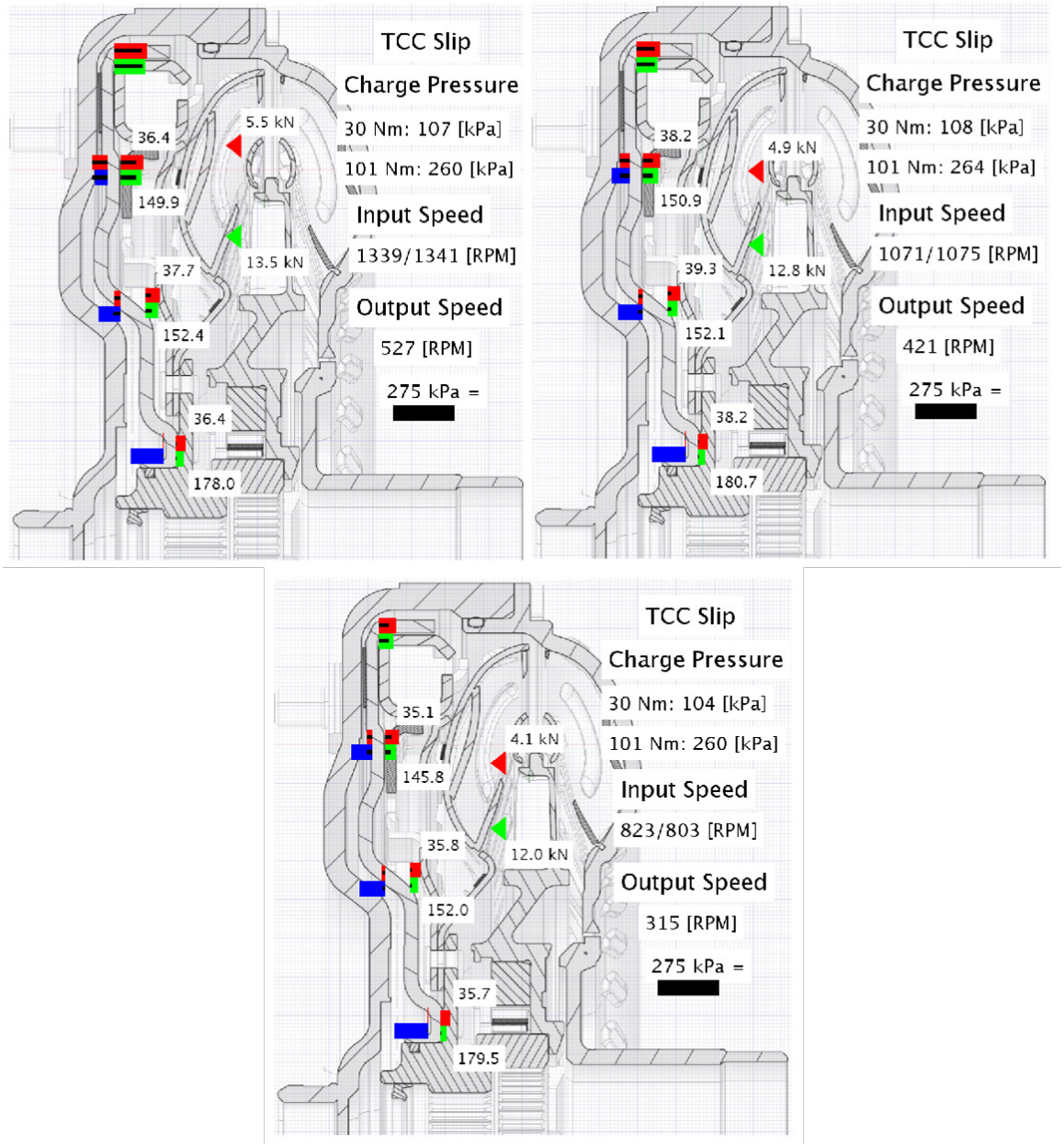


Figure 4-17. Pressure across TCC and resultant force for 20 RPM slip

www.manaraa.com

4.2 Transient

Transient events are the main interest in this study because controllability of transient events can be challenging. By increasing the knowledge about a transient event better calibration or hardware design can be implemented. Two main transient events were studied: back driving the transmission and gear shifting.

4.2.1 Back Drive

Back drive was completed with the TCC released with the input torque sweeping between 45 to -45 Nm with a constant output speed 550 RPM in 5th gear. The back drive tests used the transient testing methodology described in chapter 3. Methods. Figure 4-18 and Figure 4-19 show the test conditions for the 45 to -45 Nm sweep scenario and the resulting speed ratios throughout the test respectively. Back drive tests were also completed for 35 to -35 Nm, 25 to -25 Nm, and 15 to -15 Nm sweeps. The torque levels used are low to represent the back drive scenario where the engine is not driving or creating small amounts of torque.

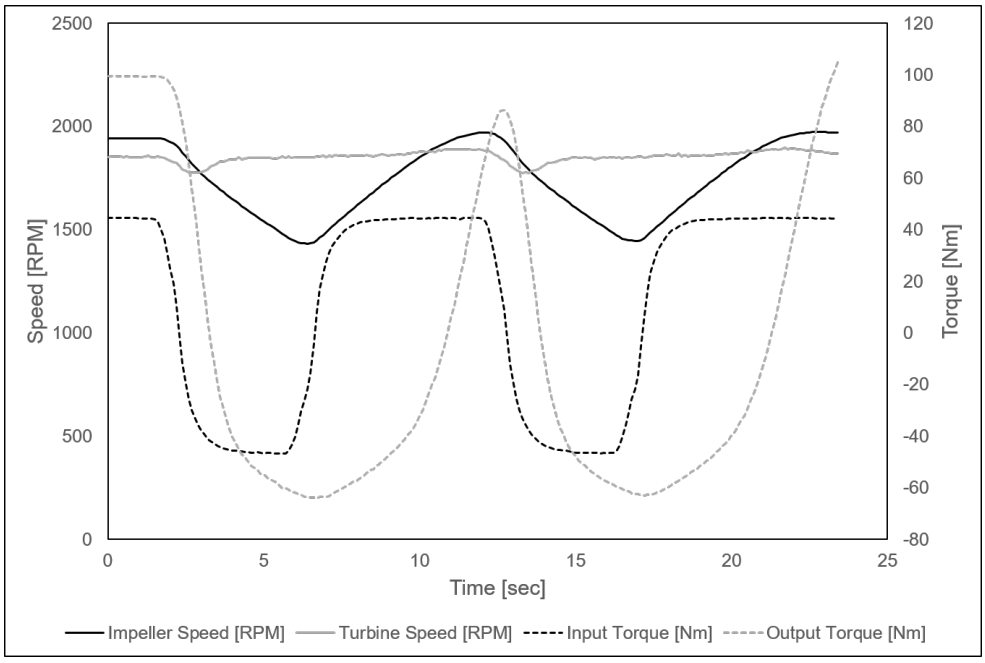


Figure 4-18. 45 to -45 Nm test scenario for back drive

www.manaraa.com

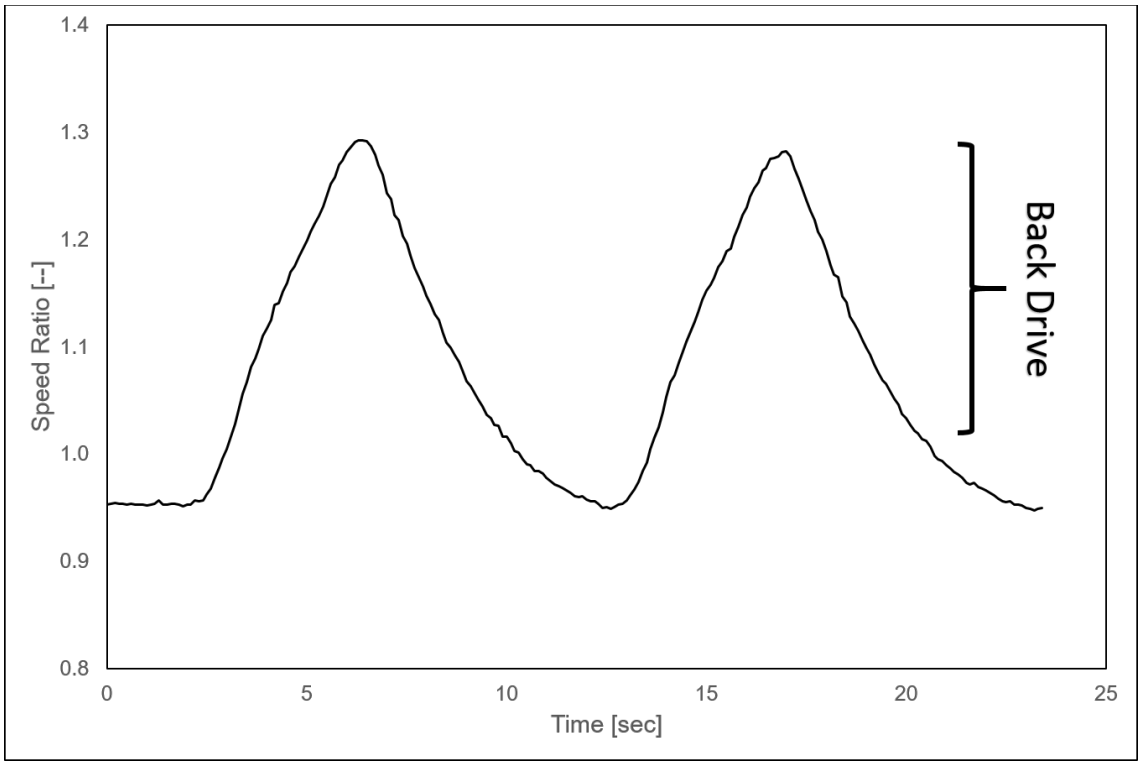


Figure 4-19. Speed ratio achieved during 45 to -45 Nm test

The stitched time histories for the 45 to -45 Nm for the impeller/cover, stator, turbine, and TCC are given in Figure 4-20, Figure 4-21, Figure 4-22, and Figure 4-23 respectively. Each channel's time history has arrows pointing to the sensor's location in the torque converter. The gray areas on the time history plots represent the time when the input torque is negative. The pressures in the impeller, turbine, and TCC see a decrease in pressure as the speed ratio increases from 0.95 to 1.3 while the pressure on the stator increases. The reason for increased pressure across the stator will be explained in a later section.

www.manaraa.com

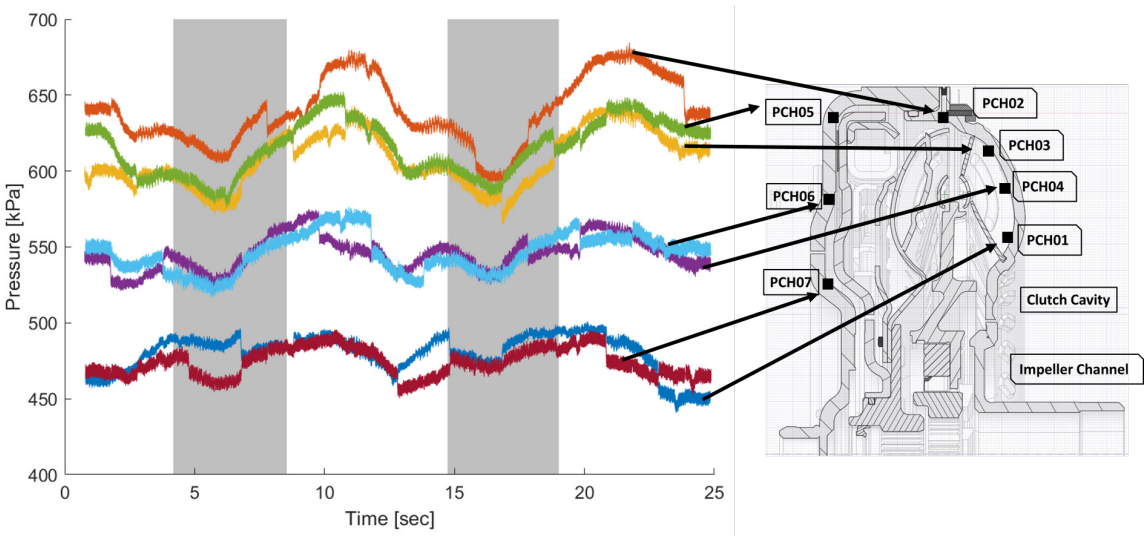


Figure 4-20. Back drive stitched time history for impeller and cover channels

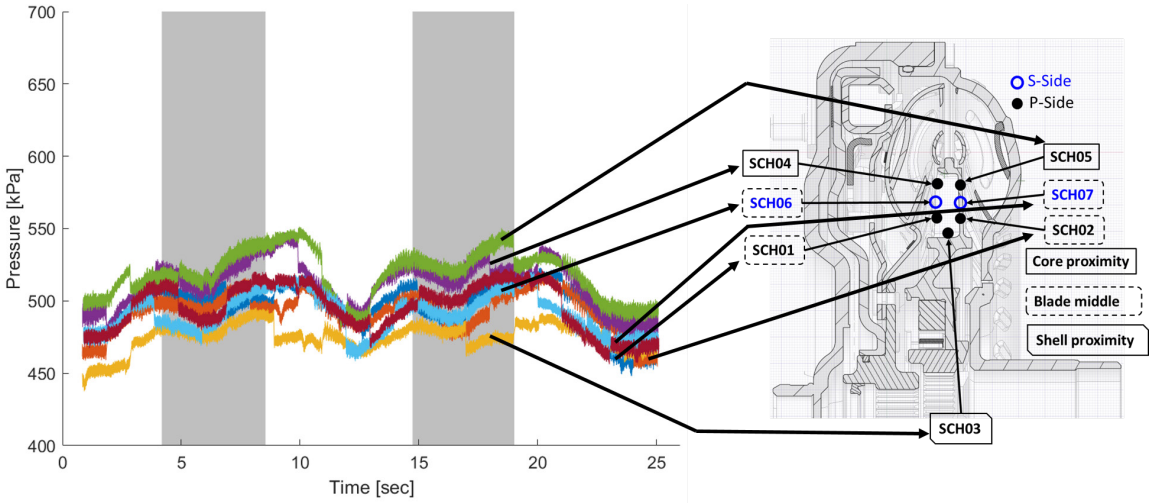


Figure 4-21. Back drive stitched time history for stator channels

www.manaraa.com

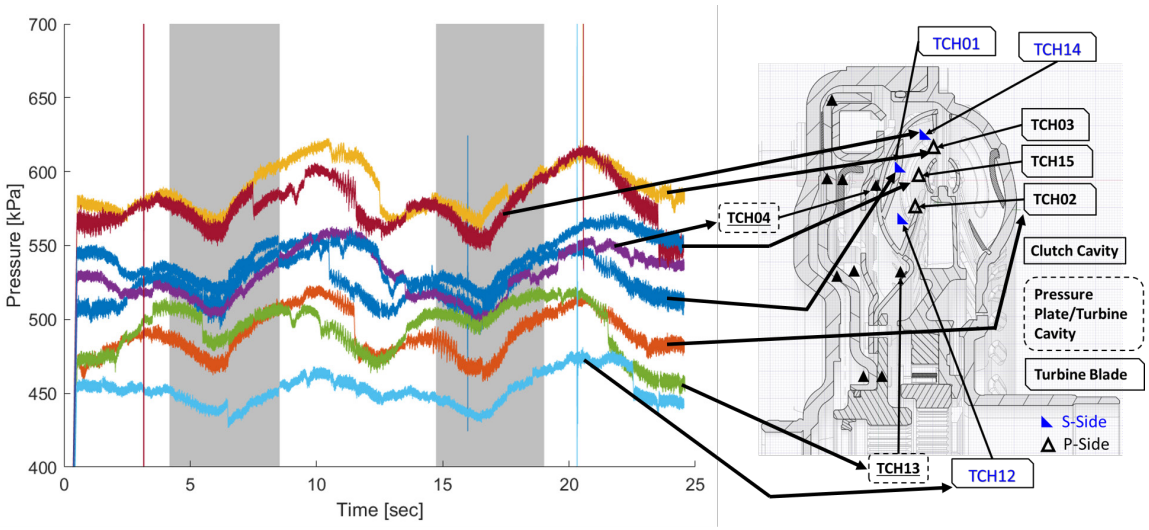


Figure 4-22. Back drive stitched time history for turbine torus and clutch cavity channels

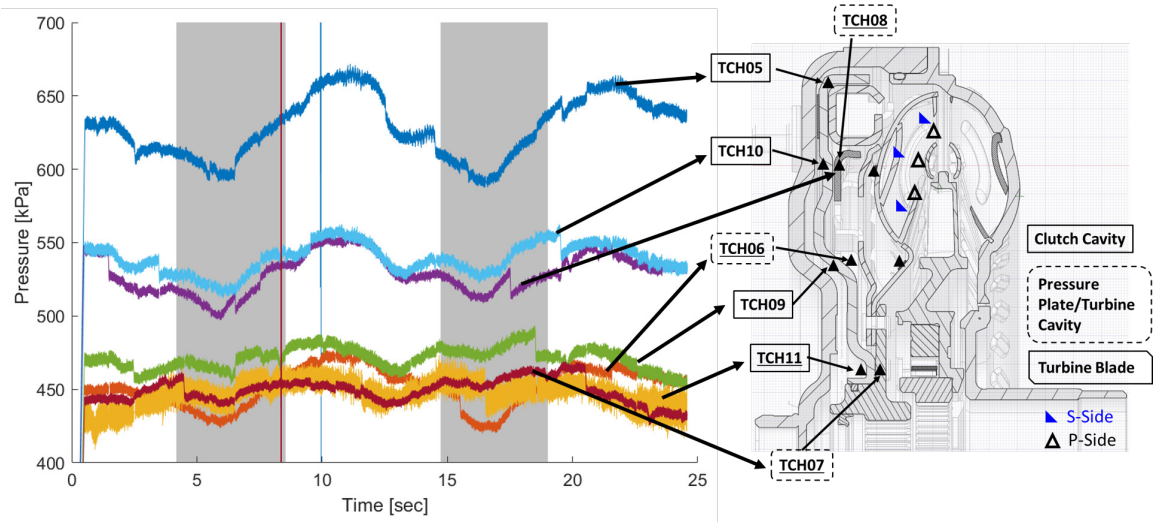


Figure 4-23. Back drive stitched time history for torque converter clutch channels

The pressures were pulled from the time history at speed ratios of 0.98, 1.1, and 1.2 and the mean pressures at each speed ratio were averaged for both positive and negative torques. This was done for all torque sweeps and complied for each channel to show the change in pressure across positive and negative torques. Figure 4-24, Figure 4-25, and Figure 4-26 are channels from the impeller, stator, and turbine respectively that were selected to show the effects at each location

www.manaraa.com

through the torque converter. Each graph is split up for each speed ratio and for a reference the neutral pressure for TCC open are shown on the right. The neutral pressures provide a range of how much the input speed can affect the pressure at that location. The impeller and turbine show how the pressure decreases as the speed ratio increases and as the torque decreases. The stator shows the opposite where the pressure increases slightly as speed ratio increases but no change is seen based on torque. The results for each channel can be seen in Appendix L.

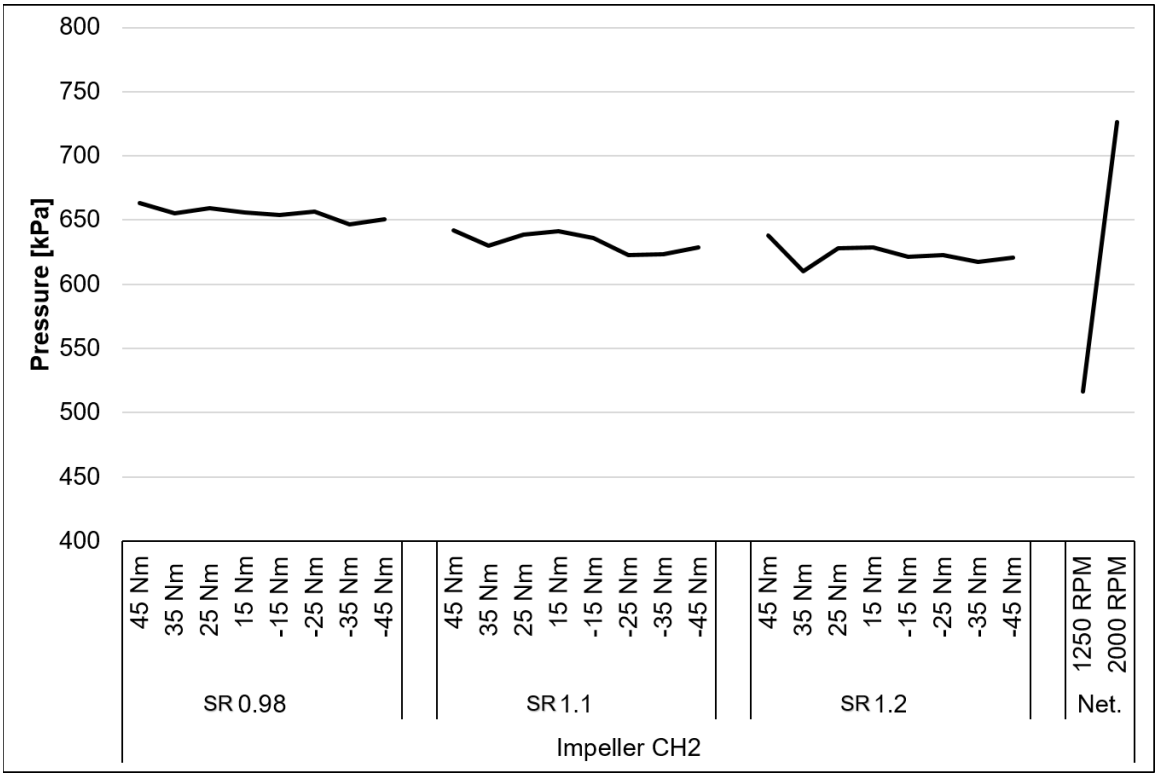


Figure 4-24. Impeller channel 2 pressures during back drive

www.manaraa.com

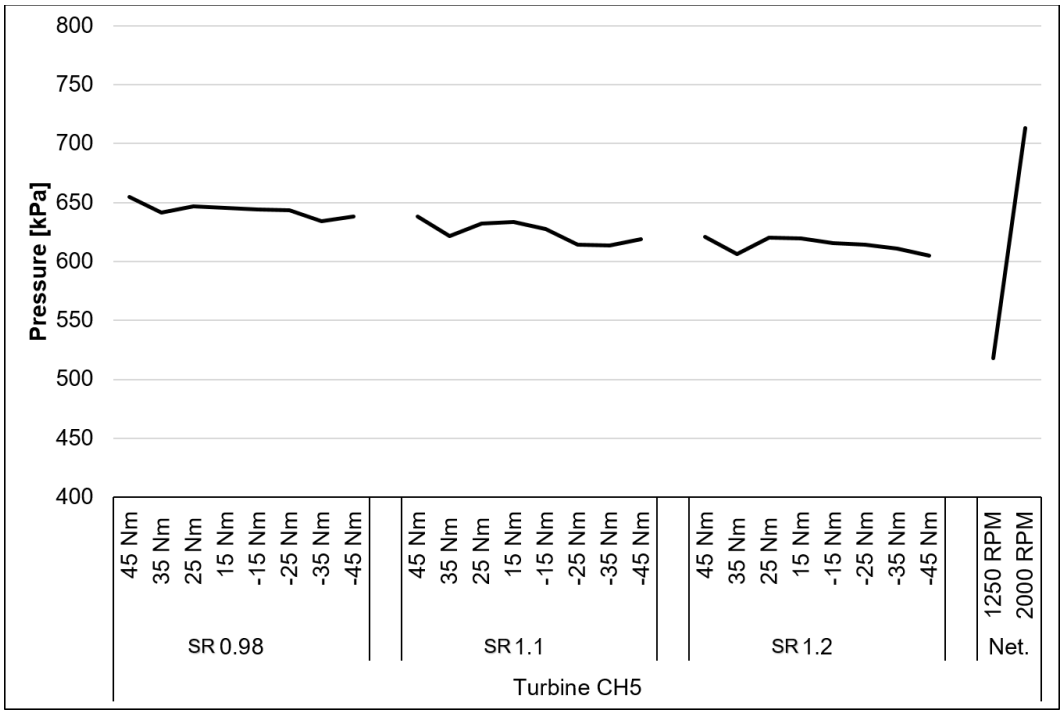


Figure 4-25. Turbine channel 5 pressures during back drive

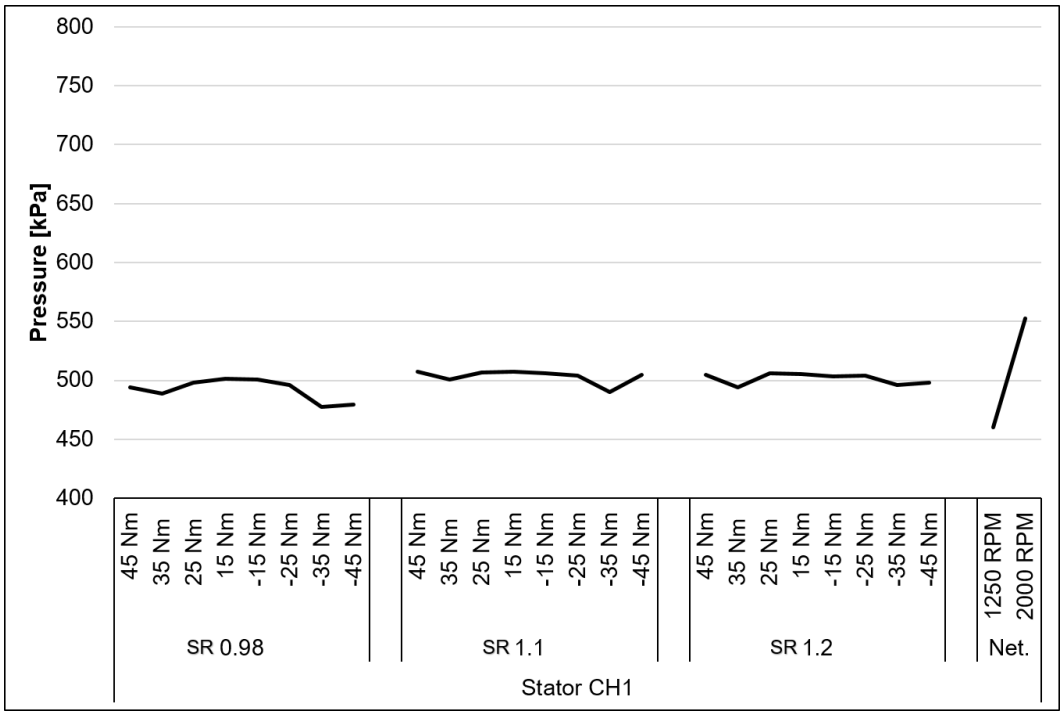


Figure 4-26. Stator channel 1 pressures during back drive

www.manaraa.com

4.2.1.1 CFD Correlations

The CFD correlations were completed with another graduate student that built the model of the torque converter. It was of interest to simulate the back drive tests to show how well the model correlates to high speed ratios. This is an addition to the research that was completed by [24].

The 45 to -45 Nm case was used as the parameters for the 0.98, 1.1, and 1.2 speed ratios. The impeller, turbine, and stator speeds were used as the input parameters to the model. The torque on each element is an output. The stator speed was estimated by finding the speed where there is zero torque on the stator because it is freewheeling at these speed ratios. The parameters and results are summarized in Table 4-3.

Table 4-3. CFD parameters and results summary

Test Torque Direction	SR	Impeller Speed [RPM]	Turbine Speed [RPM]	Stator Speed Estimate [RPM]	CFD Impeller Torque [Nm]	CFD Turbine Torque [Nm]	CFD Stator Torque [Nm]
+ 45 Nm	0.98	1806	1890	1703	-4	4	-0.01
- 45 Nm	0.98	1933	1777	1717	-8	8	-0.04
+ 45 Nm	1.10	1663	1836	2079	9	-10	-0.08
- 45 Nm	1.10	1693	1860	2090	10	-10	-0.04
+45 Nm	1.20	1535	1846	2141	12	-12	0.01
- 45 Nm	1.20	1555	1860	2172	12	-12	-0.07

The torques seen in the CFD results show a lower torque than what is seen by the test data. This is due to the CFD being a steady state calculation instead of a transient. To achieve a steady state condition of -45 Nm the speed would have to be much higher and this can be determined by using the affinity law given in Equation 4-5. Table 4-4 show the speeds required to achieve -45 Nm at the higher speed ratios.

www.manaraa.com

$$Speed_{desired} = Speed_{known} * \left(\frac{Torque_{desired}}{Torque_{known}}\right)^{\frac{1}{2}}$$ Equation 4-5

Table 4-4. Steady state speeds required to achieve -45 Nm

Speed Ratio	Impeller	Turbine
1.1	3652 RPM	4017 RPM
1.2	2993 RPM	3591 RPM

A comparison between the pressures for the test and -45 Nm steady state for the impeller, turbine, and stator are shown in Figure 4-27 for 1.1 and 1.2 speed ratios. Transducer 7 on the turbine is not shown because in the model the measurement location is deadheaded against another surface where fluid cannot be modeled.

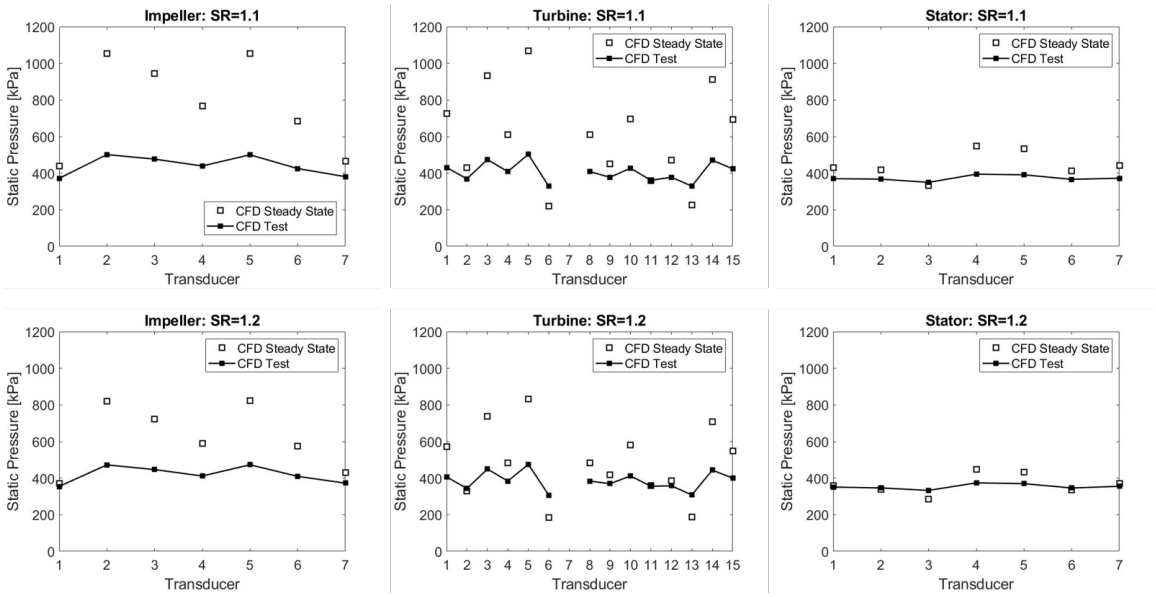


Figure 4-27. CFD comparison of test vs. steady state values to achieve -45 Nm

Figure 4-28 shows the how well the CFD correlates to the test data. As the speed ratio increases the CFD error increases. To see the results for all channels reference Appendix M. One key point to illustrate for the results is how the flow changes across the stator blade. Figure 4-29 shows the pressures across the stator blade for the test and CFD results for 45 and -45 Nm. The test results are

www.manaraa.com

higher than the CFD but the CFD does capture how the fluid field is acting across the blade. This is shown by looking at the middle of the blade and seeing how the pressures cross one another creating a figure 8 pattern between the pressure and suction sides of the blade. This can be seen in the test and the CFD meaning that the CFD can be used for stator blade design and development.

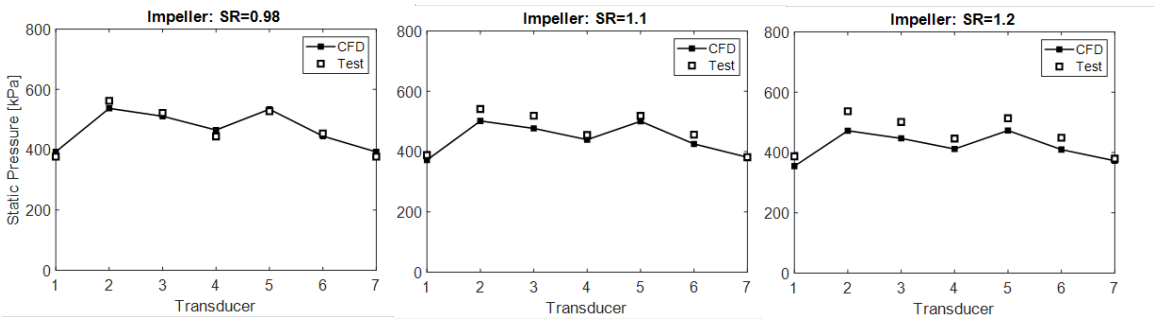


Figure 4-28. CFD correlation to high speed ratios

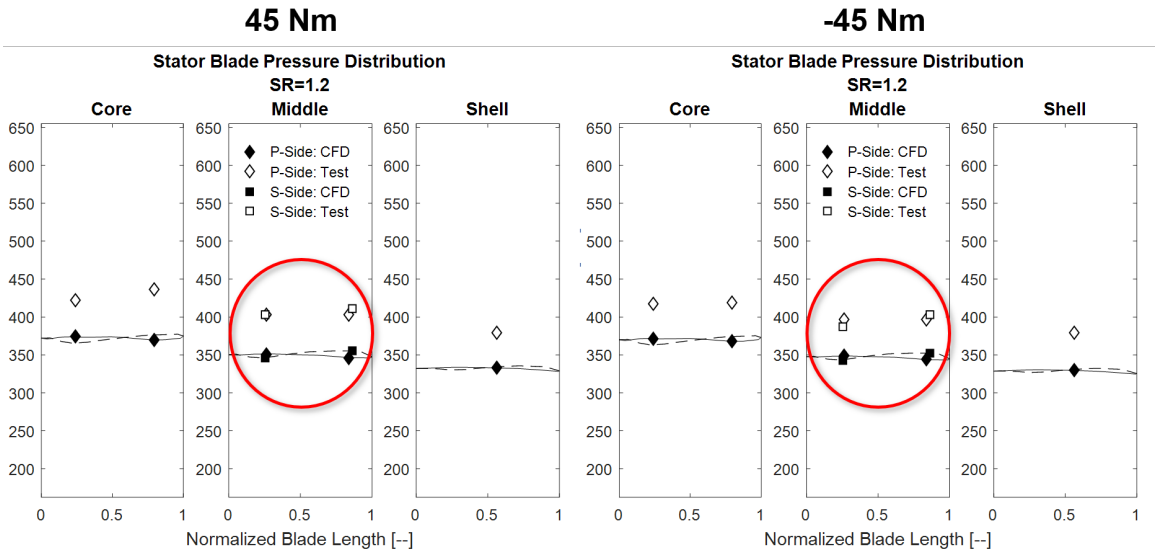


Figure 4-29. Pressure distribution across stator blade for 45 and -45 Nm

www.manaraa.com

4.2.1.2 Stator Speed Identification

The key information used from the CFD relevant to the transient testing research is the stator speed estimates, provided in Table 4-5. These values were used to compare to the test data to determine the stator speed when looking at a FFT color map.

Table 4-5. Stator speeds for each speed ratio

Speed Ratio	Impeller Speed [RPM]	Stator Speed CFD Estimate
0.98 ★	1865	~1700 (28.3 Hz)
1.10 ★	1675	~2080 (34.7 Hz)
1.20 ★	1550	~2150 (35.8 Hz)

Identifying the stator speed is of interest because understanding what happens to the stator at high speed ratios can drive innovation and calibration techniques. To identify the stator speed using the pressure data the stitched time history was split into blocks. Only the data that was recorded continuously can be placed in a block. Data blocks cannot contain data where stitching occurs. An FFT was taken on each of these blocks to create a color map showing the frequency on the x-axis and time on the y-axis. The primary frequency of the stator can be found by applying this process on one of the stator channels, as seen in Figure 4-30. The primary frequency is determined by Equation 4-6 where N is the rotational speed in RPM and F is the primary frequency in Hz. The stator speeds obtained from the CFD are indicated by stars along the color map. This verifies that expensive instrumentation is not needed to estimate stator speed instead cheaper models can be used.

$$F = \frac{N}{60} \qquad \text{Equation 4-6}$$

www.manaraa.com

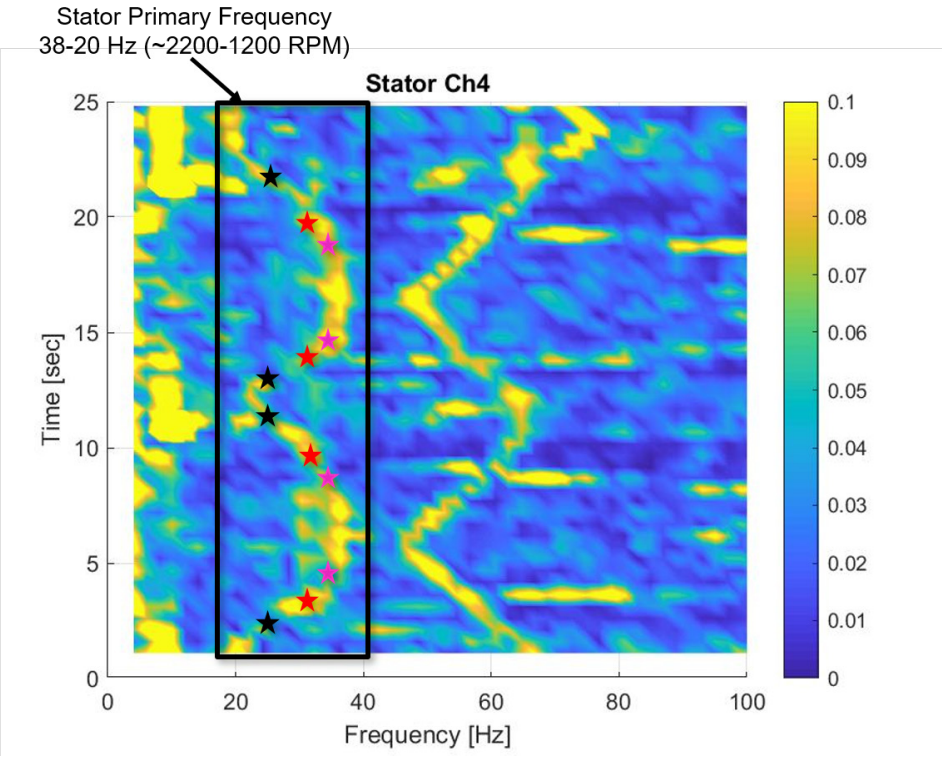


Figure 4-30. Stator speed identification using pressure data FFT color map

4.2.1.3 Hydraulic Pump Frequency Content

A frequency was noticed to appear on all channel color maps and was identified to be the hydraulic pump. Figure 4-31 shows the color map for the line pressure measurement where the hydraulic pump has the largest impact. The hydraulic pump primary frequency was identified to be between 24-32.5 Hz, which is also the impeller primary frequency because the pump in concentrically driven by the impeller. The second order of the hydraulic pump primary frequency is 48-65 Hz as seen in Figure 4-31. This second order from the hydraulic pump is what can be seen across all other channels in the torque converter. Seeing the hydraulic pump appear on the other color maps is not a surprise since the hydraulic pump is the primary excitation to the ATF. This means modifications made to the hydraulic pump performance, such as changing the number of lobes on gerotor gear, can be seen and impact the pressures in the torque converter.

www.manaraa.com

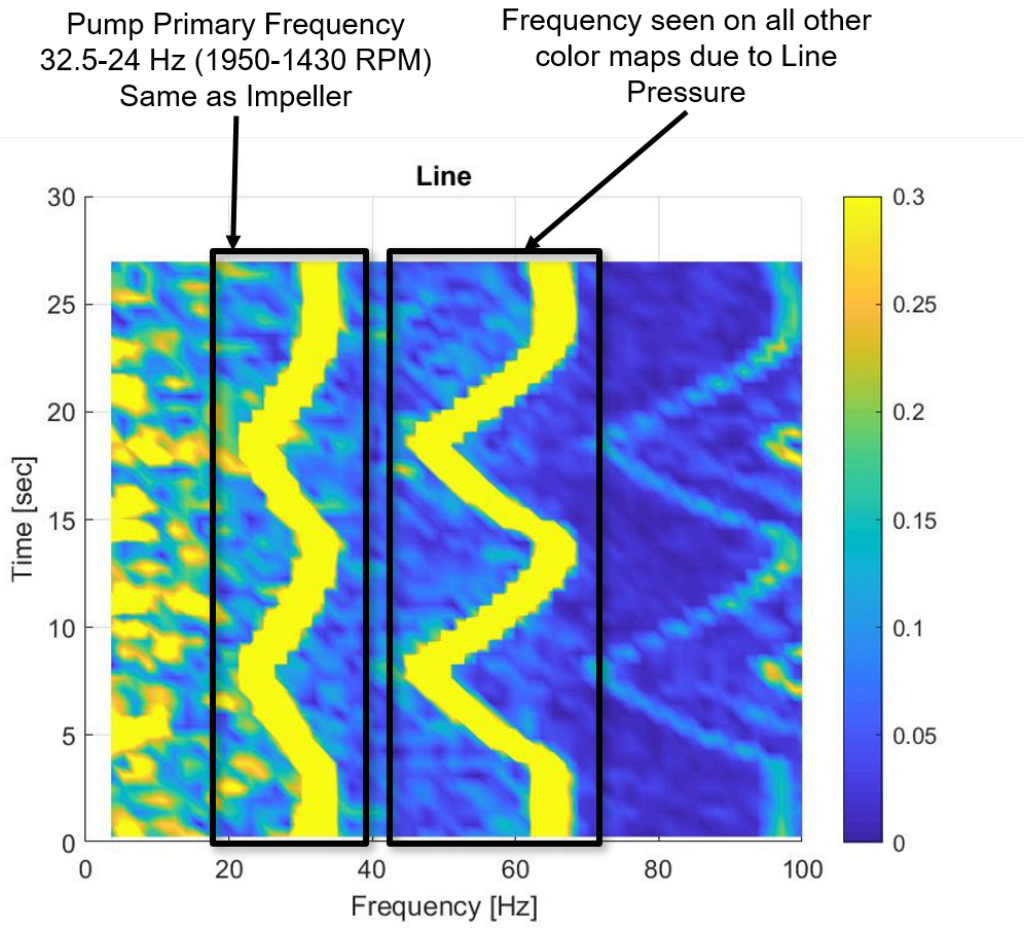


Figure 4-31. Hydraulic pump primary frequency

Additional frequencies caused by the hydraulic pump were found at higher frequencies ranging from 95-260 Hz. The frequency with the highest amplitude is gear mesh frequency of the inner rotor of the gerotor hydraulic pump. Multiple other frequencies were also seen for different number of lobes. These frequencies are identified on the color map seen in Figure 4-32. Additional research is required to better understand the frequencies caused by the gerotor pump. All channel color maps can be found in Appendix N.

www.manaraa.com

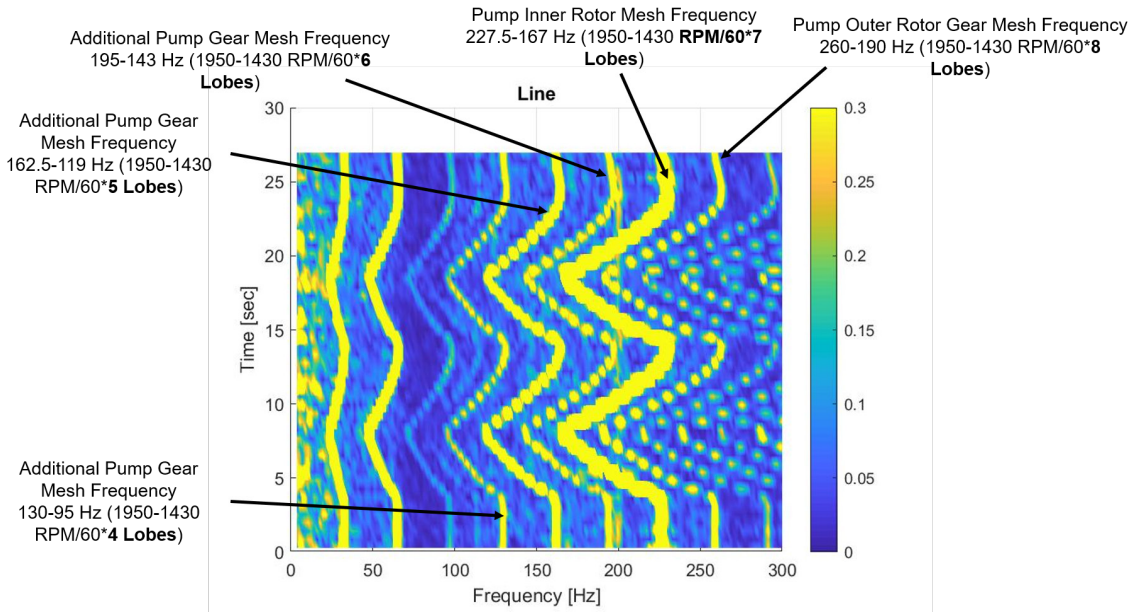


Figure 4-32. Multiple frequencies associated with the hydraulic pump

4.2.2 Gear Shift

Being able to achieve gear shifting while under load was of interest to study how the hydraulics from the transmission interact with the torque converter during the shift. Both power-on upshifts and downshifts were completed for a medium and low load input torque at both cruising and low speeds. The operating conditions for each shift scenario are summarized in Table 4-6.

Table 4-6. Gear shifts completed operating conditions

Case	Input Torque	Vehicle Speed Equivalent
Low Load, Cruising Speed	30 Nm [22.1 ft-lb]	88.5 kph [55 mph]
Medium Load, Low Speed	100 Nm [73.7 ft-lb]	48.3 kph [30 mph]
Low Load, Low Speed	30 Nm [22.1 ft-lb]	48.3 kph [30 mph]

www.manaraa.com

4.2.2.1 Test Repeatability

To be able use the multiplexed telemetry transient data method that was developed the shift must be repeatable so the pressure time history can be stitched together properly. Each shift maneuver was verified to be repeatable and the pressure data can be stitched together. Figure 4-33 and Figure 4-34 are 16 test runs overlapped showing the test repeatability. The figures include the dyno speeds, TCC slip speed, dyno torques and clutch pressures. Note there is some variation in the output dyno torque and this is due to the transmission triggering activating a delta time after seeing the trigger event. The output torque variation is noticeable because by changing when the shift occurs in relationship to the torque management a smaller or larger output torque can occur. This variation in output torque was considered acceptable and the shift strategy was used.

The torque management used for down and upshift can be seen on the input torque in Figure 4-33 and Figure 4-34. The torque does not match the step response examples that were described in the methods because the dyno controls take time to adjust for the inertia. This creates a smoother torque curve. To compensate the torque management is started prior to the shift to allow the dyno to reach the proper torque to achieve the shift safely.

During the shift the TCC slip varies from the control of 20 RPM. This is due to the control pressure is being held constant throughout the shift without any feedback controls. By having a constant charge pressure the TCC does not have the capacity to hold the fluctuating torque. Once the shift is completed and the torque returns to its starting value, the TCC has the capacity to maintain 20 RPM of slip once again.

www.manaraa.com

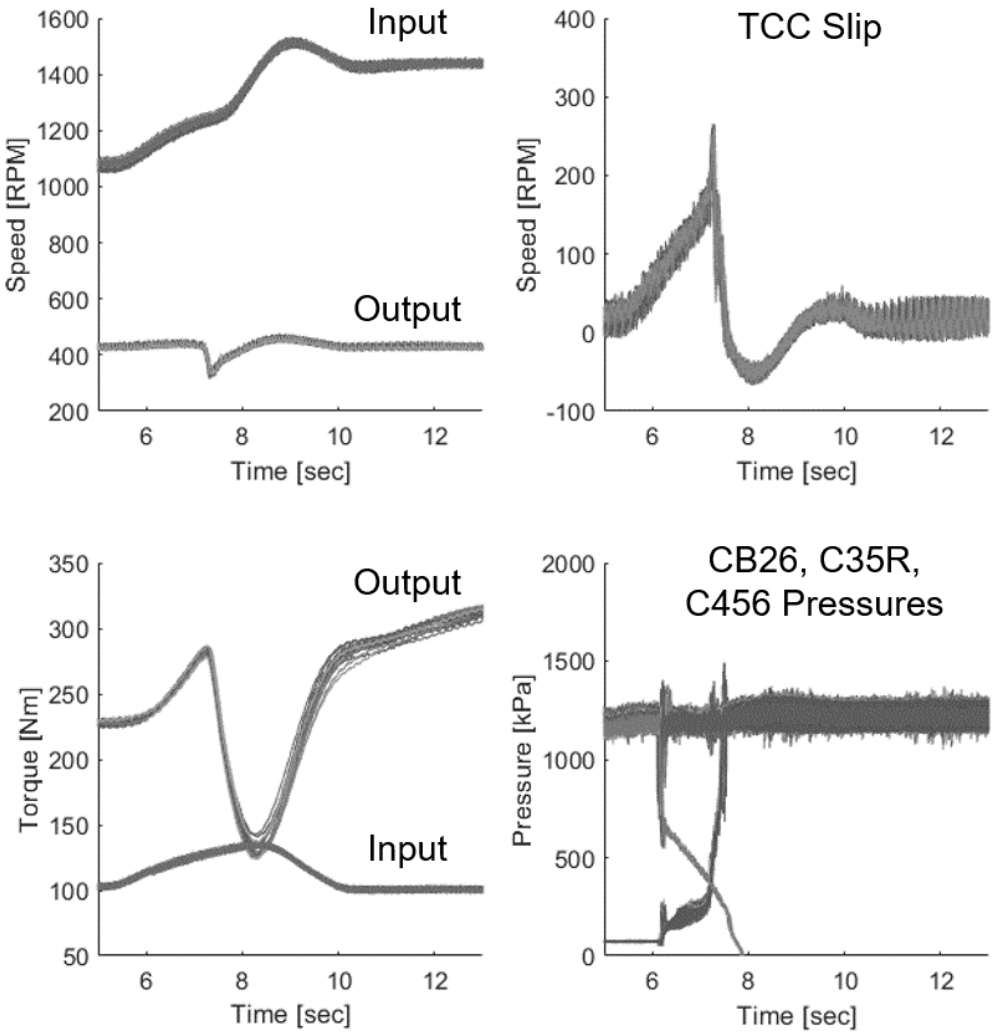


Figure 4-33. TCC slipping downshift repeatability verification

www.manaraa.com

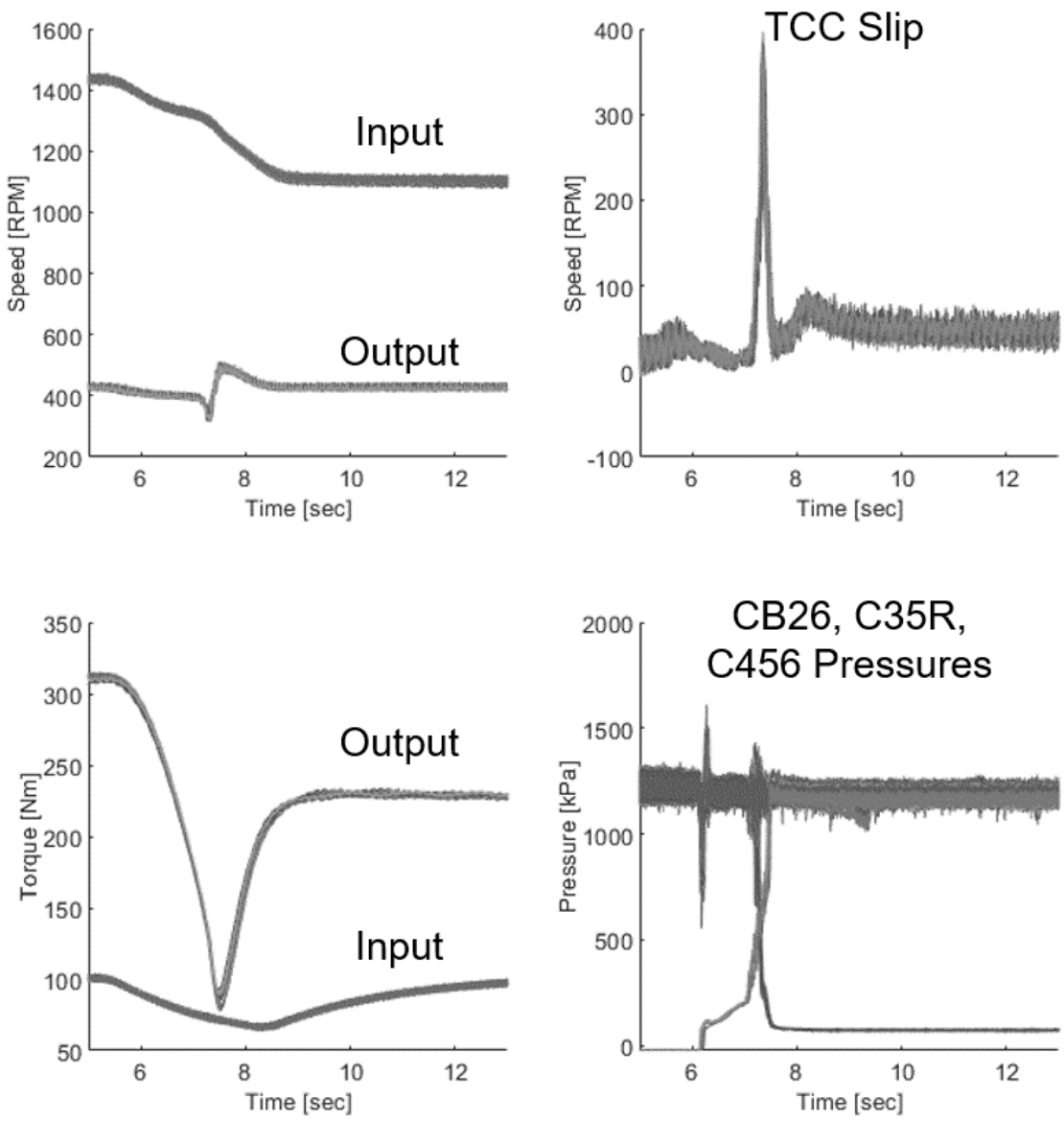


Figure 4-34. TCC slipping upshift repeatability verification

www.manaraa.com

4.2.2.2 Shift Command Profile Comparison

To ensure that the shifts used in this study were comparable to in-vehicle performance an average pressure profile was used to validate the profiles. Vehicle data for clutch pressures during a shift were averaged together for each gear state and converted to a current profile. The averaged current profile and test current profile were overlaid to validate that the pressure measurement would represent the shift properly. Figure 4-35 and Figure 4-36 show the current command profiles for the in-vehicle and test calibration. Majority of the current command profile was identical other than the end of the shift. The test calibration has a shallower slope to aid in accommodating for the large input inertia from the dynamometer. By having a less aggressive inertia phase the output torque fluctuation will be less. This variation at the end of the shift was considered acceptable because the clutch fill and torque phase pressures would mimic in-vehicle performance properly.

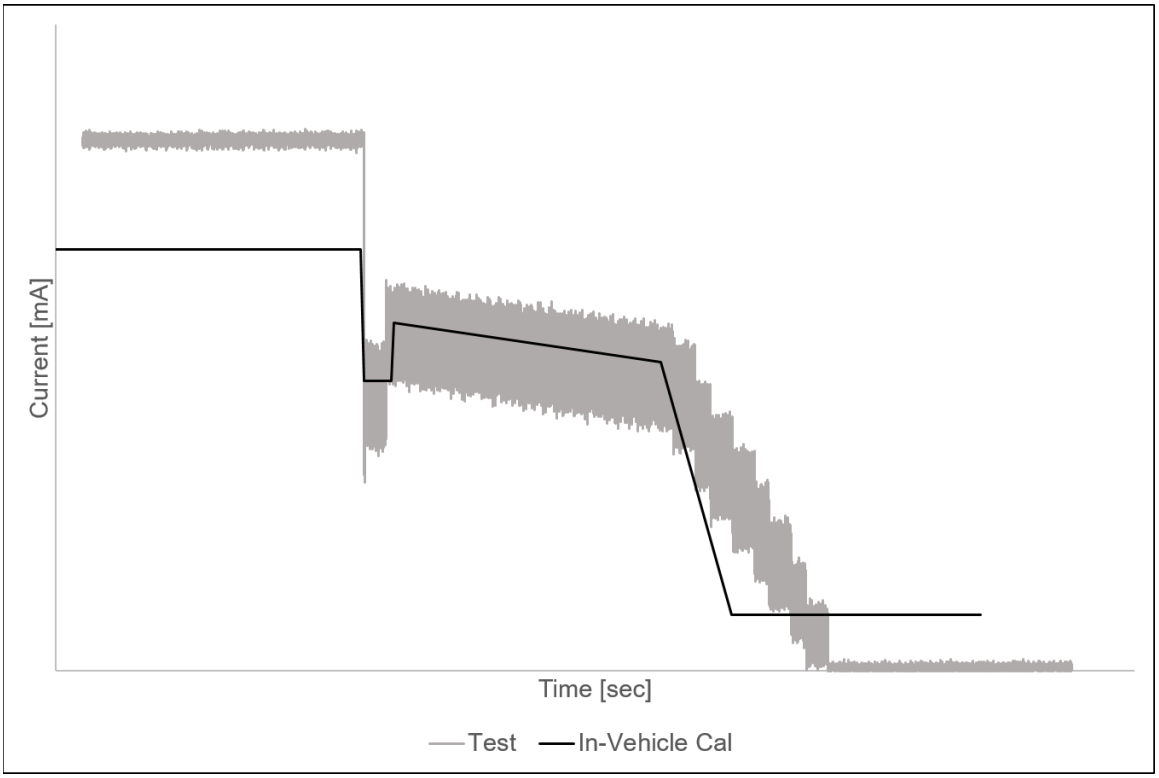


Figure 4-35. C35R current command profile comparison

www.manaraa.com

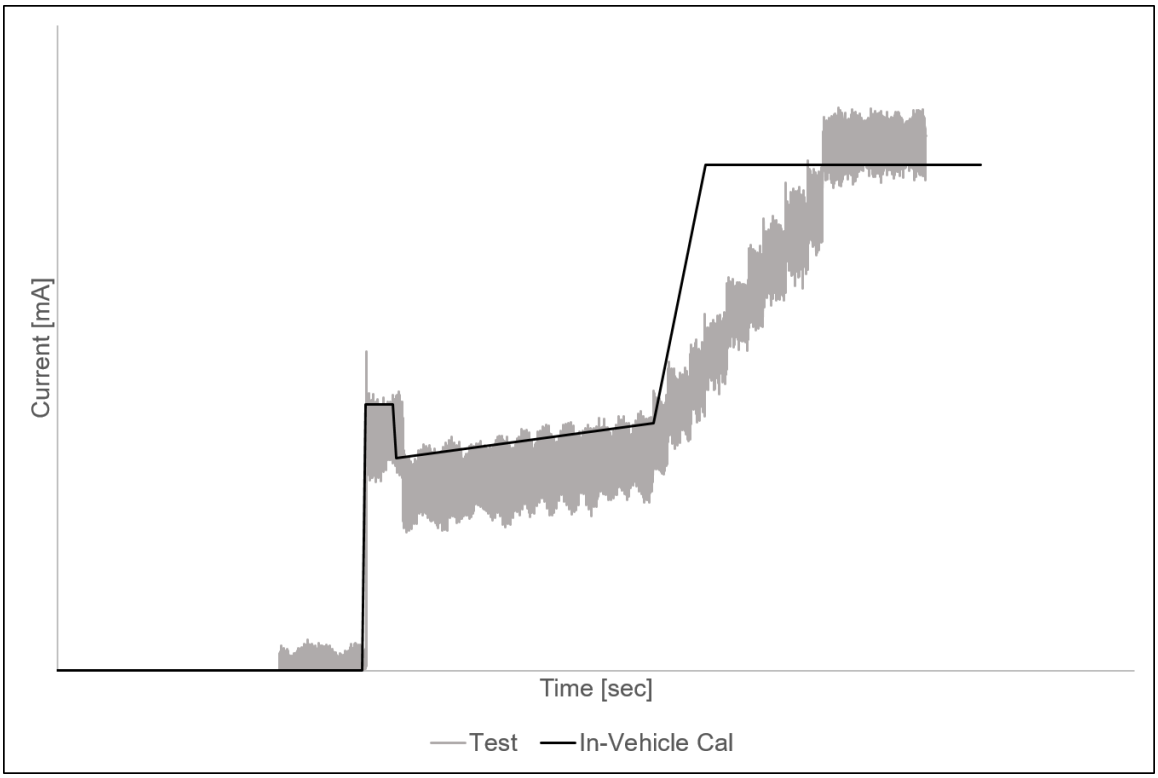


Figure 4-36. CB26 current command profile

4.2.2.3 Low Speed Shifting

Only the low load, low speed downshift results are presented here because these test conditions are the most likely to induce low hydraulic capacity to the torque converter. The low load, low speed upshift was tested but not reported here because calibrating for an upshift that results in an engine speed of approximately 1000 RPM is not common, but it is possible for a downshift if the vehicle is slowing down. All other testing conditions presented in Table 4-6 were used to develop a base understanding of what the pressures may appear to look like when the system has enough hydraulic capacity to feed all clutches and torque converter.

Figure 4-37, Figure 4-38, and Figure 4-39 are the results for a low load, low speed downshift with the TCC released, applied, and slipping respectively. When the TCC is released the input and output dynamometer are not mechanically

www.manaraa.com

connected, which allows the input dyno to transition slowly during the shift event. This can be seen in Figure 4-37 where the turbine speed has completed the shift but the input is slowly ramping up to the final speed. The torque fluctuation seen during the shift is low with the TCC open because the torque is being transmitted via the ATF instead of a mechanical connection through the TCC. There is a fluctuation on the line pressure due to the change in gear clutch pressures and the fluctuation can be seen on the clutch pressures, but is not seen on the charge or torque converter pressures. All the torque converter pressures are higher than the charge pressure because all locations in the torque converter are affected by the charge pressure when the TCC is released.

When the TCC is applied the input and turbine speeds are identical with little to no slip across the TCC. The torque fluctuation is the largest when the TCC is applied because the dynamometers are mechanically connected via the TCC and the output dyno has to compensate for the additional inertia on the input to achieve the commanded control speed. A similar line pressure fluctuation is seen as compared to having the TCC open. The torque converter pressures now have channels that are lower than the charge pressure. These channel locations are between the TCC and cover where the charge pressure does not impact. All other torque converter pressures are above the charge pressure.

When the TCC is slipping the input and turbine speed were held at a constant 20 RPM slip for the starting conditions. When the torque management for the shift was active the slip speed increases because the clutch capacity is held constant but the input torque increases and cannot maintain the 20 RPM slip. Once the shift and torque management are complete the slip across the TCC returns to 20 RPM. The torque fluctuation during the shift is lower because the TCC is not transmitting all the torque between the dynamometers resulting in a smoother torque profile. The torque converter pressures are seen to be lower because the charge pressure is low, compared to TCC applied and released, to achieve a slipping clutch

www.manaraa.com

condition. It was determined that the transmission still had the hydraulic capacity at low speed, low load to control the TCC properly.

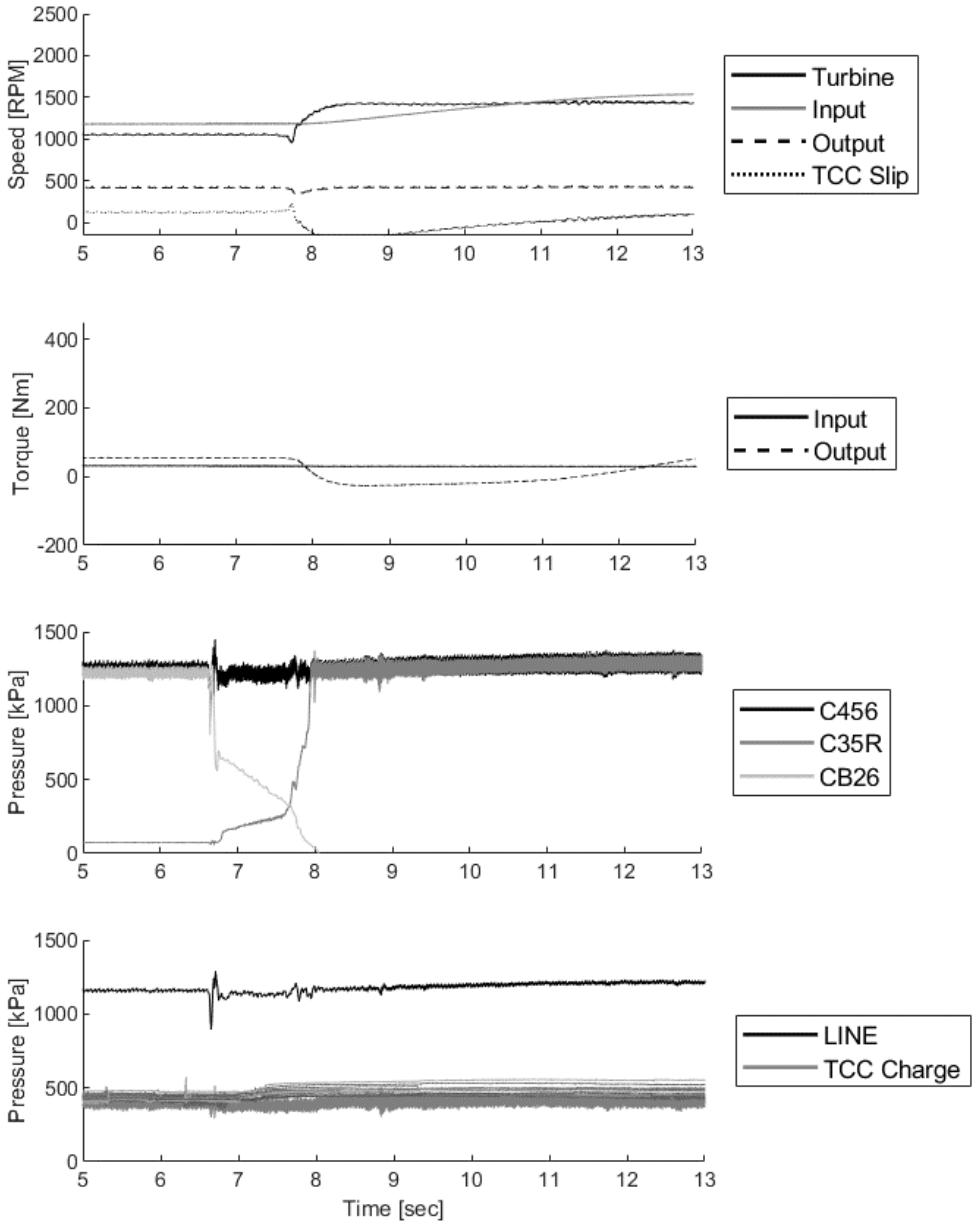


Figure 4-37. Low load, low speed downshift with TCC released- (top to bottom): transmission speeds, transmission torques, clutch pressures, stitched torque converter pressure time history

www.manaraa.com

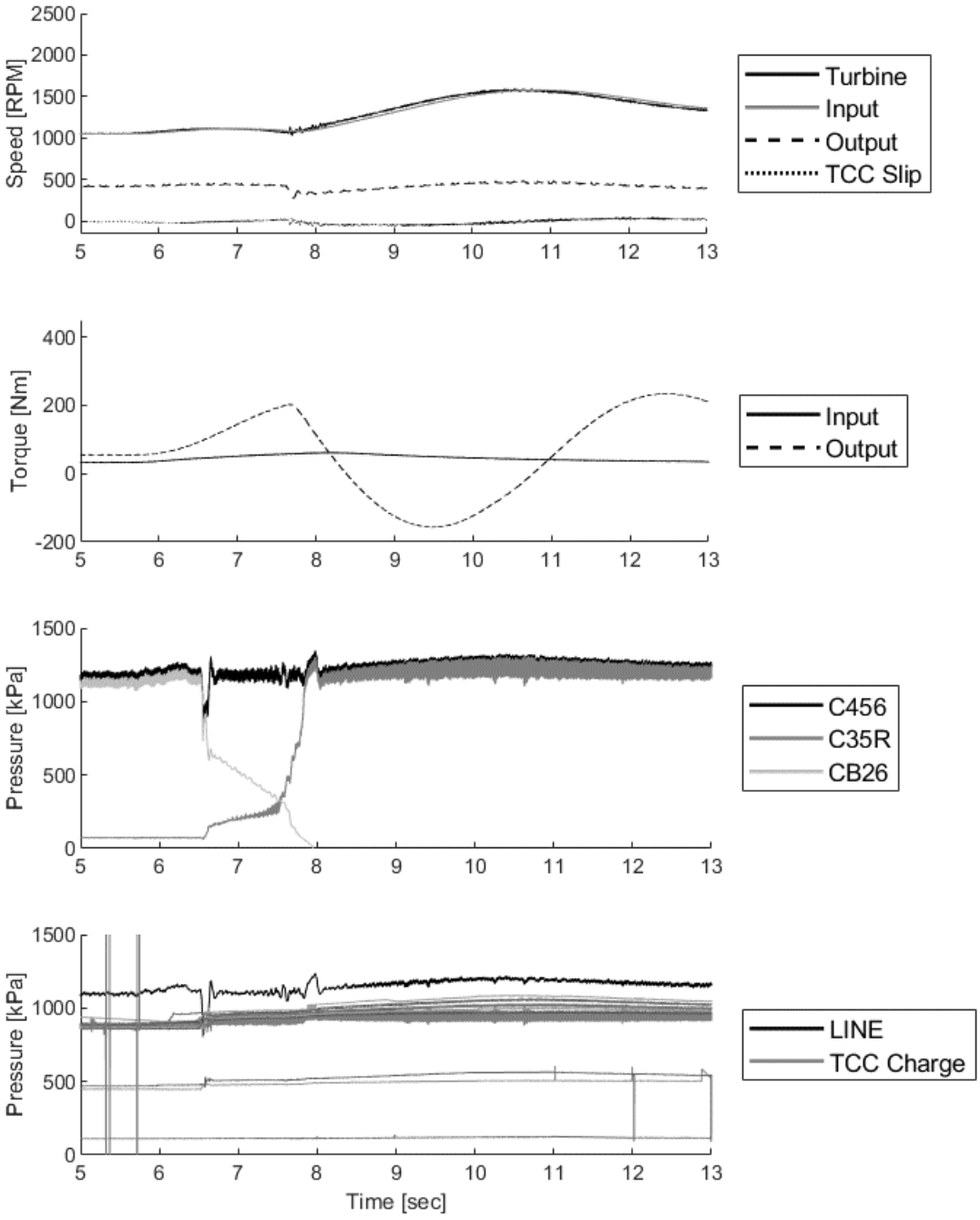


Figure 4-38. Low load, low speed downshift with TCC applied- (top to bottom): transmission speeds, transmission torques, clutch pressures, stitched torque converter pressure time history

www.manaraa.com

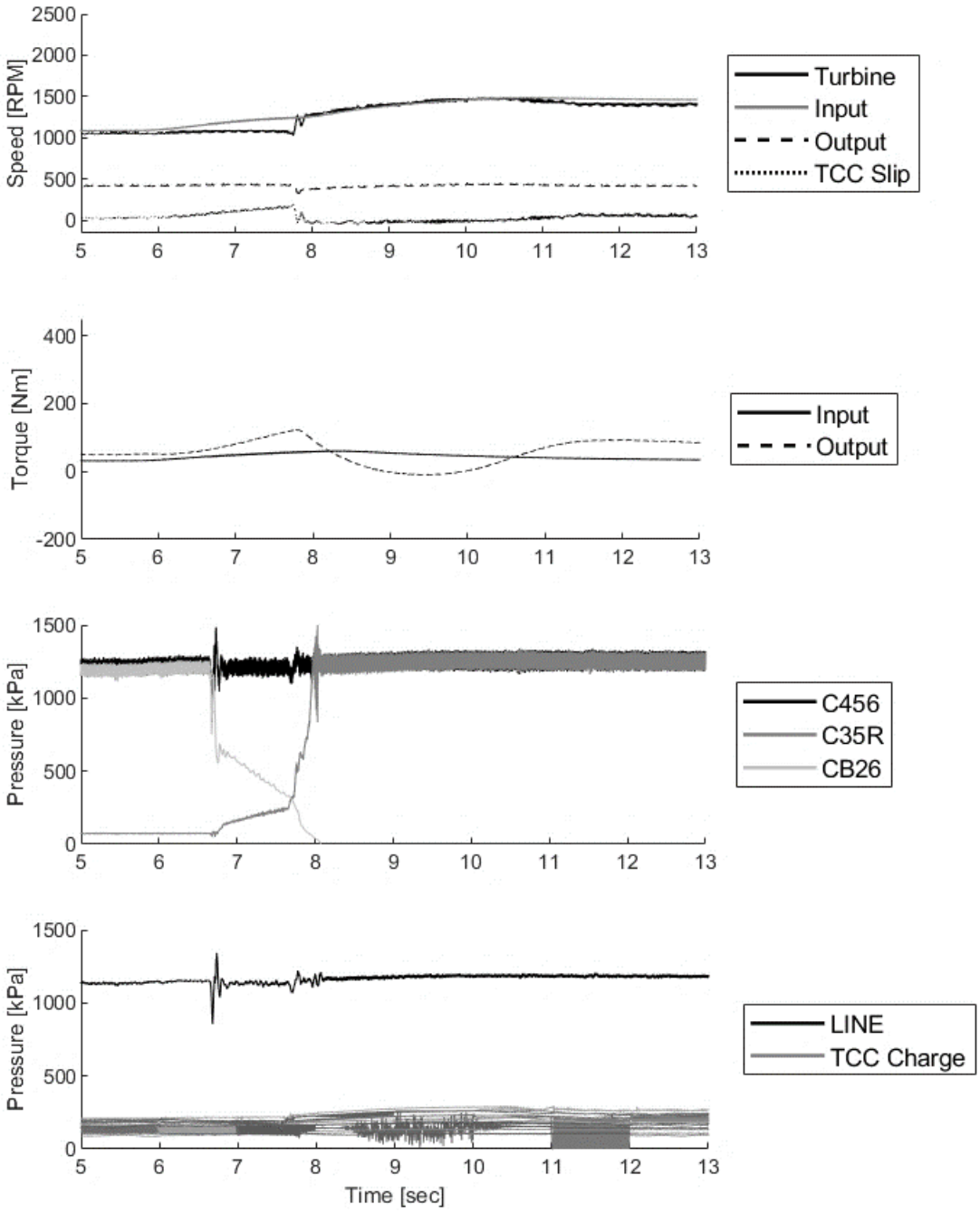


Figure 4-39. Low load, low speed downshift with TCC slipping 20 RPM- (top to bottom): transmission speeds, transmission torques, clutch pressures, stitched torque converter pressure time history

www.manaraa.com

4.2.2.4 Pressure Shift Profiles Using Zero Load Estimates

Shift profiles were estimated by using the zero load pressure measurements are shown in Figure 4-2, Figure 4-3, and Figure 4-4. The estimate pressure profiles were compared to the test results for the low load, low speed downshift to see if there is a correlation between speed, load, and pressure.

The estimated pressure profile for when the TCC is released is illustrated in Figure 4-40. The turbine speed was used as the estimation speed because the input speed has a long transition period and does not follow the speed of the shift quickly. The turbine speed can be used because all the zero load data is steady state with a high speed ratio of 0.95 or higher. By using the turbine speed a decent correlation is seen between the zero load estimate and the measured pressure results. The measure pressures have the change in pressure earlier than the estimated profile, which is attributed to the pressures changes occur first and the then the speed follows. The estimated pressure matches well with the measured pressure when in 5^{th} gear, but underestimates the pressure when in 6^{th}. This could mean that each gear has different zero load pressures, but additional research is required to verify this hypothesis.

www.manaraa.com

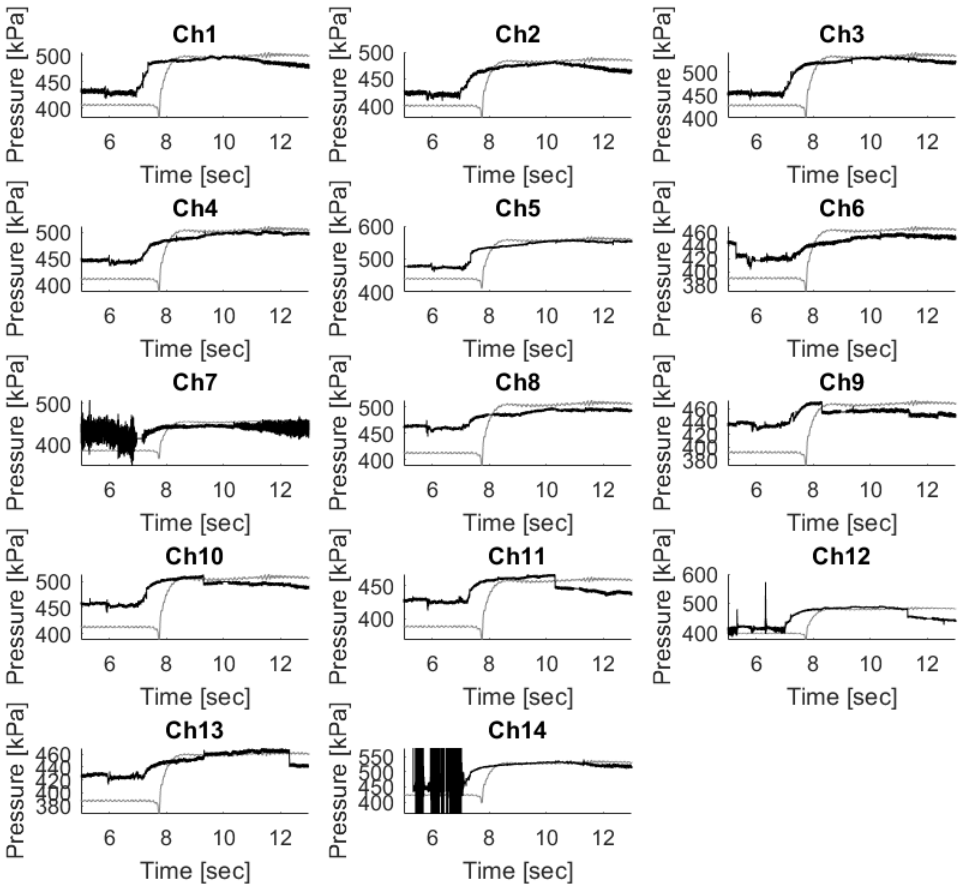


Figure 4-40. Low load, low speed shift with TCC released pressure data comparison

The comparison between the zero load estimate profile and the measured pressures for when the TCC is applied can be seen in Figure 4-41. Since the TCC is applied the input and turbine have the same speed and the input can be used to estimate the pressure profile. Again, the pressure estimate profiles match the measured pressures when in 5th gear, but now overestimate the pressure when in 6th gear.

www.manaraa.com

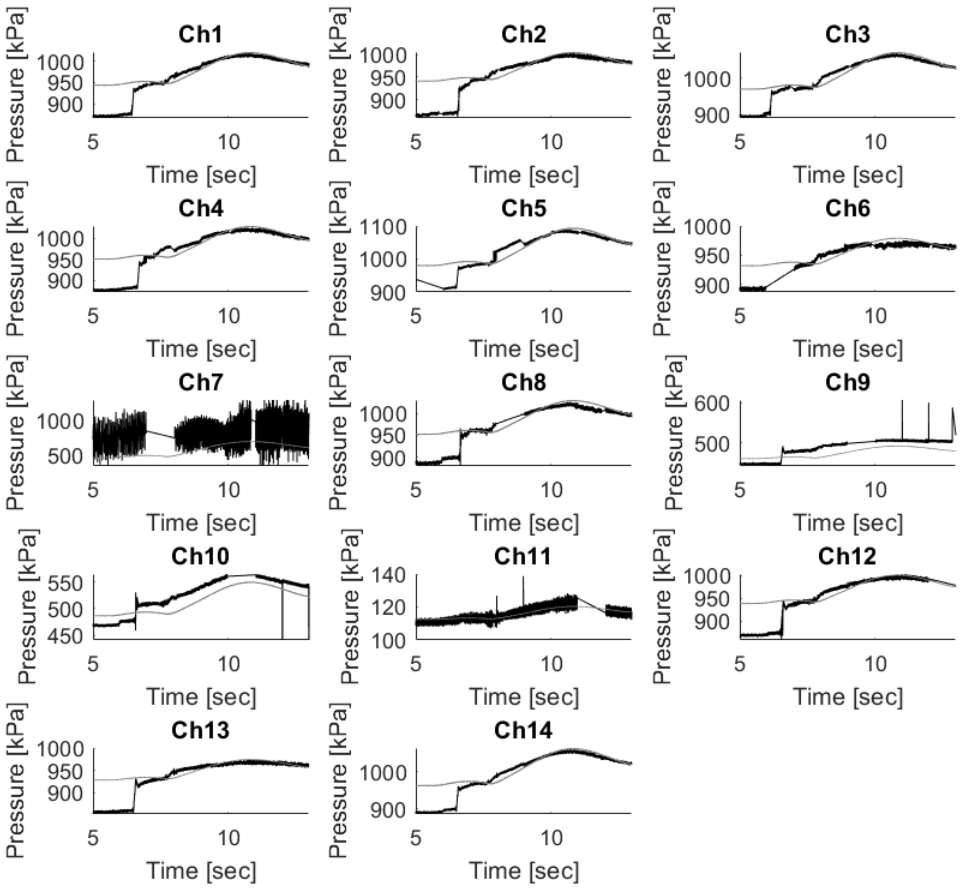


Figure 4-41. Low load, low speed shift with TCC applied pressure data comparison

The pressure profile comparison for when the TCC is slipping can be seen in Figure 4-42. The estimated pressure appears to underestimate the measured pressure, which can be attributed to the how the zero load slip pressures were measured. Since there is zero load it is difficult to cause the clutch to slip because torque is required to break the clutch away from the cover. To achieve slip in a zero load condition only a small amount of charge pressure is required, thus giving lower pressure estimates. Although the pressures are lower than measured the estimated profile follows the same trend as the measured.

www.manaraa.com

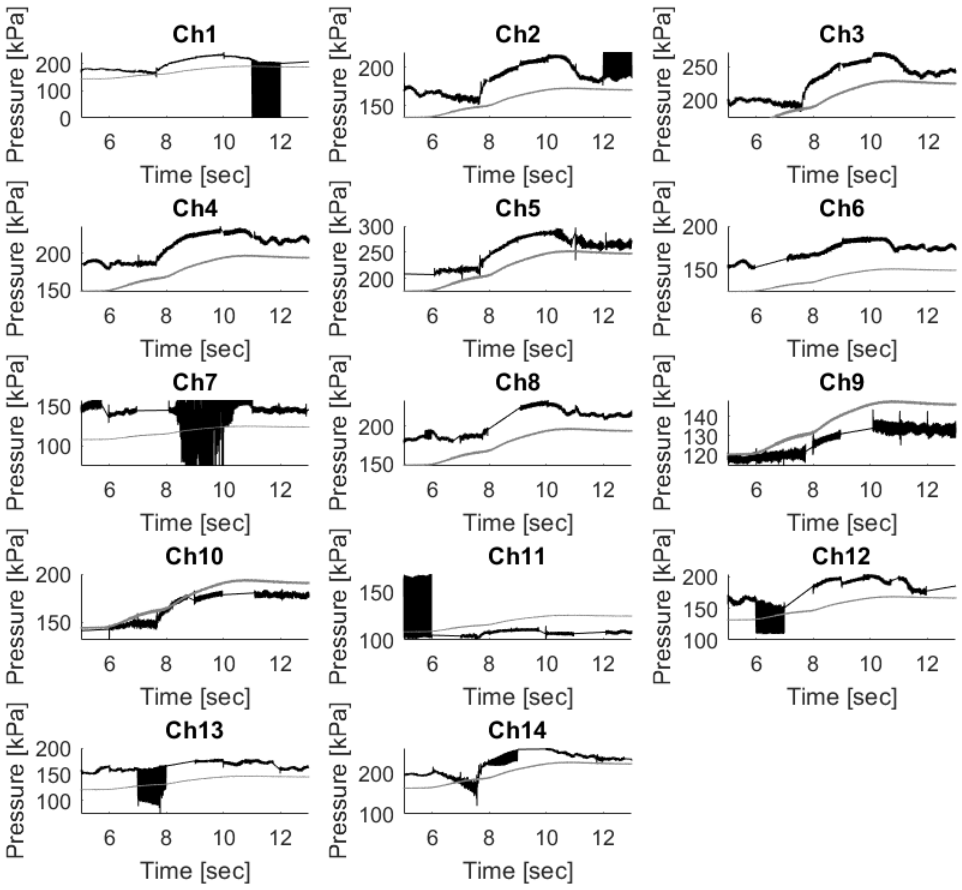


Figure 4-42. Low load, low speed shift with TCC slipping pressure data comparison

By knowing that the zero load pressures can an estimate the pressures during a shift only one measurement is required. A shift can be measured once and by using the input and turbine speed estimate the profile shape and magnitude. This would reduce the measurement time from 16 repeated runs to a single shift measurement. Further research should be conducted on other gears to validate this method and reduce the errors seen in 6th gear.

www.manaraa.com

4.2.2.5 TCC Oscillation

Oscillation was seen on every channel caused by the hydraulic pump, but channel 7 had a larger magnitude than the others when the TCC was applied. An FFT, using a hanning window on the data, was computed for channel 7, channel 6, and the line pressure for the low load, low speed downshift, shown in Figure 4-43, Figure 4-44, and Figure 4-45 respectively. Channel 6 was selected because it is the next closest measured location to channel 7. An FFT was computed before, during, and after the shift to see how the frequency may change across the shift profile. In each of the figures the primary operating frequency of the impeller is shown by a (*). Note each figure has different y axis magnitudes to be able to identify the frequency content.

Both Figure 4-43 and Figure 4-44 show that the primary frequency has the largest magnitude. The primary frequency can be seen in Figure 4-45 for the line pressure but is smaller in magnitude compared to the gerotor pump equivalent gear mesh frequency that was identified in the back drive results. Although the mesh frequency can be identified on the line pressure, channel 7 and 6 show little no excitation for that frequency.

Channel 7 can be a channel of interest because if the clutch is oscillating between applied and released the oscillation would be noticeable as a frequency not associated with the gerotor pump. This tool should be used for future analysis when testing power-off downshifts where TCC controllability may be reduced.

www.manaraa.com

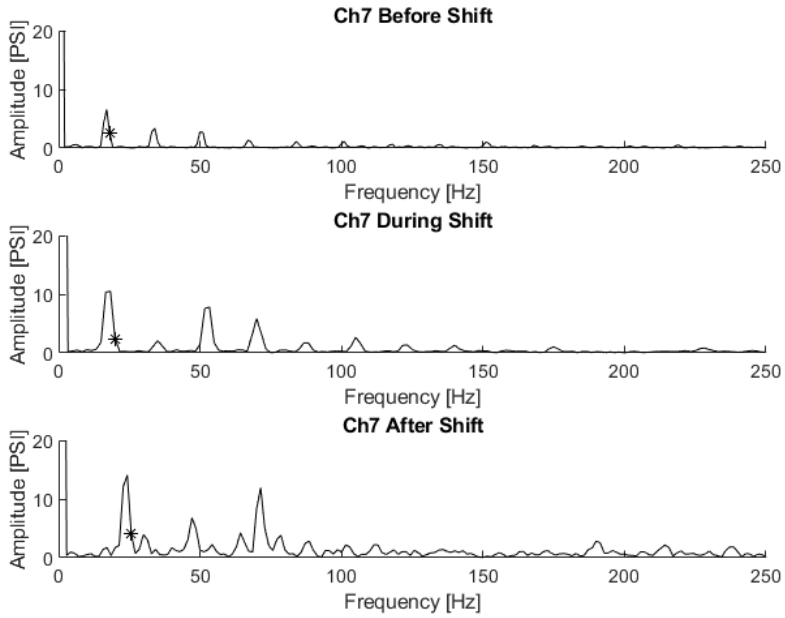


Figure 4-43. FFT of channel 7 measured pressure on the TCC for before, during, and after the shift

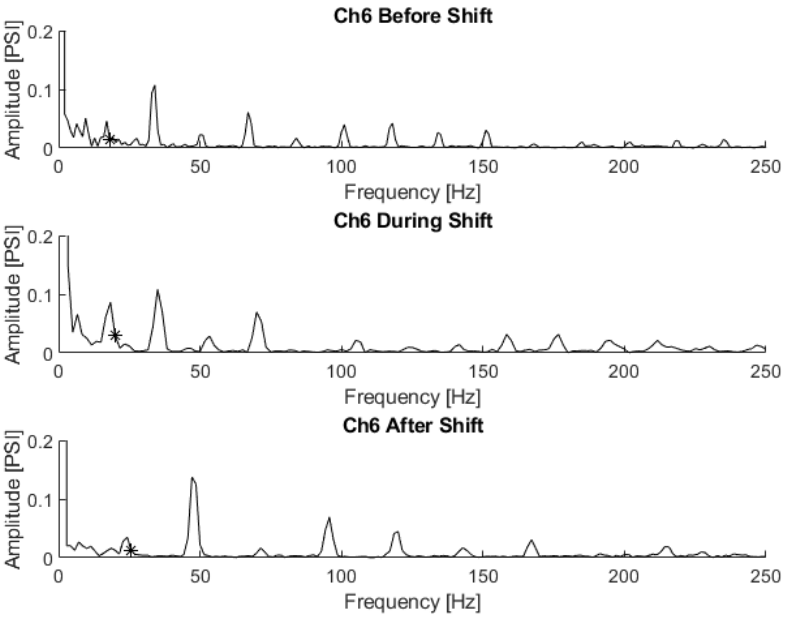


Figure 4-44. FFT of channel 6 measured pressure on the TCC for before, during, and after the shift

www.manaraa.com

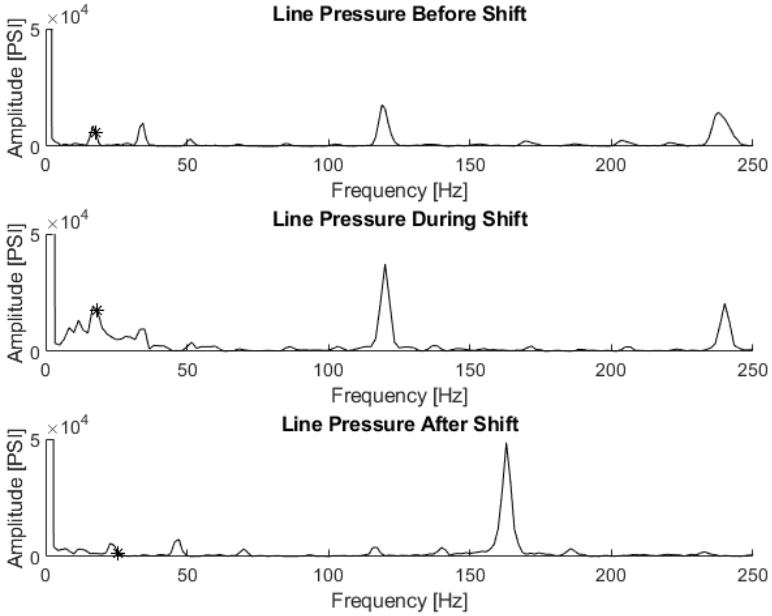


Figure 4-45. FFT of Line pressure for the transmission for before, during, and after the shift

www.manaraa.com

5 Summary and Conclusions

5.1 Steady State Results Summary

- Centripetal pressure can be calculated to be within ±15% of true pressure and can be used for quick design calculations or estimates.

- There is a constant relationship between charge pressure and internal torque converter pressure. As the charge pressure increases at a constant speed the torque converter pressures will increase the identical amount. If the TCC is applied the pressure between the cover and clutch will not be affected by the charge pressure.

- The TCC capacity was verified to follow a linear trend, as charge pressure increases the more torque capacity available. The friction coefficient was found to be 0.19 which is within the range for design specifications and other literature.

- The pressure profiles acting on the TCC were characterized and the resultant force was found to act on the center of the clutch. When the TCC is slipping the resultant force acts on the center when under medium loads of torque (similar to TCC applied), but under low loads the force was found to be acting at a larger radial location closer to the friction material. This transition of resultant force location between medium and low loads may have an impact when calibrating transitional points.

5.2 Transient Results Summary

- A procedure to use multiplexed telemetry data for transient events was developed and implemented. The procedure allows for the 1 sec channels to capture different portions of a transient event and then are stitched together to

www.manaraa.com

show a full time history of the event. The data may appear to be continuous but the time history is POINT DATA and must be treated as separate blocks.

- A back drive scenario was achieved to have the turbine drive the impeller resulting in speed ratios up to 1.3. The impeller and turbine pressures were found to decrease in pressure during the high speed ratios (1-1.2) while the stator increased in pressure. This is due to the stator inlet changing from the turbine to the impeller.

- A CFD model, created by [24], was correlated to the back drive test results showing good pressure estimate at SR 0.98 and increased in error as speed ratio increased. The torque results were underestimated by the CFD because the CFD is a steady state calculation, while the test is a transient measurement. Using the CFD stator speeds were estimated and used for verification.

- The stator speed was identified by using a FFT color map created from the pressure measurements taken on the stator. The stator speed was verified by comparing the speed estimates acquired from the CFD results. By being able to identify the stator speed and verify that the CFD can estimate the speed accurately future development can use the model results reliably.

- The pressure oscillations created in the gerotor hydraulic pump were identified throughout the whole torque converter. Changes made to the hydraulic pump will have an impact on torque converter pressures.

- Gear shifting while under load was achieved using the dynamometers as a driver and absorber to the transmission. The hydraulic shift profile was implemented to mimic in vehicle shifting strategies as close as possible. Limitations to completing the shift as quickly as in vehicle were found due to the large inertia for the input dynamometer.

www.manaraa.com

- The shift events were repeatable to allow for the telemetry transient procedure of repeating the test 16 times could be used.

- Power-on up and downshifts with the TCC released, slipping, and applied were completed. The results showed that the hydraulic system is capable of keeping the system saturated during medium and low load. The TCC was able to be controlled properly during all maneuvers tested.

- Zero load pressures were compared to the measured pressures during a shift to show that by using the input and turbine speed the pressure profile can be estimated. Good correlation was found when in 5^{th} but not in 6^{th} gear. By using the zero load pressure profile estimates only one test run is required to estimate the pressures during the shift instead of the current 16 repeated test runs. Additional research is needed to see how zero load pressures change between gears.

- A large pressure oscillation was found on the sensor between the clutch plate and turbine output wall when the TCC is applied. At this location the ATF is blocked and the frequencies from the hydraulic pump can be seen, such as in the back drive color maps. The lower frequencies were found to be present while the higher were not. This is not a concern at the moment but should be an area to continue looking as future research is conducted.

www.manaraa.com

6 Recommendations

6.1 Testing Recommendations

- Reduce the amount of time that the instrumented torque converter is ran. The torque converter instrumentation has a finite life and it has been seen that channel 15 on the turbine is already intermittent. Run test scenarios on the non-instrumented torque converter and then repeat test on the instrumented.

- Install a smaller inertia drive dynamometer and apply similar control strategy as developed for torque converter research [46]. This setup would allow for oscillating excitation as an input instead of a constant drive torque. An oscillating input torque would mimic closer to that of an engine and may open the window for more detailed analysis of the hydraulic interaction between the torque converter and transmission.

- Continued shift profile development is necessary as only a selected few were studied. Other operating conditions may show additional insight to the hydraulics. Power-off shifts was determined to be a point of interest late into the research and was not able to be part of this study.

- Replace the NI 9234 card that is currently being used for triggering the shift events with a NI card that has built in triggering capabilities, such as NI 9205 or 9206. Purchase this for the test cell if continued testing is of interest because NI 9234 is on loan from Dr. Blough.

6.2 Instrumentation Recommendations

- On future instrumentation projects, the addition of thermal couples for the inlet and outlet of the torque converter would provide additional insight. By

www.manaraa.com

knowing the temperature for the torque converter a better understanding of what the instrumentation is experiencing can give a better estimation on instrumentation life.

- When dealing with transient testing, try to get as many key transducers to be simultaneous. It is understood that packaging is the reason for the multiplexed transmitted data. When packaging limitations are not restricted simultaneous channels should be used. For example, since the transmitter for the impeller and cover are on the outside of the torque converter cover. By having simultaneous channels, the number of times to repeat a test can be reduced and additional correlations, such as cross-spectrums and frequency response functions, can be calculated.

- When multiplexed transmitted data is required use the same number of channels, preferably all 7 channel transmitters instead of 15, to reduce the number of times a test has to be reran. It was also found that the 7 channel transmitters take less time to power down to resync than the 15 channel transmitter, thus reducing the total test time.

www.manaraa.com

7 References

1. Hachisuwa, I., et al., *Development of Compact Torque Converter with New Multiple Disk Clutch for Toyota New FWD Eight-Speed Transmission Direct Shift-8AT*. 2017, SAE International.

2. Robinette, D. and T. Skrzycke, *A Dual Clutch Torque Converter for Dual Input Shaft Transmissions*. 2013, SAE International.

3. *The Design of a Single-Stage Three-Element Torque Converter*. 1961, SAE International.

4. Bai, S., J. Maguire, and H. Peng, *Dynamic Analysis and Control System Design of Automatic Transmissions*. 2013: SAE International.

5. De Jesus Rivera, E., *Blade Induced Tipe Loading on a 310 mm Torque Converter Turbine Blade*, in *Mechanical Engineering*. 2003, Michigan Technological University.

6. Sweger, P.O., C.L. Anderson, and J.R. Blough, *Measurements of Strain on 310 mm Torque Converter Turbine Blades.* International Journal of Rotating Machinery, 2004. **10**(1): p. 55-63.

7. By, R.R. and B. Lakshminarayana, *Static Pressure Measurement in a Torque Converter Stater*. 1991, SAE International.

8. Numazawa, A., et al., *An Experimental Analysis of Fluid Flow in a Torque Converter*. 1983, SAE International.

9. Brun, K. and R.D. Flack, *The Flow Field Inside an Automotive Torque Converter: Laser Velocimeter Measurements*. 1996, SAE International.

10. Anderson, C.L., et al., *Experimental Investigation of Cavitation Signatures in an Automotive Torque Converter Using a Microwave Telemetry Technique.* International Journal of Rotating Machinery, 2003. **9**(6).

11. Mekkes, J.A., Carl & Narain, Amitabh, *Static Pressure Measurements and Cavitation Signatures on the Nose of a Torque Converters Stator Blades.* 2004.

12. Robinette, D.L., *Detecting and predicting the onset of cavitation in automotive torque converters*. 2007: Thesis (Ph.D.)--Michigan Technological University, 2007.

13. Pohl, B., *Transient Torque Converter Performance, Testing, Simulation and Reverse Engineering*. 2003, SAE International.

www.manaraa.com

14. Robinette, D., M. Grimmer, and R. Beikmann, *Dynamic Torque Characteristics of the Hydrodynamic Torque Converter.* SAE International Journal of Passenger Cars - Mechanical Systems, 2011. **4**(2): p. 1023-1032.

15. Robinette, D., et al., *Torque Converter Clutch Optimization: Improving Fuel Economy and Reducing Noise and Vibration*. 2011, SAE International.

16. Throop, M.J. and D.G. McWatt, *Slipping Torque Converter Clutch Interface Temperature, Pressure and Torque Measurements Using Inductively Powered Radiotelemetry*. 1997, SAE International.

17. Otanez, P., et al., *Aggressive Torque Converter Clutch Slip Control and Driveline Torsional Velocity Measurements*. 2008, SAE International.

18. Kono, K., et al., *Torque Converter Clutch Slip Control System*. 1995, SAE International.

19. Rivera, E.D.J., et al., *CFD Correlation of a Torque Converter with 29 Pressure Transducers.*

20. Chen, J. and G. Wu, *Numerical Investigation of Jet-Wake and Secondary Flows in a Hydrodynamic Torque Converter*. 2017, SAE International.

21. Sawkar, N.A., P. Modi, and M. Fingerman, *Numerical Investigation of Flow Induced Excitations in a Torque Converter*. 2017, SAE International.

22. Tsangarides, M.C., W.E. Tobler, and C.R. Heermann, *Interactive Computer Simulation of Drivetrain Dynamics*. 1985, SAE International.

23. Yamaguchi, T. and K. Tanaka, *Transient Flow Field Analysis Around a Lockup Clutch Inside a Torque Converter*. 2012, SAE International.

24. Rivera, E.D.J., *Pressure Measurements Inside Multiple Cavities of a Torque Converter and CFD Correlation*, in *Mechanical Engineering*. 2018, Michigan Technological University.

25. CHASE, H., *PRACTICE AND THEORY IN CLUTCH DESIGN*. 1921, SAE International.

26. Dundore, M.W. and R.C. Schneider, *Clutch Energy — A Criteria of Thermal Failure*. 1968, SAE International.

27. Mohire, S., et al., *Derivation of Test Schedule for Clutch Using Road Load Data Analysis and Energy Dissipation as Basis*. 2018, SAE International.

www.manaraa.com

28. Devlin, M., et al., *Effect of Fluid Flow through Clutch Material on Torque Fluctuations in Clutches*. 2016, SAE International.

29. Iqbal, S., et al., *Experimental Characterization of Drag Torque in Open Multi-Disks Wet Clutches*. 2013, SAE International.

30. Okamoto, D., *A Study on Friction Characteristics at Low Pressure Slip Condition of Wet - Clutch*. 2014, SAE International.

31. Martin, B., et al., *62TE 6-Speed Transaxle for Chrysler Group*. 2007, SAE International.

32. Ota, H., et al., *Toyota's World First 8-Speed Automatic Transmission for Passenger Cars*. 2007, SAE International.

33. Scherer, H., M. Bek, and S. Kilian, *ZF New 8-speed Automatic Transmission 8HP70 - Basic Design and Hybridization.* SAE International Journal of Engines, 2009. **2**(1): p. 314-326.

34. Stuhldreher, M., et al., *Testing and Benchmarking a 2014 GM Silverado 6L80 Six Speed Automatic Transmission*. 2017, SAE International.

35. Watechagit, S. and K. Srinivasan, *Modeling and Simulation of a Shift Hydraulic System for a Stepped Automatic Transmission*. 2003, SAE International.

36. Zheng, Q. and K. Srinivasan, *Transmission Clutch Pressure Control System: Modeling, Controller Development and Implementation*. 2000, SAE International.

37. Robinette, D., et al., *Performance Characterization of Automatic Transmission Upshifts with Reduced Shift Times.* SAE International Journal of Engines, 2015. **8**(3): p. 1359-1373.

38. Robinette, D., *A Two Degree of Freedom, Lumped Inertia Model for Automatic Transmission Clutch-to-Clutch Shift Dynamics.* SAE International Journal of Passenger Cars - Mechanical Systems, 2014. **7**(3): p. 1163-1174.

39. Deur, J., et al., *Modeling of Wet Clutch Engagement Including a Thorough Experimental Validation*. 2005, SAE International.

40. Yin, X., et al., *Shift Quality Improvement through Integrated Control of Dual Clutches Pressure and Engine Speed for DCT*. 2014, SAE International.

41. Woodland, M., et al., *Testing Methods and Signal Processing Strateqies for Automatic Transmission Transient Multiplexed Pressure Data.* SAE International, 2019.

www.manaraa.com

42. Blough, J.R., S.M. Dumbacher, and D.L. Brown, *Time Scale Re-Sampling to Improve Transient Event Averaging*. 1997, SAE International. p. 3028-3036.

43. Mendenhall, W. and T. Sincich, *Statistics for the Engineering and Computer Sciences*. 1984: Dellen Publishing Company.

44. IR Telemetrics, I.-G.L.B., P.E., *IR Telemetrics Signal Evolution*.

45. Juvinall, R.C. and K.M. Marshek, *Fundamentals of Machine Component Design*. Vol. 3rd. John Wiley & Sons, Inc.

46. Mordorski, E., *Development of Dynamic Torsional Actuator for Torque Converter Clutch Characterization*, in *Mechanical Engineering*. 2018, Michigan Technological University.

47. *SAE No. 2 Friction Test Machine Durability Test*. 2012, SAE International.

www.manaraa.com

A Copyright Permission

A.1 Edward De Jesus Rivera Dissertation Reference Permission

Michigan Tech

Mark Woodland <mtwoodla@mtu.edu>

Copyright Agreement
2 messages

Mark Woodland <mtwoodla@mtu.edu> Fri, Mar 22, 2019 at 6:20 PM
To: Edward De Jesus Rivera <edejesus@mtu.edu>

Hey Edward,

I would like to use some of your figures from your dissertation describing the telemetry hardware used in our setup. Can I get your permission to use just the figures? All new text will accompany the figures.

Thanks,

--
Mark Woodland
Michigan Tech University
Mechanical Engineering Graduate
MEEM 401B
208-961-1538

Edward De Jesus Rivera <edejesus@mtu.edu> Sun, Mar 24, 2019 at 10:42 AM
To: Mark Woodland <mtwoodla@mtu.edu>

Mark,

Please go ahead and re-use any figure you may need.

Thanks,

Edward De Jesús Rivera
01000101 01100100 01110111 01100001 01110010 01100100

[Quoted text hidden]

www.manaraa.com

A.2 SAE Copyright agreement for Transient Testing in Methods Section

("Work"). If the Work is a work-made-for-hire pursuant to 17 USC Â§ 101 of the Copyright Act, then such undersigned entity (e.g., employer) shall be deemed the Author for purposes of this Assignment.

Assignor represents, warrants and guarantees, either individually or on behalf of all co-authors, that (1) the Work is an original unpublished work; (2) Assignor is the sole and exclusive owner and claimant of all right, title and interest in and to the Work, including all copyrights therein unless otherwise documented through a permissions release, and neither the Work nor copyrights have been assigned, transferred or otherwise encumbered; (3) the Work contains no material whose publication would violate any copyright or other personal or proprietary right of any person or entity; (4) the Work is not a work made for the United States Government; and (5) Assignor has the authority to transfer the rights to Assignee and cause this Agreement to be executed as of the date first written above.

Assignor further represents, warrants and guarantees, to the best of Assignor's knowledge and ability, that the Work is NOT controlled for export from the United States to any non-U.S. person or any other nation under the International Traffic in Arms Regulations (22 CFR Parts 120-130) or the Export Administration Regulations (15 CFR Parts 730-774) and, accordingly, may be modified, used, copied, distributed or circulated by SAE, in whole or in part, without any export licenses under the foregoing regulations.

Assignor hereby assigns to SAE all rights, titles and interest in and to Assignor's copyright in the Work in the exclusive rights: (1) to reproduce the Work in all media now known or hereinafter devised; (2) to distribute copies of the Work in all media now known or hereinafter devised; and (3) to prepare derivative works based upon the Work including, for example, but not limited to, the right with respect to all or part of the Work to edit, annotate, comment, format/reformat and abstract the Work or incorporate it into a compilation, collection or other work. No other exclusive rights in the Work are hereby assigned.

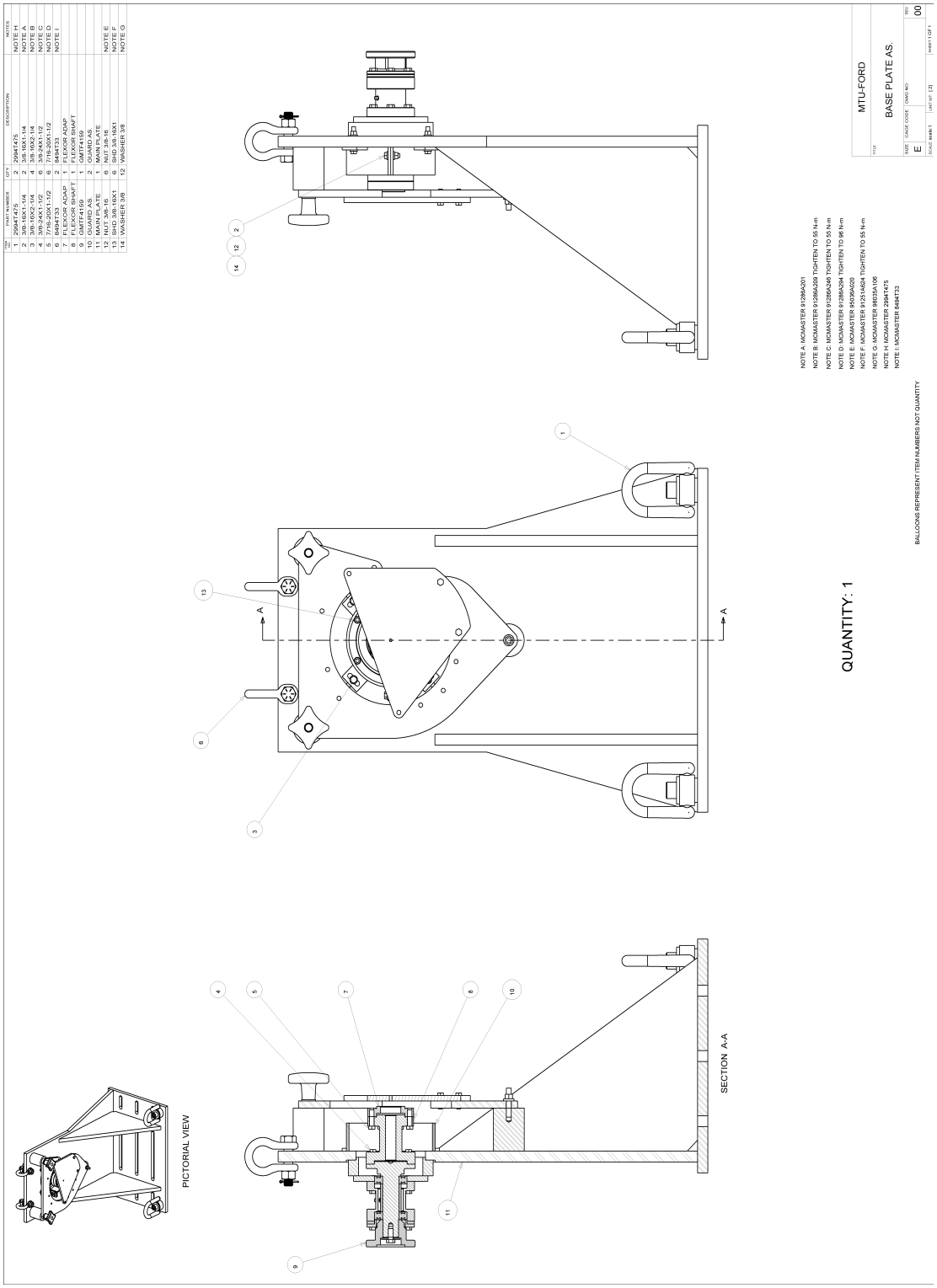
Assignor agrees that it shall not dispute, contest, or aid or assist others in disputing or contesting, either directly or indirectly, SAE's exclusive right, title and interest in the Work and in any and all compilations, collective works and derivative works based on the Work, including copyrights therein or other proprietary rights therein claimed by SAE.

Assignor agrees that, for no additional compensation, Assignor will execute any and all documents that may be necessary to assist SAE to register, perfect and enforce SAE's rights in and to the Work and any and all compilations, collective works and derivative works based on the Work.

SAE hereby grants Assignor the nonexclusive right to reproduce and publicly distribute the Work in print/film format for one (1) year and in electronic/optical media for five (5) years following a six (6) month embargo after first publication, either in print or digitally, by SAE. Any such reproduction or distribution of the Work shall include the SAE copyright notice thereon and shall not be offered for sale or used to imply endorsement by SAE of a service or product. The Assignor may also post an electronic version of the accepted Work to an institutional repository, but not the final typeset Work. Nothing herein shall prohibit Assignor's reproduction and noncommercial distribution of the Work for its own use.

www.manaraa.com

B Main Test Stand Drawing



www.manaraa.com

C Channel Calibration List

Channel Number	Channel Name	DAQ Name	Sensitivity	Units	Offset
3	Tachometer- Input Dyno	DC_Tach	1.001	mV/RPM	35.836
4	Tachometer- Output Dyno	AC_Tach	-1.033	mV/RPM	41.423
5	Torque- Input Dyno	DC_Torque	-4.936	mV/Nm	-12.316
6	Torque- Output Dyno	AC_Torque	1.2147	mV/Nm	-0.2309
7	Tachometer- Turbine Speed Sensor	TSS_Tach	36 pusles per revolution		
8	Tachometer- Output Speed Sensor	OSS_Tach	24 pusles per revolution		
9	Pressure- Transmission Inlet	Trans_IN_Pressure	33.3163	mV/PSI	0
10	Pressure- Transmission Outlet	Trans_OUT_Pressure	33.3.3156	mV/PSI	0
11	Pressure- Line	LINE_Pressure	33.317	mV/PSI	0
12	Pressure- Variable Bleed Solenoid TCC	VBS_TCC_Pressure	33.27	mV/PSI	0
13	CB26 Pressure	CB26_Pressure	33.33	mV/PSI	0
14	Pressure- Solenoid Feed	SOL_FEED_Pressure	33.335	mV/PSI	0
15	Pressure- CB 1234	CB1234_Pressure	36.116	mV/PSI	0
16	Pressure- CBLR	CBLR_Pressure	33.587	mV/PSI	0
17	Pressure- TCC Apply	TCC_APPLY_Pressure	31.97	mV/PSI	0
18	Pressure- TCC Release	TCC_REL_Pressure	32.299	mV/PSI	0
19	Solenoid Driver- SSA	SD1_SSA	1000	mV/V	0
20	Solenoid Driver- SSB	SD2_SSB	1000	mV/V	0
21	Solenoid Driver- SSC	SD3_SSC	1000	mV/V	0
22	Solenoid Driver- SSD	SD4_SSD	1000	mV/V	0
23	Solenoid Driver- Line	SD5_Line	1000	mV/V	0
24	Solenoid Driver- TCC	SD6_TCC	1000	mV/V	0
25	Solenoid Driver- SSE	SD7_SSE	1000	mV/V	0
26	Flow Meter	Flow_Meter	1000	mV/V	0

www.manaraa.com

27	Tachometer-Output Dyno Extra tach for transient events	AC_Tach2	60 pulses per revolution		
28	Dyno Trigger	Dyno _Trigger	1000	mV/V	0
29	TOM Trigger	Arduino_Trigger	1000	mV/V	0
31	C35R Pressure	C35R_Pressure	33.33	mV/PSI	0
32	C456 Pressure	C456_Pressure	33.33	mV/PSI	0
33	One Pulse Per Revolution Tachometer- Input Dyno (DC)	DC_One_Tach	1 pulse per revolution		
34	One Pulse Per Revolution Tachometer-Output Dyno (AC)	AC_One_Tach	1 pulse per revolution		

www.manaraa.com

D Siemens Test Lab Guide

DISCLAIMER: Test Lab has numerous functionalities and a variety of ways to achieve the same task. This guide is only to describe the methods that were used to acquire data for this research. A previous understanding about digital signal processing is required to set all parameters properly as this guide does not cover every setting in detail. It is very likely that there is additional functionality built into Test Lab that was missed and not used.

1. Turn on Scadas III DAQ and open Signature Acquisition on main desktop. The DAQ may take a few moments to initialize before the software will connect.
2. A new project is started when Signature Acquisition opens.

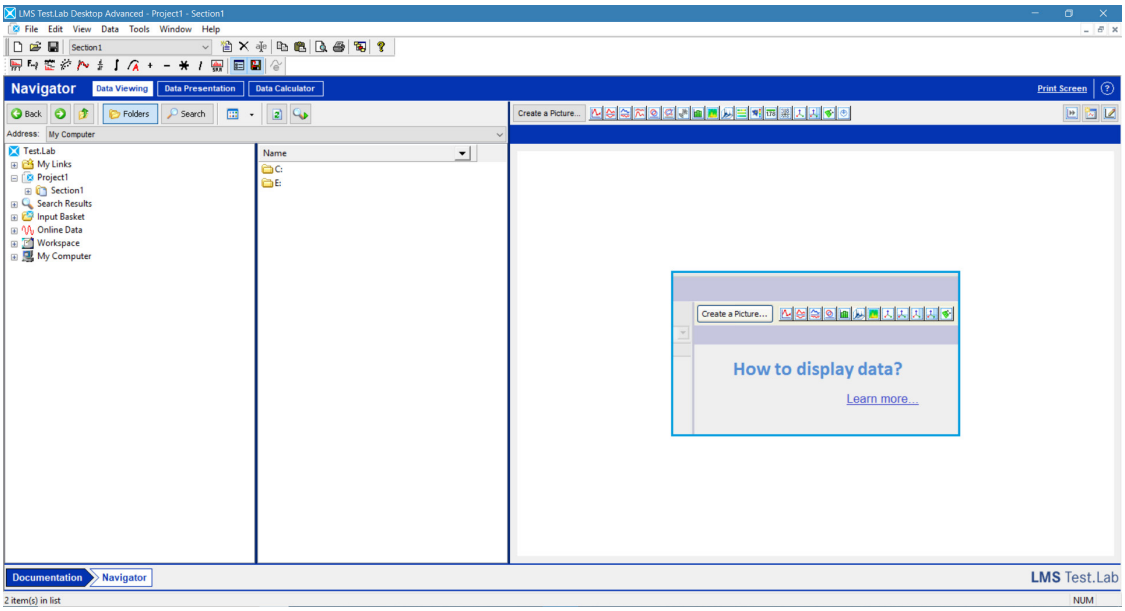


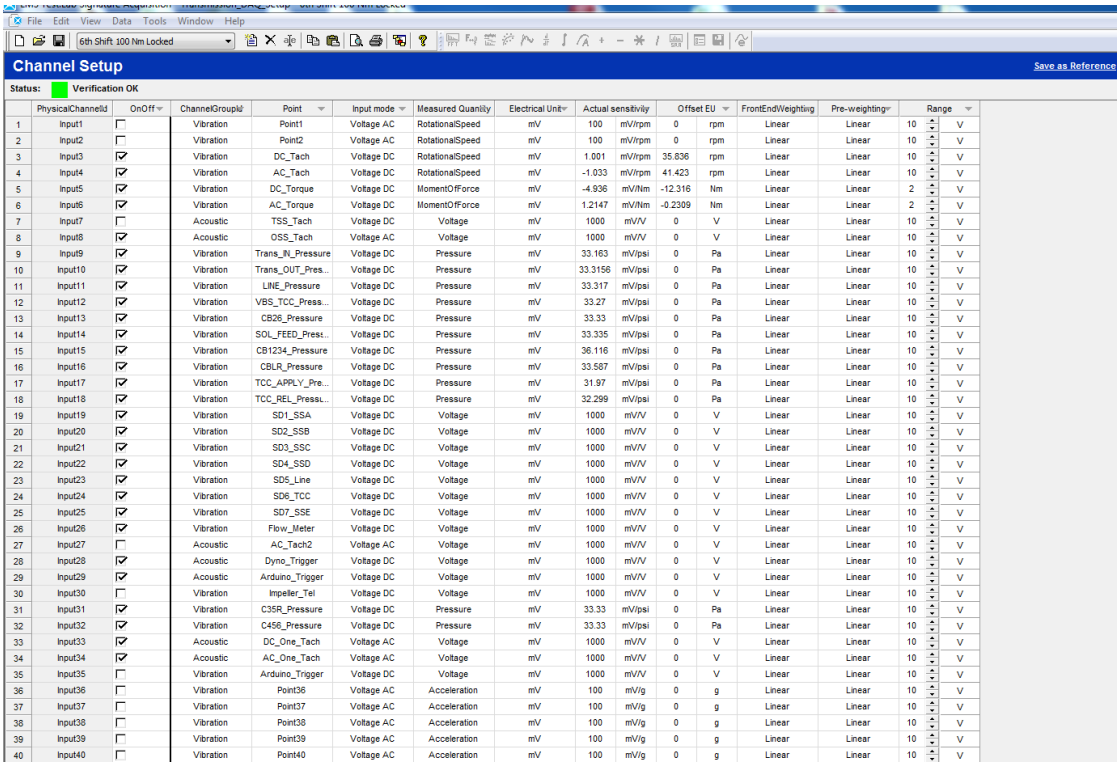
Figure D-1. Navigation pane for Test Lab

3. Open *Transmission DAQ Setup* saved in the *Testing* folder. At the bottom of the page there is a tab selector that switches between windows

www.manaraa.com

Figure D-2. Navigation bar to select Test Lab window

4. To setup new or edit existing channels select Channel Setup
5. In the channel setup the channels can be toggled on/off, names assigned, coupling type (AC, DC, ICP) selected, calibration values set, units applied and voltage operation range of the signal.



	PhysicalChannelId	OnOff	ChannelGroupId	Point	Input mode	Measured Quantity	Electrical Unit	Actual sensitivity		Offset EU		FrontEndWeighting	Pre-weighting	Range	
1	Input1	☐	Vibration	Point1	Voltage AC	RotationalSpeed	mV	100	mV/rpm	0	rpm	Linear	Linear	10	V
2	Input2	☐	Vibration	Point2	Voltage AC	RotationalSpeed	mV	100	mV/rpm	0	rpm	Linear	Linear	10	V
3	Input3	☑	Vibration	DC_Tach	Voltage DC	RotationalSpeed	mV	1.001	mV/rpm	35.836	rpm	Linear	Linear	10	V
4	Input4	☑	Vibration	AC_Tach	Voltage DC	RotationalSpeed	mV	-1.033	mV/rpm	41.423	rpm	Linear	Linear	10	V
5	Input5	☑	Vibration	DC_Torque	Voltage DC	MomentOfForce	mV	-4.936	mV/Nm	-12.316	Nm	Linear	Linear	2	V
6	Input6	☑	Vibration	AC_Torque	Voltage DC	MomentOfForce	mV	1.2147	mV/Nm	-0.2309	Nm	Linear	Linear	2	V
7	Input7	☐	Acoustic	TSS_Tach	Voltage DC	Voltage	mV	1000	mV/V	0	V	Linear	Linear	10	V
8	Input8	☑	Acoustic	OSS_Tach	Voltage AC	Voltage	mV	1000	mV/V	0	V	Linear	Linear	10	V
9	Input9	☑	Vibration	Trans_IN_Pressure	Voltage DC	Pressure	mV	33.163	mV/psi	0	Pa	Linear	Linear	10	V
10	Input10	☑	Vibration	Trans_OUT_Pres...	Voltage DC	Pressure	mV	33.3156	mV/psi	0	Pa	Linear	Linear	10	V
11	Input11	☑	Vibration	LINE_Pressure	Voltage DC	Pressure	mV	33.317	mV/psi	0	Pa	Linear	Linear	10	V
12	Input12	☑	Vibration	VBS_TCC_Press...	Voltage DC	Pressure	mV	33.27	mV/psi	0	Pa	Linear	Linear	10	V
13	Input13	☑	Vibration	CB26_Pressure	Voltage DC	Pressure	mV	33.33	mV/psi	0	Pa	Linear	Linear	10	V
14	Input14	☑	Vibration	SOL_FEED_Press...	Voltage DC	Pressure	mV	33.335	mV/psi	0	Pa	Linear	Linear	10	V
15	Input15	☑	Vibration	CB1234_Pressure	Voltage DC	Pressure	mV	36.116	mV/psi	0	Pa	Linear	Linear	10	V
16	Input16	☑	Vibration	CBLR_Pressure	Voltage DC	Pressure	mV	33.587	mV/psi	0	Pa	Linear	Linear	10	V
17	Input17	☑	Vibration	TCC_APPLY_Pre...	Voltage DC	Pressure	mV	31.97	mV/psi	0	Pa	Linear	Linear	10	V
18	Input18	☑	Vibration	TCC_REL_Pressu...	Voltage DC	Pressure	mV	32.299	mV/psi	0	Pa	Linear	Linear	10	V
19	Input19	☑	Vibration	SD1_SSA	Voltage DC	Voltage	mV	1000	mV/V	0	V	Linear	Linear	10	V
20	Input20	☑	Vibration	SD2_SSB	Voltage DC	Voltage	mV	1000	mV/V	0	V	Linear	Linear	10	V
21	Input21	☑	Vibration	SD3_SSC	Voltage DC	Voltage	mV	1000	mV/V	0	V	Linear	Linear	10	V
22	Input22	☑	Vibration	SD4_SSD	Voltage DC	Voltage	mV	1000	mV/V	0	V	Linear	Linear	10	V
23	Input23	☑	Vibration	SD5_Line	Voltage DC	Voltage	mV	1000	mV/V	0	V	Linear	Linear	10	V
24	Input24	☑	Vibration	SD6_TCC	Voltage DC	Voltage	mV	1000	mV/V	0	V	Linear	Linear	10	V
25	Input25	☑	Vibration	SD7_SSE	Voltage DC	Voltage	mV	1000	mV/V	0	V	Linear	Linear	10	V
26	Input26	☑	Vibration	Flow_Meter	Voltage DC	Voltage	mV	1000	mV/V	0	V	Linear	Linear	10	V
27	Input27	☐	Acoustic	AC_Tach2	Voltage AC	Voltage	mV	1000	mV/V	0	V	Linear	Linear	10	V
28	Input28	☑	Acoustic	Dyno_Trigger	Voltage DC	Voltage	mV	1000	mV/V	0	V	Linear	Linear	10	V
29	Input29	☑	Acoustic	Arduino_Trigger	Voltage DC	Voltage	mV	1000	mV/V	0	V	Linear	Linear	10	V
30	Input30	☐	Vibration	Impeller_Tel	Voltage DC	Voltage	mV	1000	mV/V	0	V	Linear	Linear	10	V
31	Input31	☑	Vibration	C35R_Pressure	Voltage DC	Pressure	mV	33.33	mV/psi	0	Pa	Linear	Linear	10	V
32	Input32	☑	Vibration	C456_Pressure	Voltage DC	Pressure	mV	33.33	mV/psi	0	Pa	Linear	Linear	10	V
33	Input33	☑	Acoustic	DC_One_Tach	Voltage AC	Voltage	mV	1000	mV/V	0	V	Linear	Linear	10	V
34	Input34	☑	Acoustic	AC_One_Tach	Voltage AC	Voltage	mV	1000	mV/V	0	V	Linear	Linear	10	V
35	Input35	☐	Vibration	Arduino_Trigger	Voltage DC	Voltage	mV	1000	mV/V	0	V	Linear	Linear	10	V
36	Input36	☐	Vibration	Point36	Voltage AC	Acceleration	mV	100	mV/g	0	g	Linear	Linear	10	V
37	Input37	☐	Vibration	Point37	Voltage AC	Acceleration	mV	100	mV/g	0	g	Linear	Linear	10	V
38	Input38	☐	Vibration	Point38	Voltage AC	Acceleration	mV	100	mV/g	0	g	Linear	Linear	10	V
39	Input39	☐	Vibration	Point39	Voltage AC	Acceleration	mV	100	mV/g	0	g	Linear	Linear	10	V
40	Input40	☐	Vibration	Point40	Voltage AC	Acceleration	mV	100	mV/g	0	g	Linear	Linear	10	V

Figure D-3. Channel setup window

6. The calibration type is used if sensors are being calibrated live with Test Lab or, if the calibration values are known, the values can just be set in channel setup.
7. Under *Tracking Setup*, tachometer channels can be setup, such as turbine and output speed. The parameters are assigned using the controls on the

المنارة للاستشارات
www.manaraa.com

right. For each tach channel the number of pulses per revolution must to get an RPM value.

8. The desired time length for recording data is set under *Duration*. To have recording set for trigger activation select *Use Triggered Start*. The recording can also end by a second trigger instead of a time limit by activating *Use Triggered Stop*.

Figure D-4. Tracking setup window with turbine and output speed windows showing

9. Under Acquisition Setup window the sampling rate can be set for each channel type (Vibration, Acoustic, or Other). The current setup has the vibration and acoustic channels set to 6400 and 51200 Hz respectively. Acoustic channels include tachometer channels that are not measured using the tach card.

www.manaraa.com

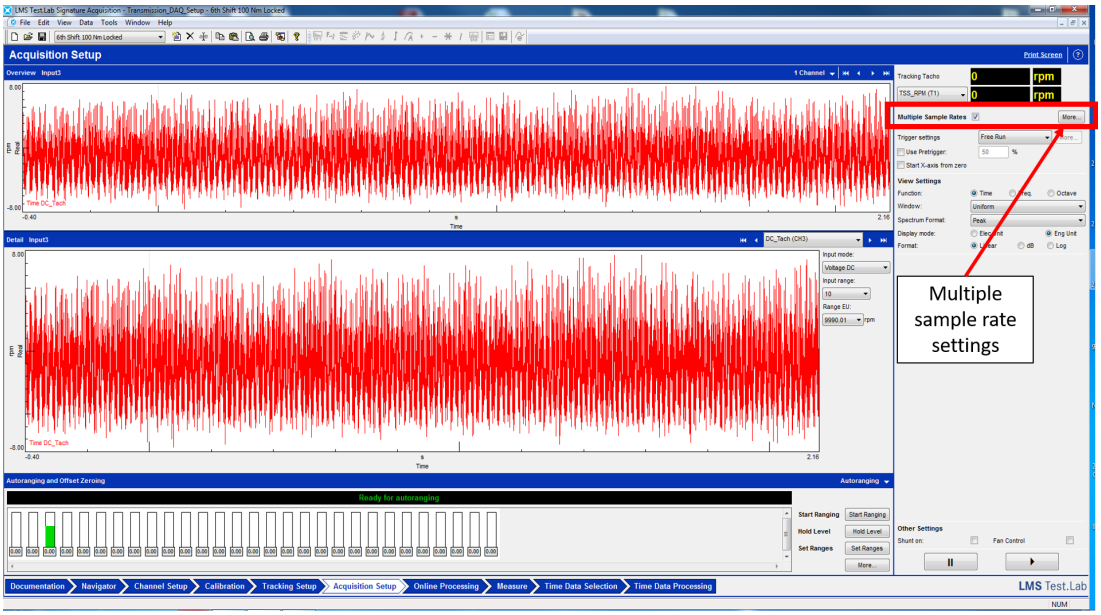


Figure D-5. Acquisition setup window pointing out sampling parameter settings

10. The Measure window is the most used when testing. This is where data is monitored and acquired. Once arming the DAQ the data will begin to stream across the plots. No data is recorded until commanded. Labeling in the green blocks describes what the system is currently doing and provides warnings.

www.manaraa.com

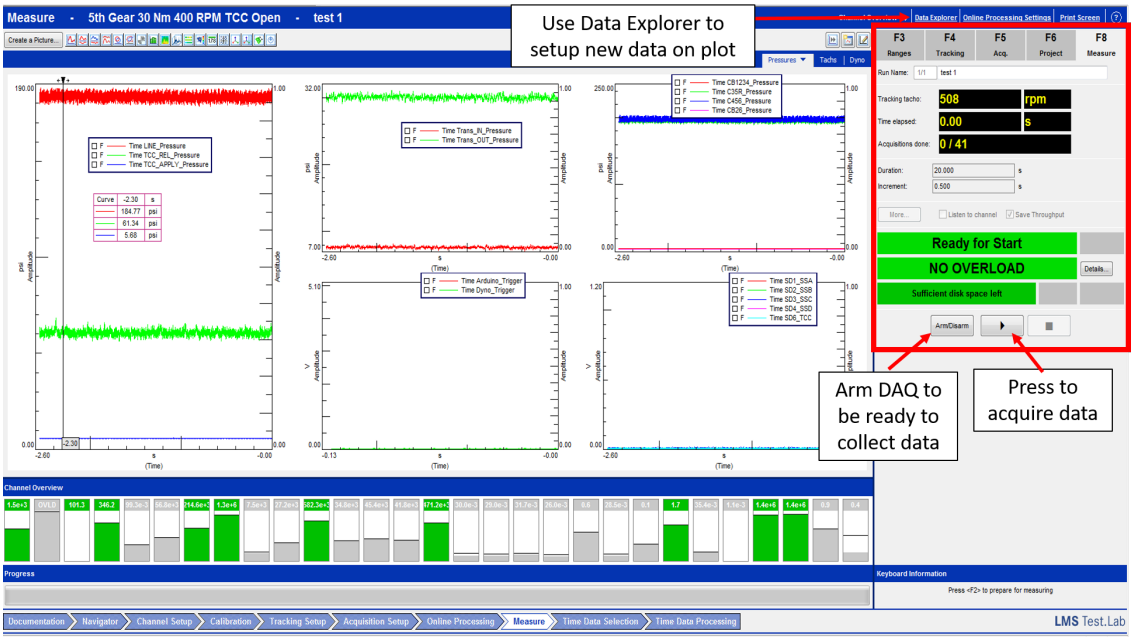


Figure D-6. Measurement window with pressure plot tab open

11. There are 3 tabs with different plots of data. First is pressure, second tachometers, and third dyno data. Additional or new channels can be added through *Data Explorer*.
12. Once data has been collected it can be analyzed in Test Lab or exported to Matlab. In the navigator window, select the Throughput from the test run and right click to export to Matlab. Figure D-7 shows the export process. Currently, each test run has to be exported individually, but a better method of exporting may be a worthwhile exploration.

www.manaraa.com

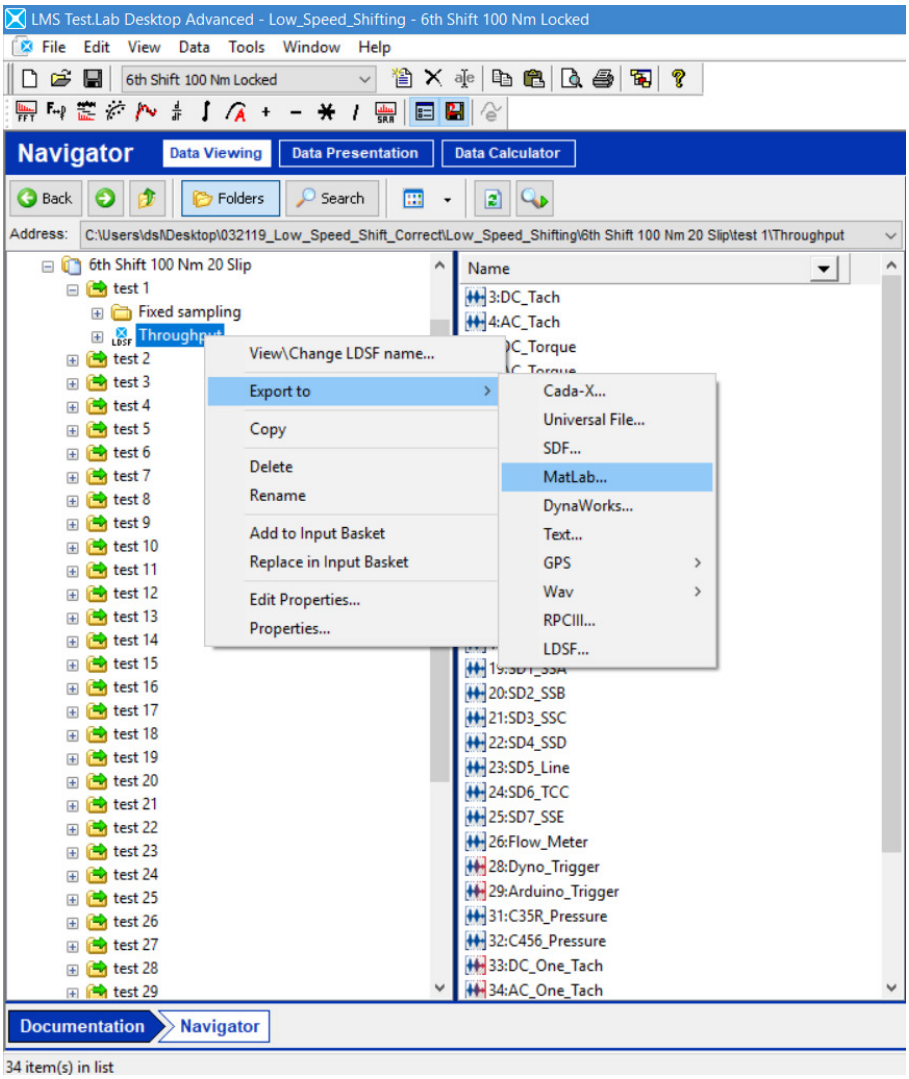
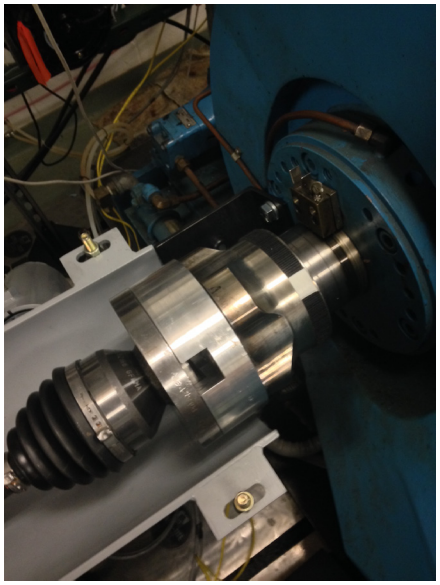


Figure D-7. Exporting data to Matlab in Navigator window

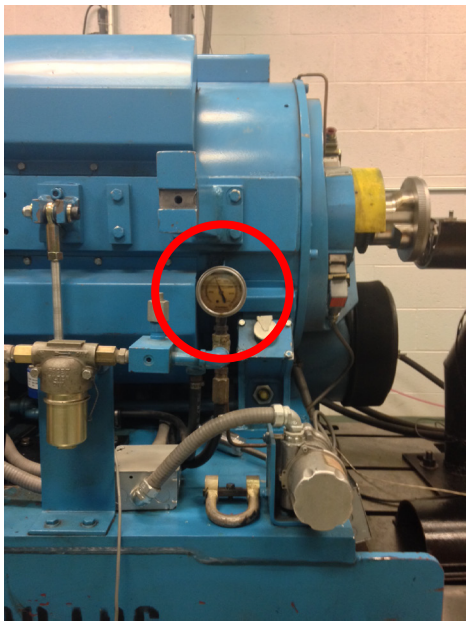
www.manaraa.com

E Test Cell Startup and Operation Procedure

1. Connect transmission output shaft to absorbing dyno and bolt shaft guard.

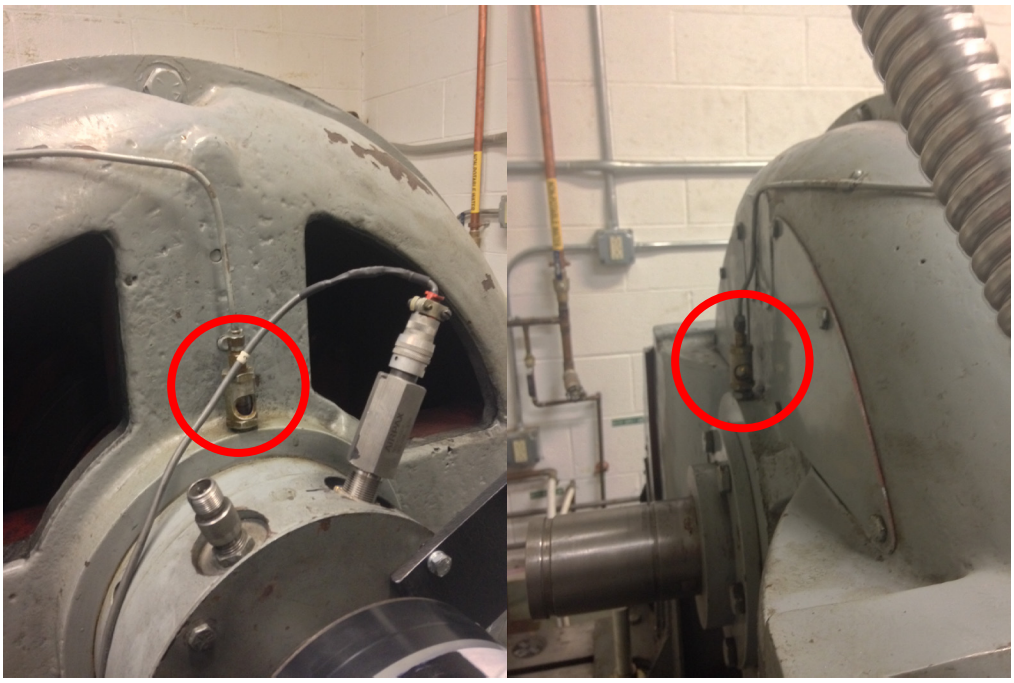


2. Turn on dyno power cabinets on upstairs.
3. Check oil pressure gauge on blue AC Dyno that journal bearings are pressurized.



www.manaraa.com

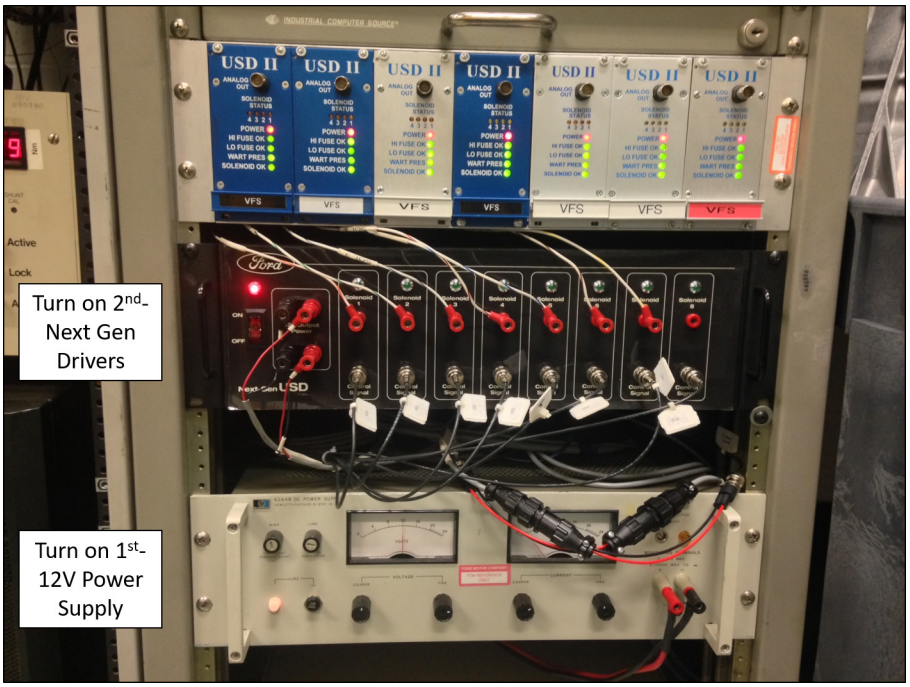
4. Check oil pressure through looking glasses on each end of tan DC Dyno. Small drops of oil should be dripping if oil pressure is on.



5. Set AC dyno direction to FORWARD on control tower.

www.manaraa.com

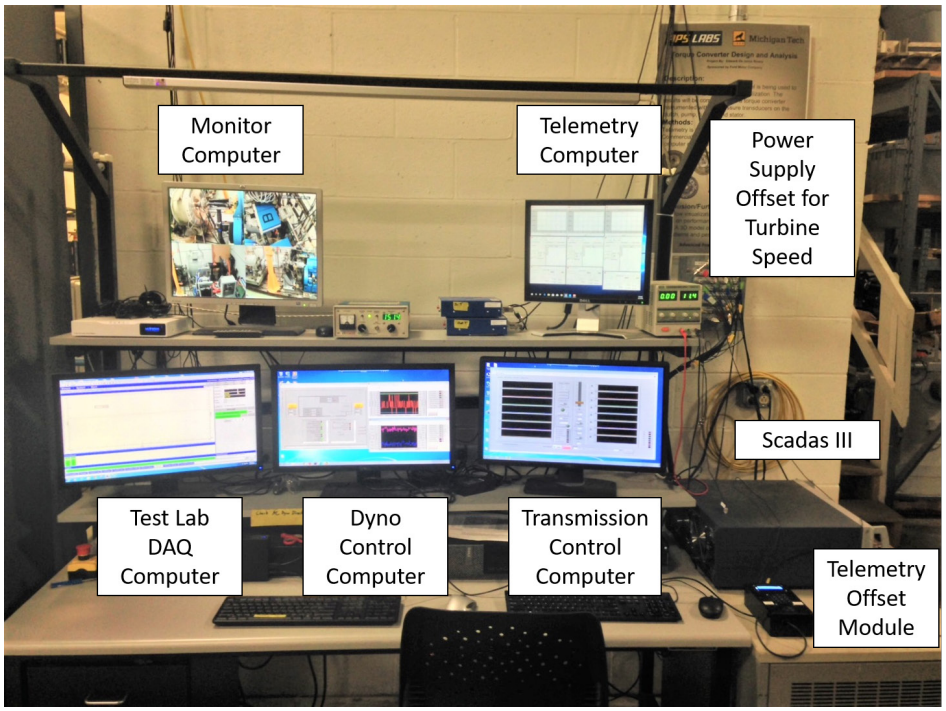
6. Turn power supply ON, then transmission controller on transmission control tower.



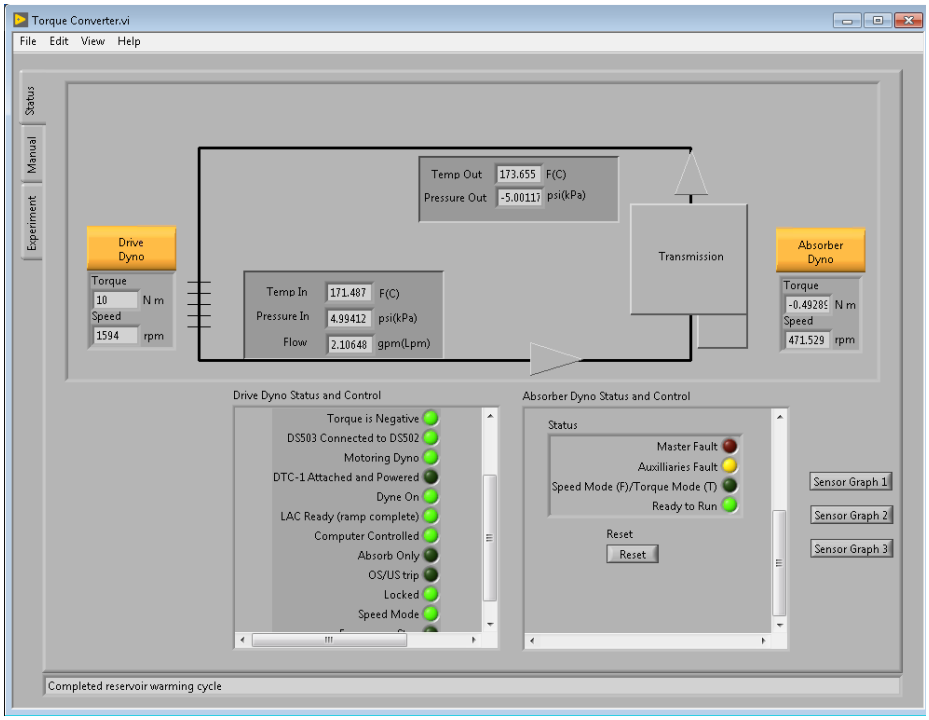
7. Turn instrumentation ON sitting on shelf

www.manaraa.com

8. Remote desktop in to dyno control tower computer on middle computer.

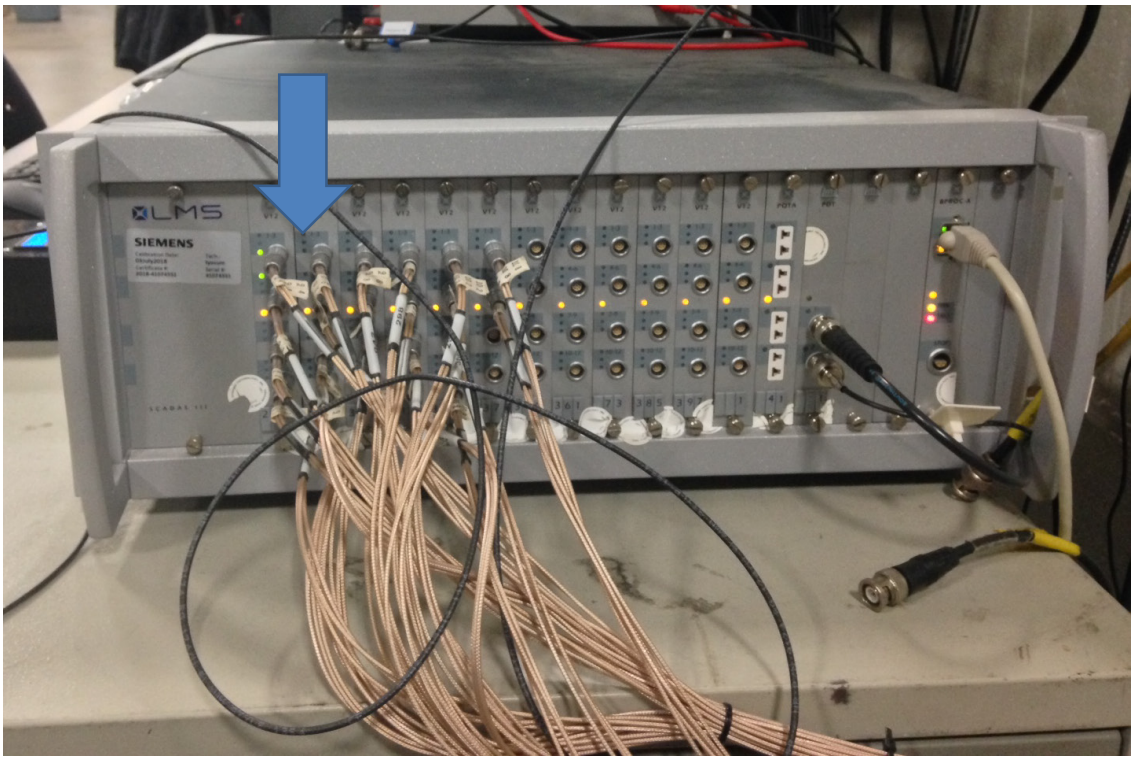


9. Open Transmission LabVIEW VI.



www.manaraa.com

10. Turn top computer monitor ON for test cell cameras.
11. Turn power supply and Scadas III frontend system ON.
12. Open Signature Acquisition Test Lab on left computer.
13. Once channels are checked ON in Test Lab, verify channels are ready by looking for green lights on Scadas frontend.



14. On far right computer remote desktop into Transmission Control tower computer and open Transmission Controller LabVIEW VI.
15. Transmission is ready to operate. Use manual or experiment mode to run.

www.manaraa.com

F USDB II Operation Guide

1. Connect the USD II rack mount to the transmission and turn on the power supply

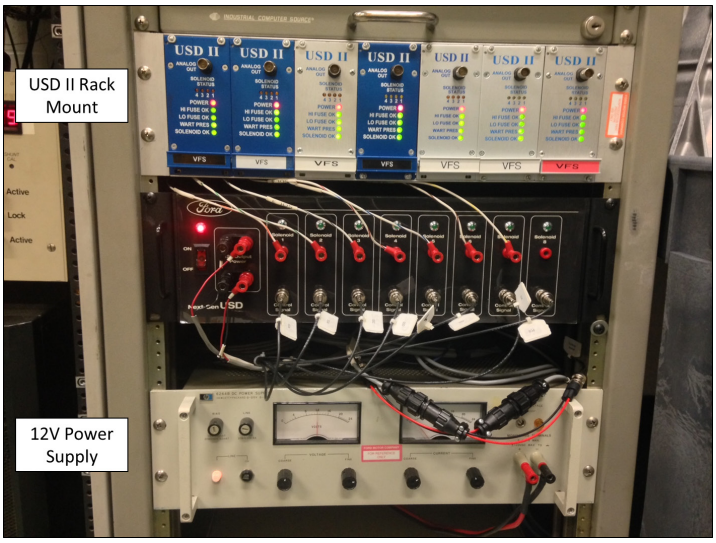


Figure F-1. Solenoid driver and power supply mounted in transmission control tower

2. Open Univ9600 on the remote desktop to the transmission control tower
3. The USD II will open a window with a control box for each solenoid on the left and command buttons on the right.

www.manaraa.com

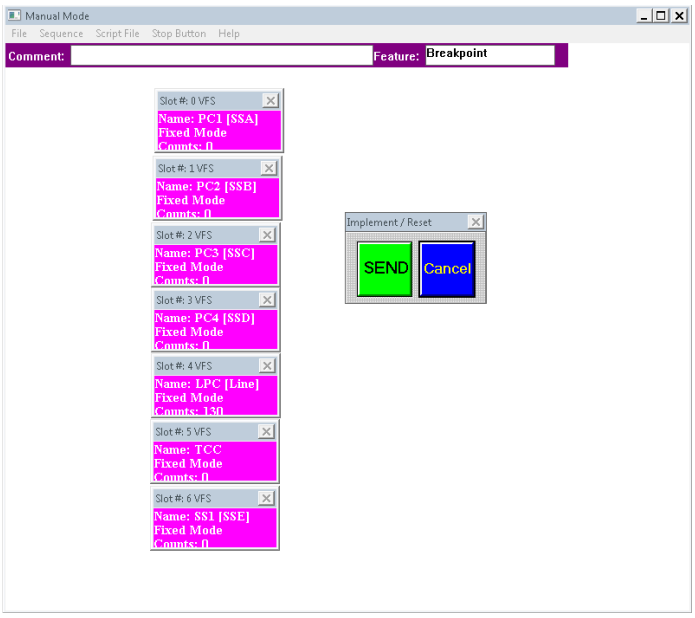


Figure F-2. Control window for USD II software

4. Set the pressure level by using SET DUTY CYCLE. Count range is 0 to 255 for off to max pressure, depending on if normally low or high solenoid.

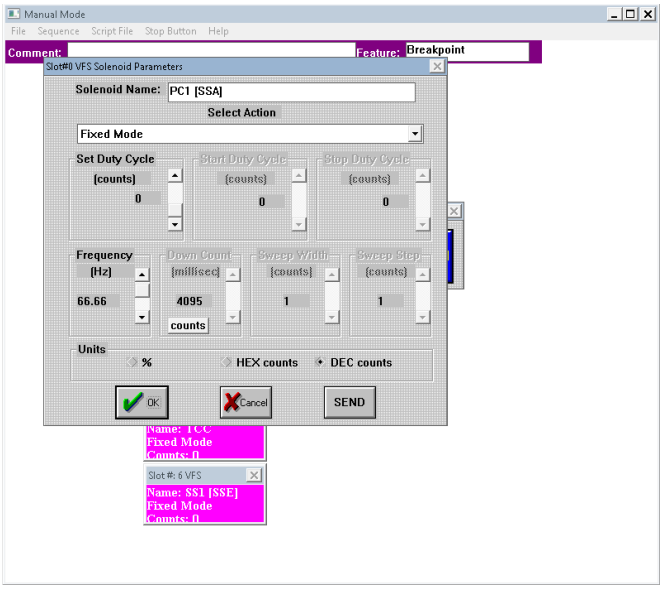


Figure F-3. Solenoid command window for each solenoid

www.manaraa.com

5. The default action for each of the drivers is FIXED MODE. Multiple modes can be selected from the list of built in operations. Each mode has a variety of commands that need to be filled in.

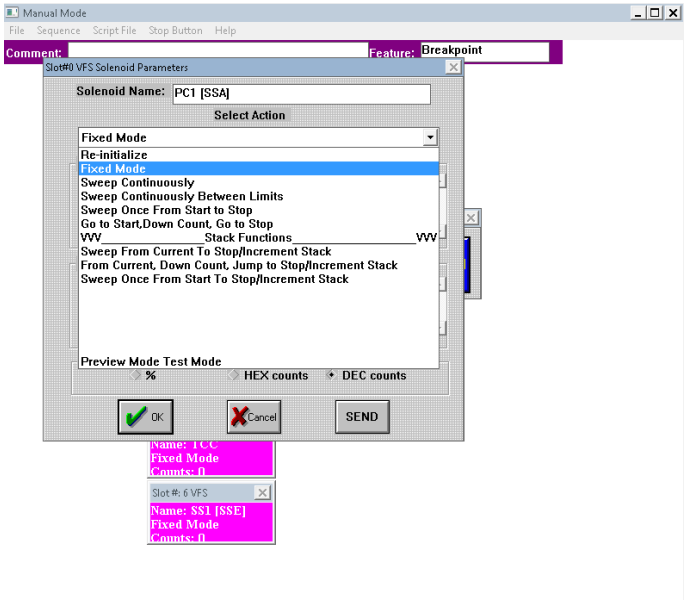


Figure F-4. Possible built in operations

6. The window will light up to indicate that commands are on standby to be sent to the transmission. Multiple commands can be stacked to be sent all at one time.

www.manaraa.com

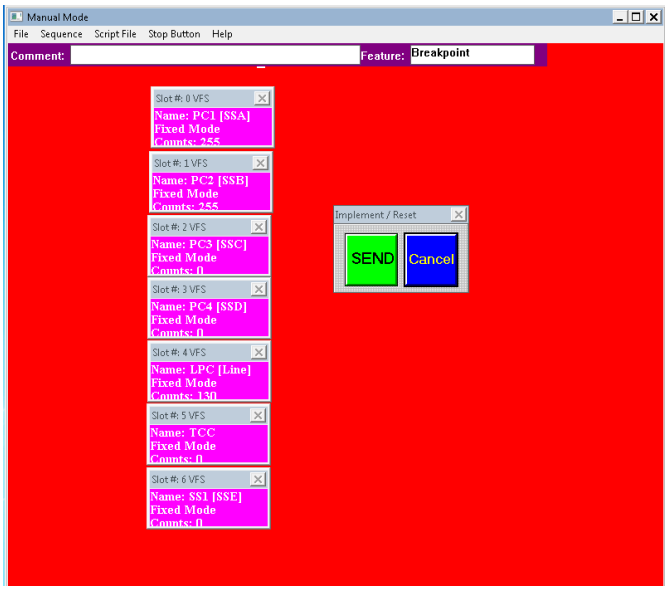


Figure F-5. Control window light up indicating commands are ready to send to transmission

7. Use the sequencer to write scripts to run multiple commands in a string. The sequence can be saved to be used later.

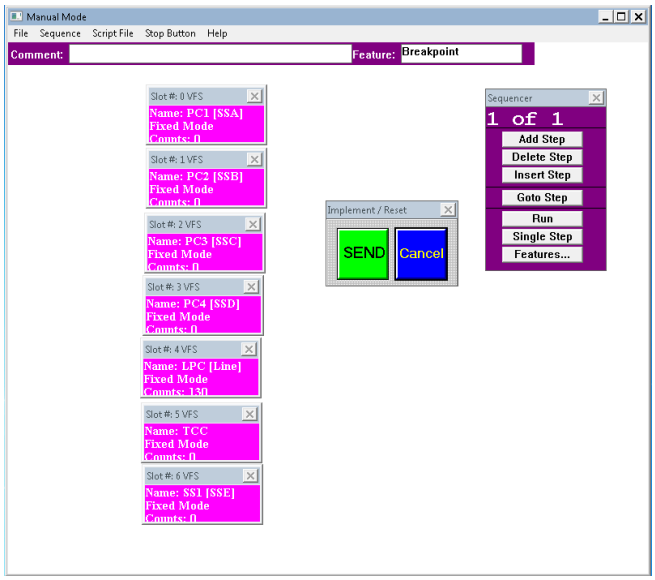
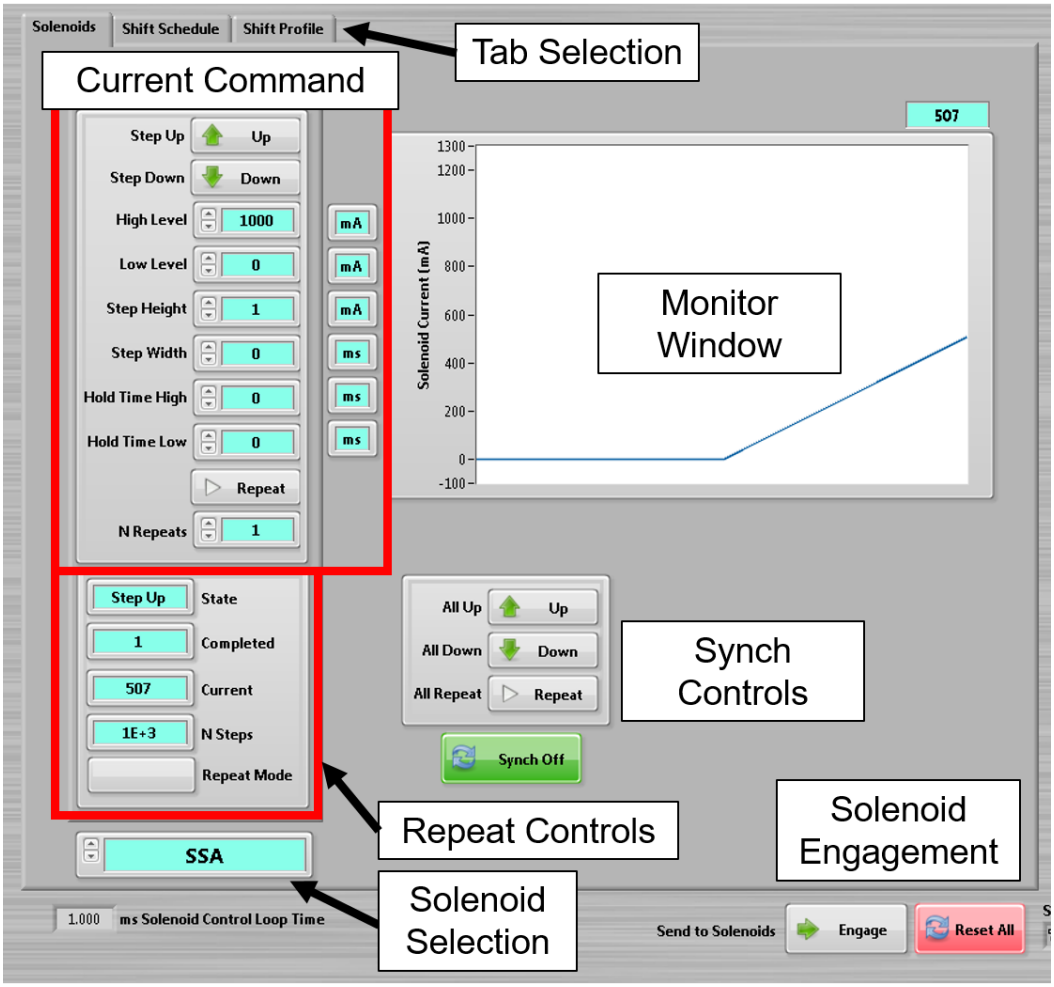


Figure F-6. Sequencer window to create a string of commands to run in a sequence.

www.manaraa.com

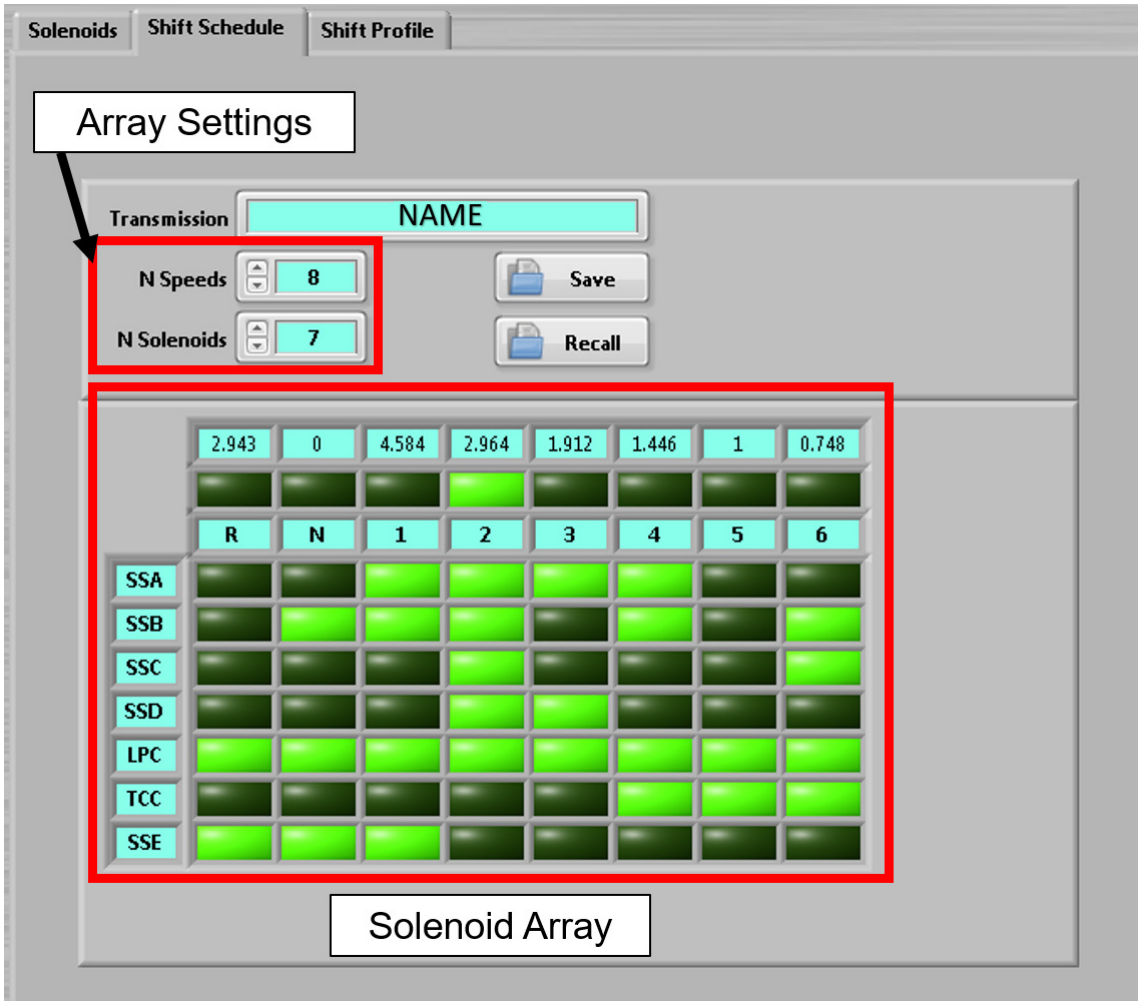
G SOL Commander Guide

There are three tabs in SOL Commander. Each that have unique controls that are used dependent on the necessary operation. The first control window is SOLENOIDS, which has similar capabilities as those of the USDB. Here each solenoid can be controlled individually and set to a specified current. A high and low limit can be set to have the solenoid sweep between the two values. All the solenoids can be synched together to have them sweep together. The sweep can be repeated by specifying the number of times to repeat the maneuver. The monitor window only shows the currently selected solenoid command. None of the commands are sent to the transmission until the ENGAGE button is activated. These controls are good for fixed gear testing.



www.manaraa.com

The second control window is SHIFT SCHEDULE. These controls specify which solenoid will be active for each gear state. First the number of speeds and solenoids are set for the application. Each solenoid is activated by turning the indicator ON/OFF for the respective gear. Labels can be added to identify the solenoids and gears for ease of array selection. Once a shift schedule is made it can be saved and reused for later testing.



www.manaraa.com

The final control window is called SHIFT PROFILE. This window is where shift profiles can be sent to the transmission and complete a shift during operation without damaging the transmission. The profiles are placed in a text file with the values and time steps for each of the solenoids, as shown in the table below. The table of values can be loaded by using the LOAD NEW PROFILE and a profile can be set for each gear by using the shift lever (described in detail in later section). Only one profile can be loaded for each gear so only an upshift or downshift can be accomplished for that gear. (Additional development should be done so both upshift and downshift profiles can be loaded simultaneously). When profiles have been loaded for each gear they can be saved as a group and reloaded for reuse. The profiles will be loaded back to their respective gears as when they were saved. The profiles can be seen in the profile viewer and will show the profiles associated with selected gear state.

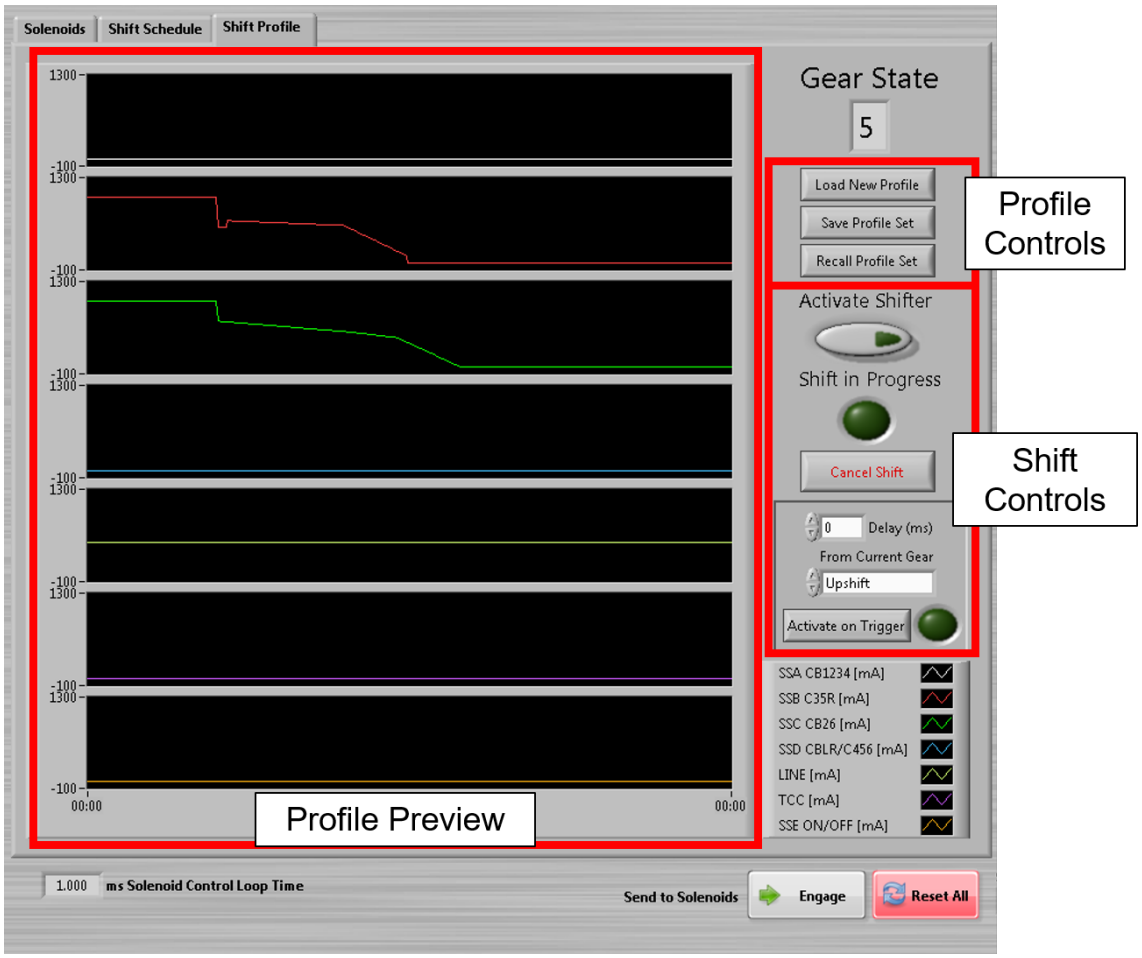
Time [sec]	SSA CB1234 [mA]	SSB C35R [mA]	SSC CB26 [mA]	SSD CBLR/C456 [mA]	LINE [mA]	TCC [mA]	SSE ON/OFF [mA]
0.00	0.00	1000.00	1000.00	0.00	500.00	0.00	0.00
0.01	0.00	1000.00	1000.00	0.00	500.00	0.00	0.00
0.02	0.00	1000.00	1000.00	0.00	500.00	0.00	0.00
0.03	0.00	1000.00	1000.00	0.00	500.00	0.00	0.00
0.04	0.00	539.00	698.40	0.00	500.00	0.00	0.00
0.05	0.00	539.00	696.80	0.00	500.00	0.00	0.00
0.06	0.00	539.00	695.20	0.00	500.00	0.00	0.00
0.07	0.00	539.00	693.60	0.00	500.00	0.00	0.00
0.08	0.00	539.00	692.00	0.00	500.00	0.00	0.00
0.09	0.00	539.00	690.40	0.00	500.00	0.00	0.00
0.10	0.00	539.00	688.80	0.00	500.00	0.00	0.00
0.11	0.00	539.00	687.20	0.00	500.00	0.00	0.00
0.12	0.00	645.84	685.60	0.00	500.00	0.00	0.00
0.13	0.00	645.04	684.00	0.00	500.00	0.00	0.00

To send the profile command to the solenoids both the ENGAGE and ACTIVATE SHIFTER must be pressed. The ENGAGE button sends the command to the solenoids while ACTIVATE SHIFTER enables the shift lever to run the profile when the shift lever changes. A shift can be done manually, using the shift lever, or by having a trigger activation. To have the shift activate on a trigger, select to have an UP or DOWNSHIFT from the current gear occur when the trigger is seen. When the settings are satisfactory press ACTIVATE TRIGGER, which will gray out and

www.manaraa.com

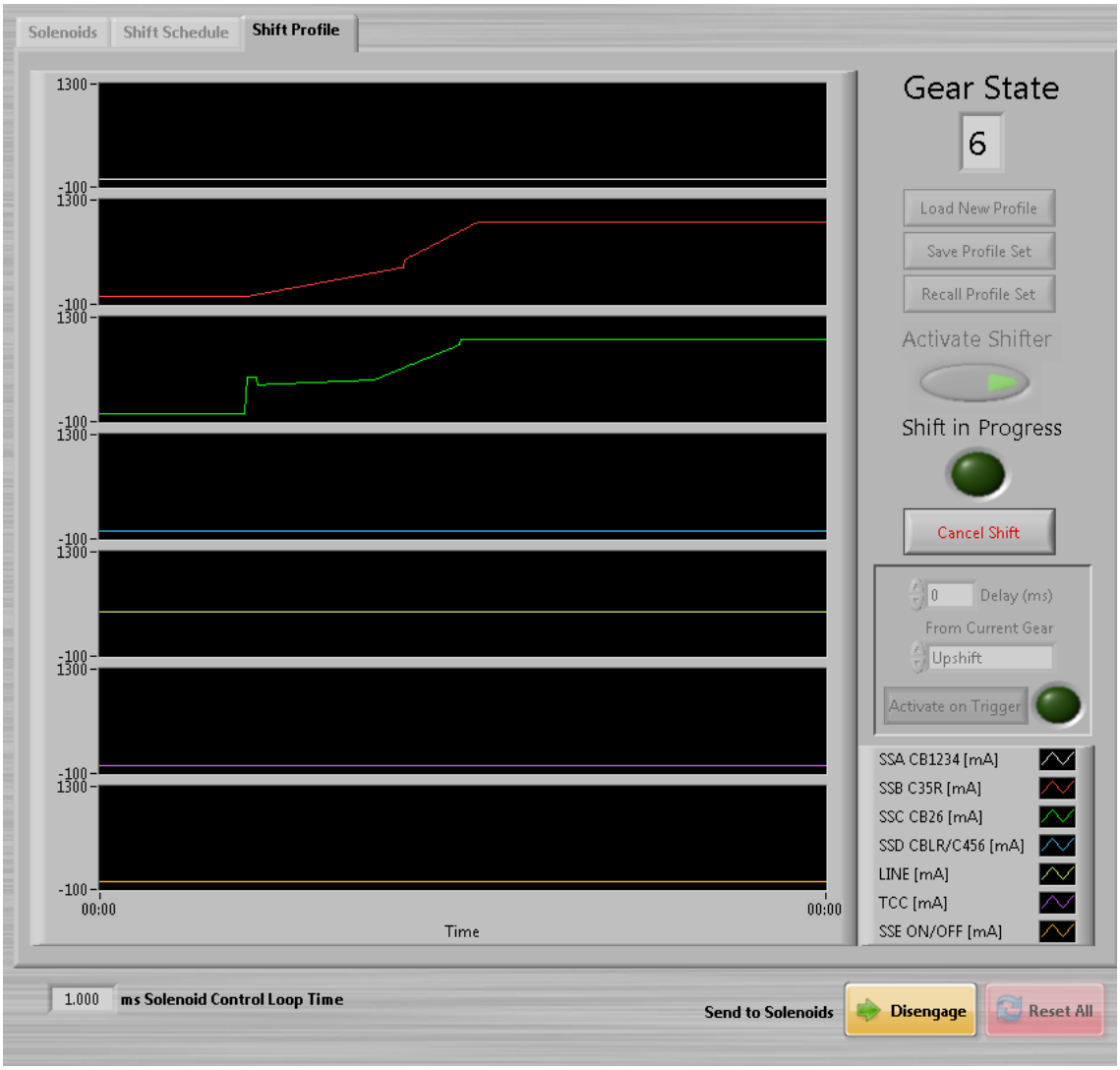
disable all controls so no changes can be made at this point. When the trigger is seen the profile commands will be sent and the shift will be completed. Once the shift is complete all controls will be re-enabled and further testing can be completed.

*Cancel button currently returns transmission to neutral, so be wary when using. Further development needs to be completed to improve cancel operations.



www.manaraa.com

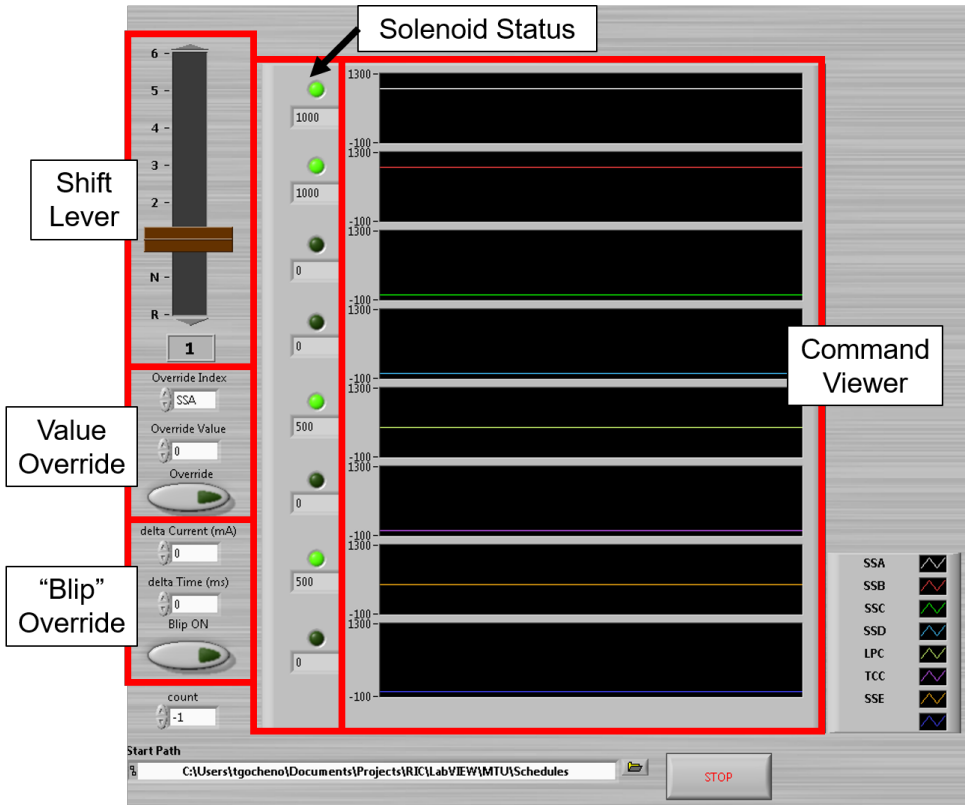
The image below shows how the window appears during a trigger activated shift. All controls are grayed out so no changes can be made. When the shift is activate, the SHIFT IN PROGRESS and trigger indicator will light up.



www.manaraa.com

Next to all the windows are universal controls and solenoid status screen. The profile viewer shows the commands for all solenoids at the same time. These commands are not sent to the solenoids until the ENGAGE button is activated. The indicators and values next to the command viewer shows the current value of the solenoid. It is possible for the solenoid status and command viewer values to not be equal. When the ENGAGE button is activate, the solenoid status and command viewer values will match. When the ENGAGE button is disabled, the solenoid status will show the last values sent to the controller and the the command viewer will show the current commands sent from the software.

The shift lever is used to change gears and view/load profiles in the SHIFT PROFILE window. Value override allows the user to change a single solenoid value on the fly. This was mainly used to set the TCC slip conditions before a shift. The “Blip” override commands an addition of current for a specified amount of time. These controls were used to see the sensitvity of the TCC pressure .



www.manaraa.com

H Pressure Transducer Specifications

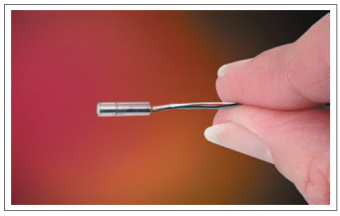
H.1 Kulite XCEL-072

kulite®

HIGH TEMPERATURE
MINIATURE PRESSURE TRANSDUCER

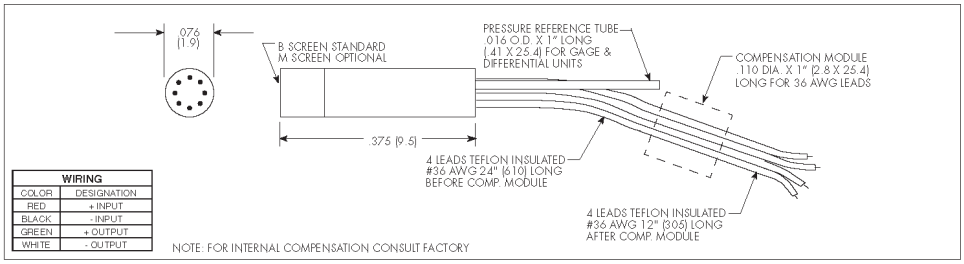
XCEL-072 SERIES

- Wide Temperature Capability -65°F To 525°F
- Designed For Harsh Environments
- Ideal For Turbine Engine Probes and Wind Tunnel Applications
- Patented Leadless Technology **VIS**®
- Designed For Both Static and Dynamic Response
- Suitable For Use in Most Conductive Liquids and Gases



The XCEL-072 design features Kulite's patented leadless technology. This allows for a very rugged package suited for probes, pressure rakes and other similar test set ups. This transducer is well suited for both dynamic and static pressure measurements in benign or harsh environments. Its wide operating temperature range (-65°F to +525°F) makes it ideal for numerous applications in Aerospace and other areas of Industry.

Kulite recommends the KSC-2 signal conditioner to maximize the measurement capability of the XCEL-072 transducer.



WIRING	
COLOR	DESIGNATION
RED	+ INPUT
BLACK	- INPUT
GREEN	+ OUTPUT
WHITE	- OUTPUT

INPUT	Pressure Range	0.7 10	1.0 15	1.7 25	3.5 50	7 100	14 200	21 300	35 500	70 BAR 1000 PSI
	Operational Mode	Absolute, Gage, Differential		Absolute, Gage, Sealed Gage, Differential			Absolute, Sealed Gage			
	Over Pressure	2 Times Rated Pressure								
	Burst Pressure	3 Times Rated Pressure								
	Pressure Media	Most Conductive Liquids and Gases - Please Consult Factory								
	Rated Electrical Excitation	10 VDC/AC								
	Maximum Electrical Excitation	12 VDC/AC								
	Input Impedance	1000 Ohms (Min.)								
OUTPUT	Output Impedance	1000 Ohms (Nom.)								
	Full Scale Output (FSO)	100 mV (Nom.)								
	Residual Unbalance	± 5 mV (Typ.)								
	Combined Non-Linearity, Hysteresis and Repeatability	± 0.1% FSO BFSL (Typ.), ± 0.5% FSO (Max.)								
	Resolution	Infinitesimal								
	Natural Frequency of Sensor Without Screen (KHz) (Typ.)	175	200	240	300	380	550	575	700	1000
	Acceleration Sensitivity % FS/g Perpendicular	$1.0x10^{-3}$	$6.5x10^{-4}$	$5.0x10^{-4}$	$3.0x10^{-4}$	$1.5x10^{-4}$	$1.1x10^{-4}$	$9.0x10^{-5}$	$6.0x10^{-5}$	$4.0x10^{-5}$
	Insulation Resistance	100 Megohm Min. @ 50 VDC								
ENVIRONMENTAL	Operating Temperature Range	-65°F to +525°F (-55°C to +273°C)								
	Compensated Temperature Range	+80°F to +450°F (+25°C to +235°C)								
	Thermal Zero Shift	± 1% FS/100°F (Typ.)								
	Thermal Sensitivity Shift	± 1% /100°F (Typ.)								
	Steady Acceleration	10,000g. (Max.)								
	Linear Vibration	10-2000 Hz Sine, 100g. (Max.)								
PHYSICAL	Electrical Connection	4 Leads 36 AWG 36" Long								
	Weight	.2 Gram (Nom.) Excluding Module and Leads								
	Pressure Sensing Principle	Fully Active Four Arm Wheatstone Bridge Dielectrically Isolated Silicon on Silicon Patented Leadless Technology								

Note: Custom pressure ranges, accuracies and mechanical configurations available. Dimensions are in inches. Dimensions in parenthesis are in millimeters. All dimensions nominal. (Q) Continuous development and refinement of our products may result in specification changes without notice. *Copyright © 2014 Kulite Semiconductor Products, Inc. All Rights Reserved.*
Kulite miniature pressure transducers are intended for use in test and research and development programs and are not necessarily designed to be used in production applications. For products designed to be used in production programs, please consult the factory.

KULITE SEMICONDUCTOR PRODUCTS, INC. • One Willow Tree Road • Leonia, New Jersey 07605 • Tel: 201 461-0900 • Fax: 201 461-0990 • http://www.kulite.com

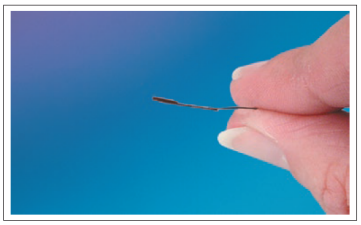
www.manaraa.com

H.2 Kulite LE-160

kulite®

MICROLINE STRESS ISOLATED SURFACE MOUNT PRESSURE TRANSDUCER

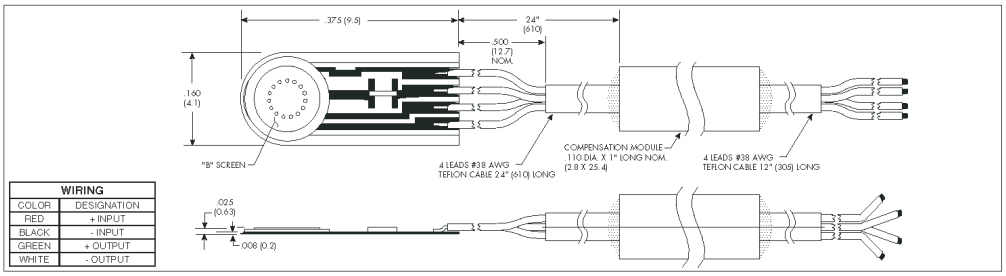
LQ-160 SERIES LE-160 SERIES



- Designed For Direct Blade Surface Mounting
- Silicon on Silicon Integrated Sensor **VIS**®
- High G Loading
- Low Base Strain Sensitivity
- High Natural Frequency
- High Temperature Operation Up To 450°F (LE Series)

The LQ/LE-160 Series microline pressure transducer represents the latest build standard in a long line of sensors designed and developed for direct mounting onto engine blades. Using a unique isolation technique to reduce base strain sensitivity effects, the LQ/LE-160 Series are the smallest, lightest units yet developed. With a maximum height of less than 0.025 inch, these units may be mounted in locations on the blade previously inaccessible with a packing density previously impossible.

Kulite recommends the KSC-2 signal conditioner to maximize the measurement capability of the LQ-160 and LE-160 transducers.



WIRING	
COLOR	DESIGNATION
RED	+ INPUT
BLACK	- INPUT
GREEN	+ OUTPUT
WHITE	- OUTPUT

INPUT	Pressure Range	0.35 5	0.7 10	1.7 25	3.5 50	7 100	17 250	35 BAR 500 PSI
	Operational Mode	Absolute		Absolute, Sealed Gage				
	Over Pressure	2 Times Rated Pressure						
	Burst Pressure	3 Times Rated Pressure						
	Pressure Media	All Nonconductive, Noncorrosive Liquids or Gases						
	Rated Electrical Excitation	10 VDC						
	Maximum Electrical Excitation	12 VDC						
	Input Impedance	1000 Ohms (Min.)						
OUTPUT	Output Impedance	1000 Ohms (Nom.)						
	Full Scale Output (FSO)	100 mV (Nom.)						
	Residual Unbalance	± 5 mV (Typ.)						
	Combined Non-Linearity, Hysteresis and Repeatability	± 0.1% FSO BFSL (Typ.), ± 0.5% FSO (Max.)						
	Resolution	Infinitesimal						
	Natural Frequency of Sensor without Screen (KHz) (Typ.)	150	175	240	300	380	550	700
	Acceleration Sensitivity % FS/g Perpendicular	$1.5x10^{-3}$	$1.0x10^{-3}$	$5.0x10^{-4}$	$3.0x10^{-4}$	$1.5x10^{-4}$	$1.0x10^{-4}$	$6.0x10^{-5}$
	Base Strain Sensitivity	Less Than 5% FSO for 1000 Microstrain						
	Insulation Resistance	100 Megohm Min. @ 50 VDC						
ENVIRONMENTAL	Operating Temperature Range	*LQ SERIES* -65°F to +250°F (-55°C to +120°C) *LE SERIES* -65°F to +450°F (-55°C to +235°C) *Sensor Only*						
	Compensated Temperature Range	*LQ SERIES* +80°F to +180°F (+25°C to +80°C) *LE SERIES* +80°F to +450°F (+25°C to +235°C) *Sensor Only*						
	Thermal Zero Shift	± 2.0% FS/100°F (Typ.)						
	Thermal Sensitivity Shift	± 2.0% /100°F (Typ.)						
	Linear Vibration	10-2,000 Hz Sine, 100g. (Max.)						
	Mechanical Shock	20g half Sine Wave 11 msec. Duration						
PHYSICAL	Electrical Connection	4 Conductor # 38 AWG Shielded Teflon Cable 24" to Module, 12" After						
	Weight	.1 Gram (Nom.) Excluding Module and Leads						
	Pressure Sensing Principle	Fully Active Four Arm Wheatstone Bridge Dielectrically Isolated Silicon on Silicon						

Note: Custom pressure ranges, accuracies and mechanical configurations available. Dimensions are in inches. Dimensions in parenthesis are in millimeters. All dimensions nominal. (A) Continuous development and refinement of our products may result in specification changes without notice. *Copyright © 2015 Kulite Semiconductor Products, Inc. All Rights Reserved.*
Kulite miniature pressure transducers are intended for use in test and research and development programs and are not necessarily designed to be used in production applications. For products designed to be used in production programs, please consult the factory.

KULITE SEMICONDUCTOR PRODUCTS, INC. • One Willow Tree Road • Leonia, New Jersey 07605 • Tel: 201 461-0900 • Fax: 201 461-0990 • http://www.kulite.com

www.manaraa.com

I Torque Converter Instrumentation Photos

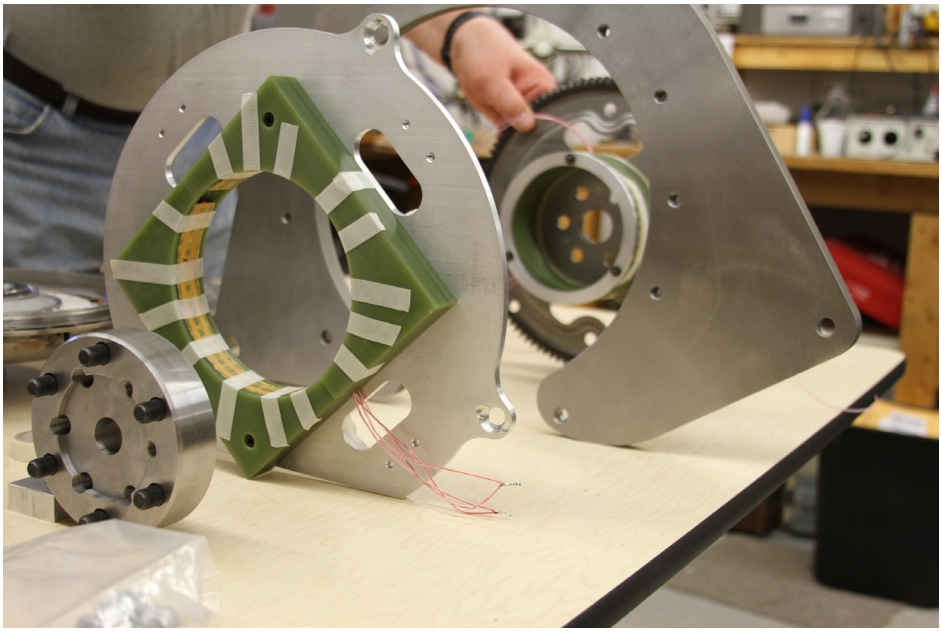


Figure I-1. Left to right: shaft coupler, transmitter induction coil, head plate, receiver coil on flex plate

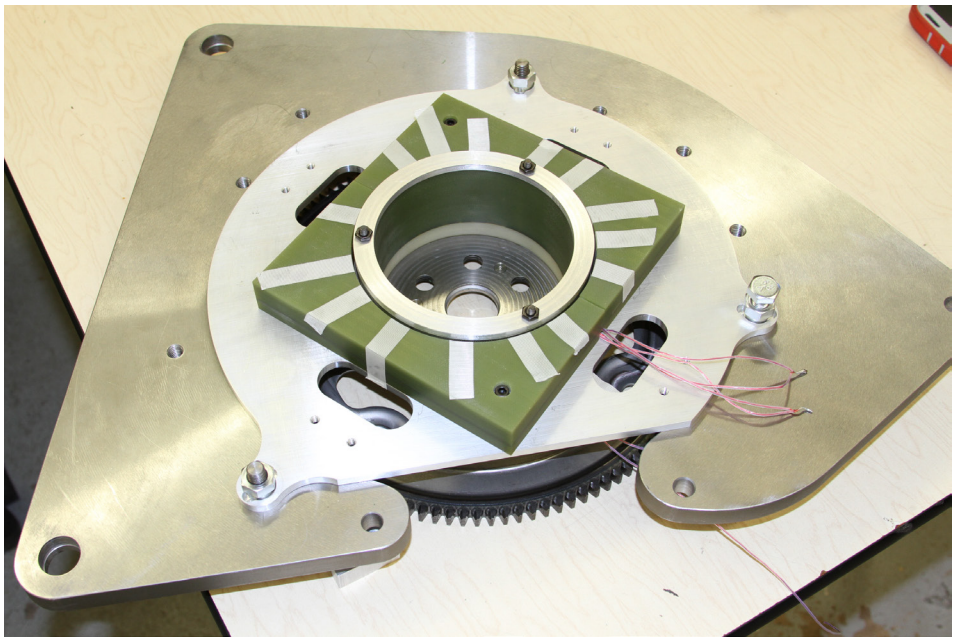


Figure I-2. Powering induction coil on head plate, receiving induction coil on flex plate

www.manaraa.com

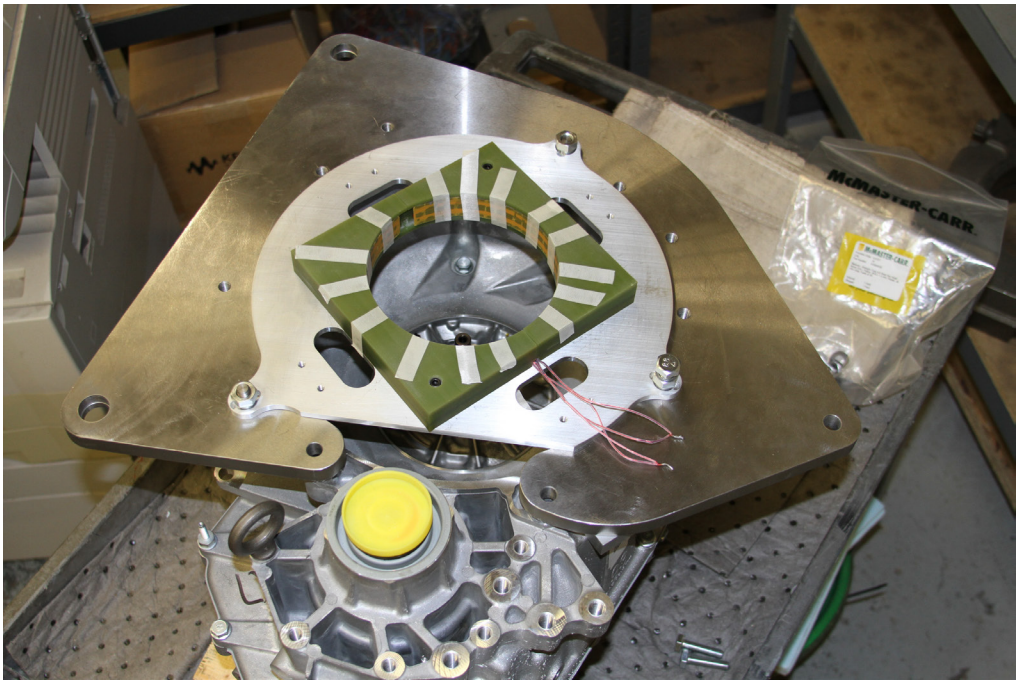


Figure I-3. Transmitter coil and head plate placement on transmission housing

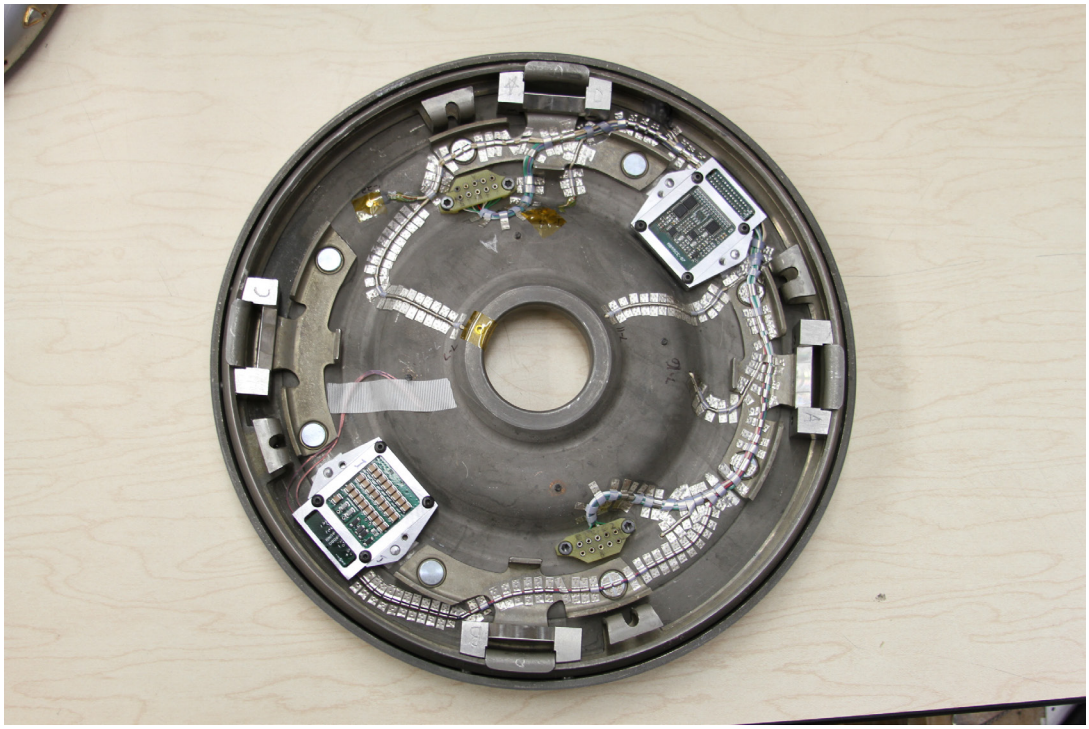


Figure I-4. Transmitter and hardware for turbine transmitter mounted on clutch plate

www.manaraa.com

Figure I-5. Kevlar patch on clutch plate for transmitter

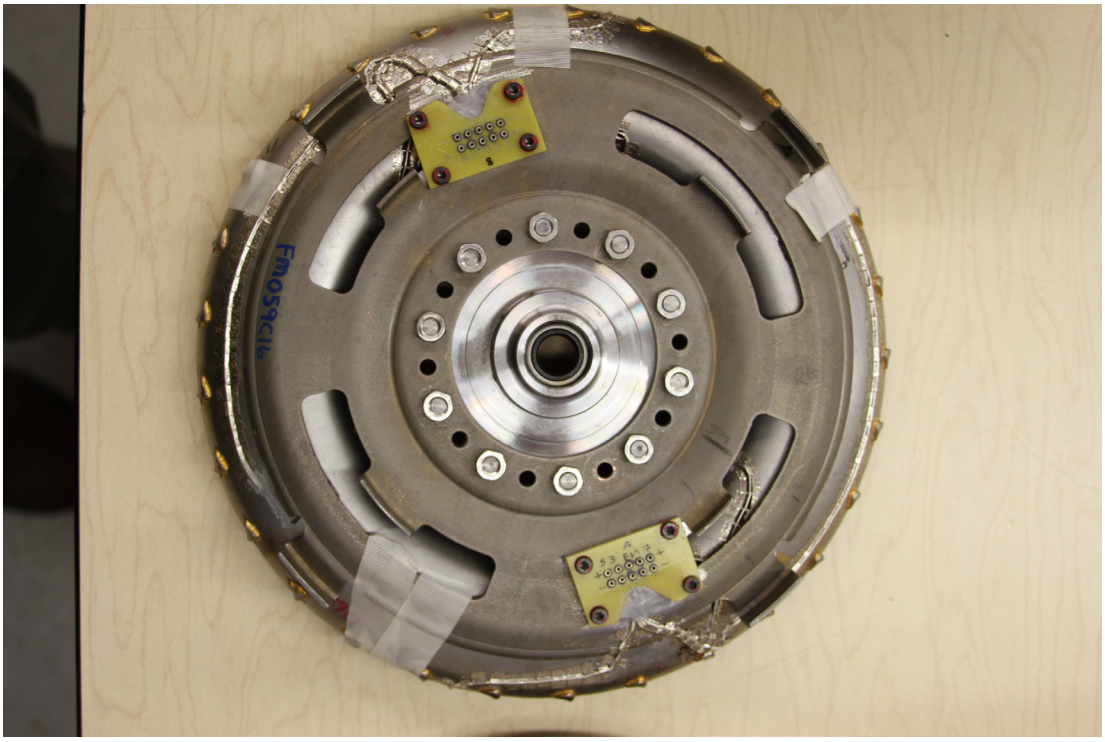


Figure I-6. Power and signal pin arrays mounted to shell of turbine

www.manaraa.com

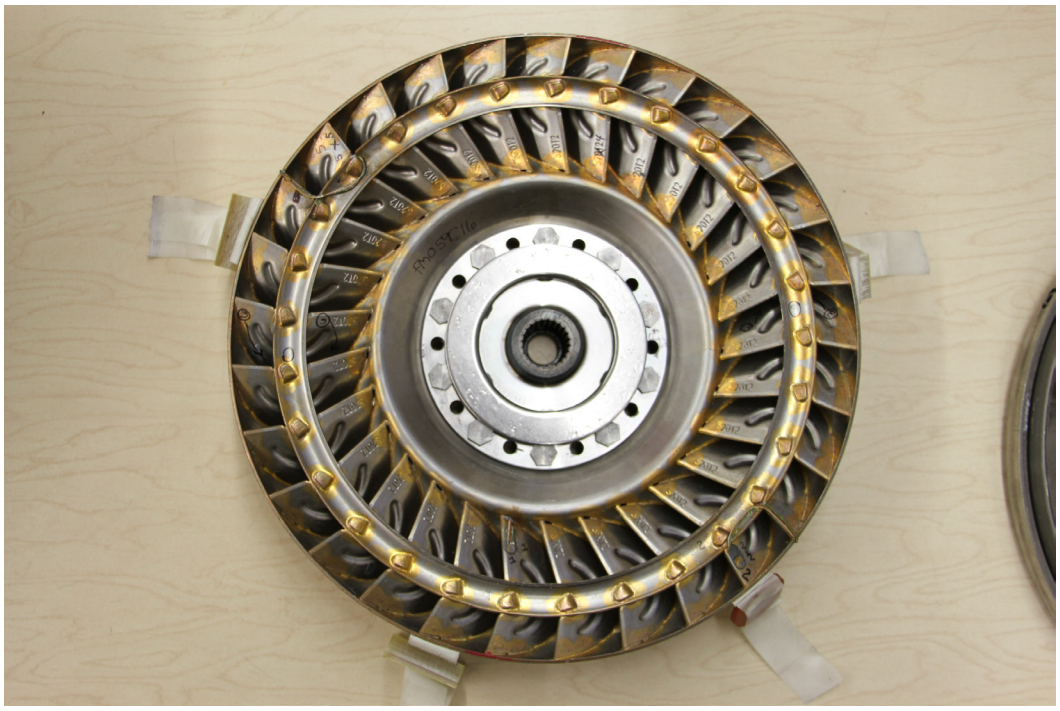


Figure I-7. Turbine torus

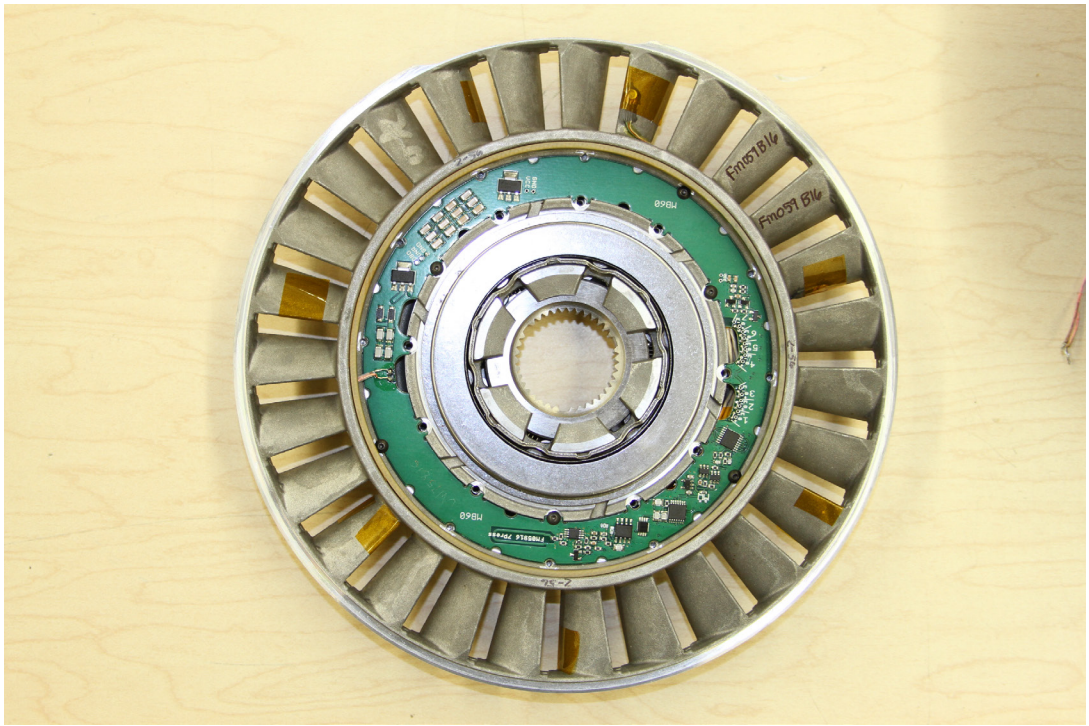


Figure I-8. Stator trailing edge side with receiver induction coil and transmitter hardware mounted in center

www.manaraa.com

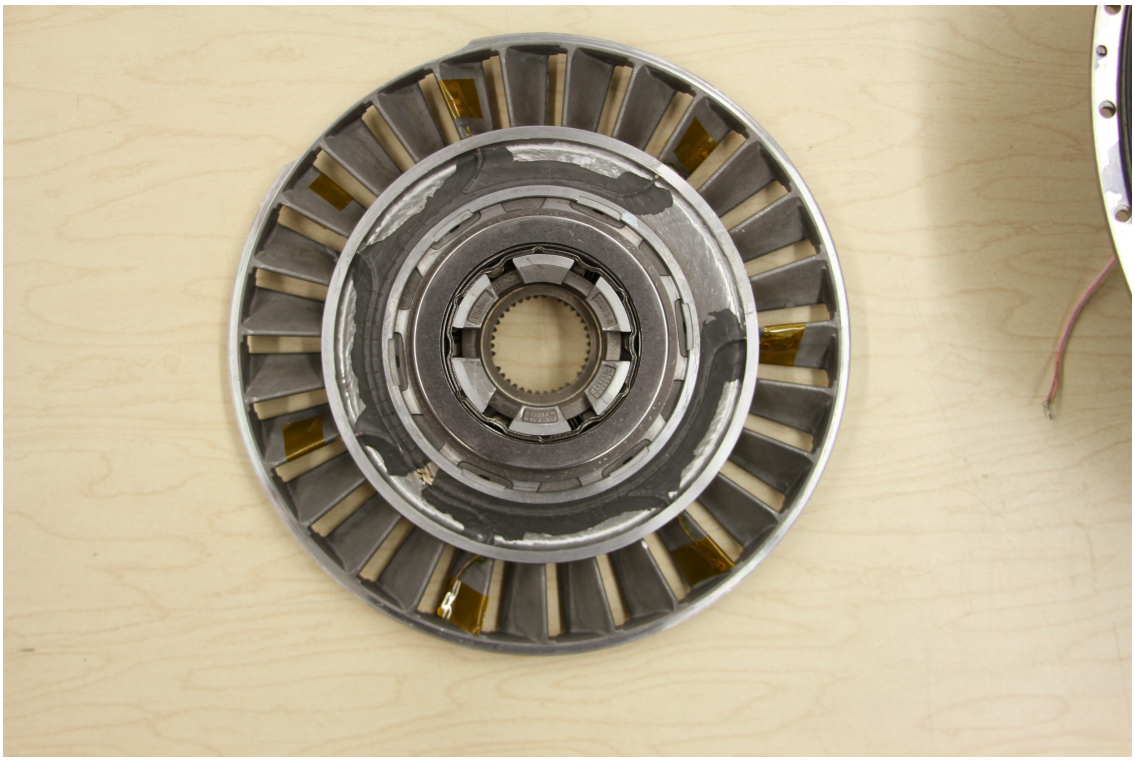


Figure I-9. Stator leading edge side

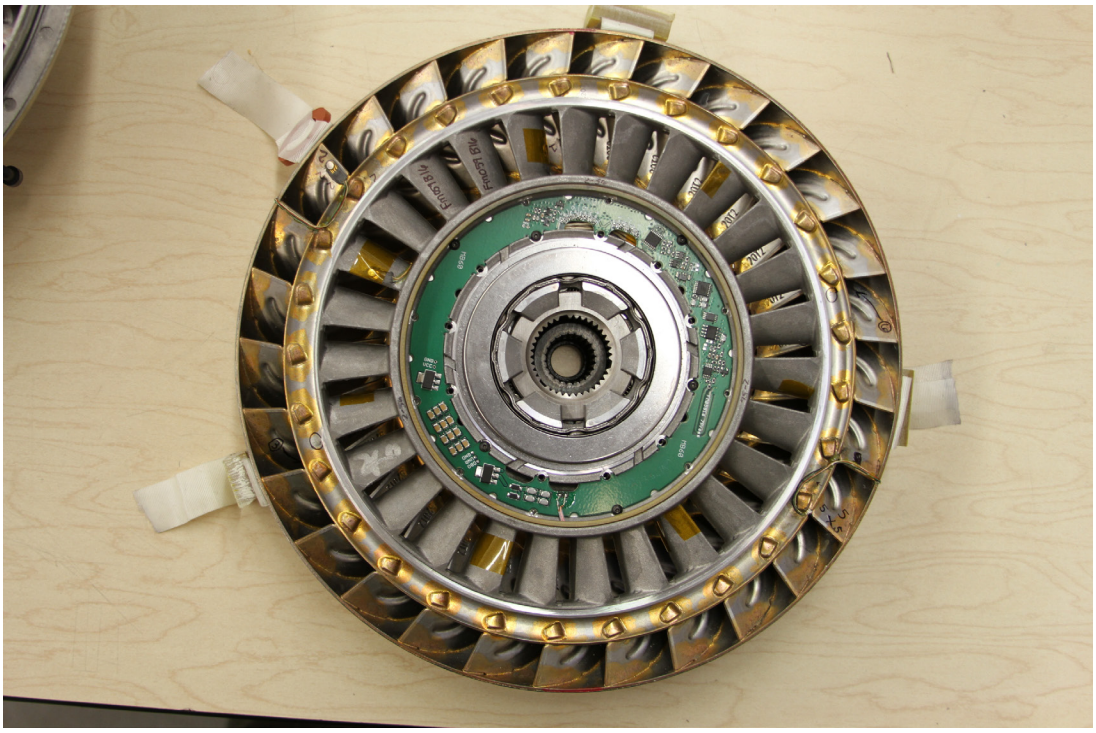


Figure I-10. Stator laying on top of turbine

www.manaraa.com

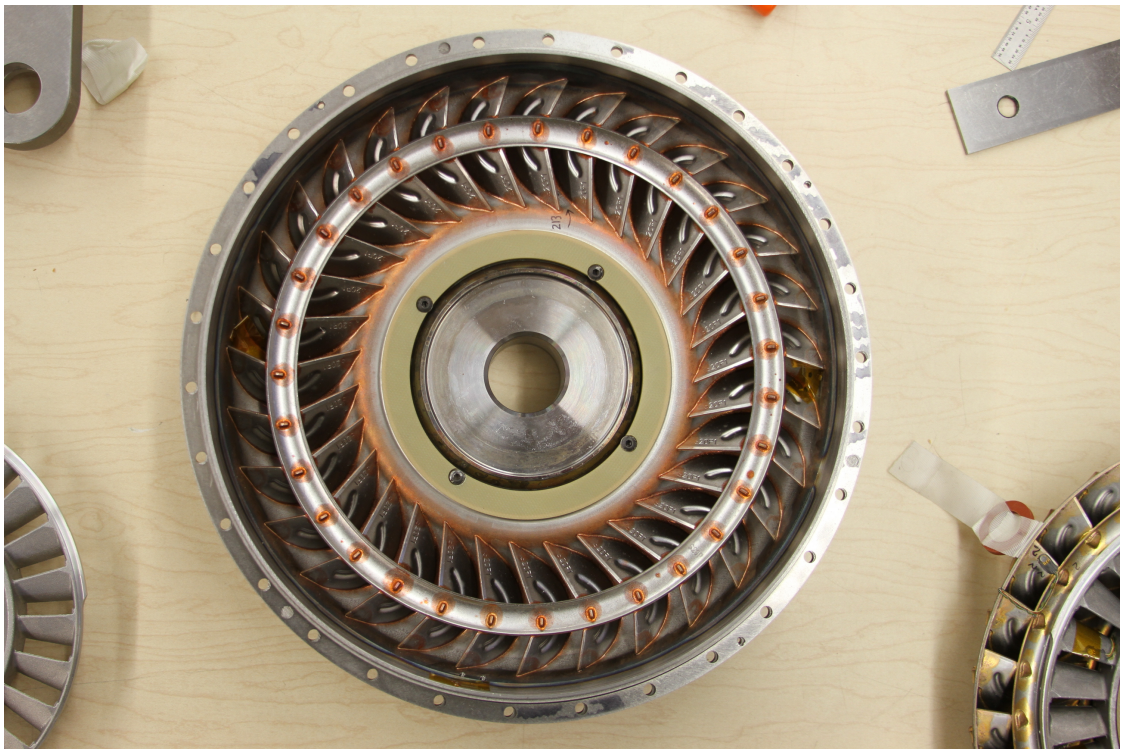


Figure I-11. Impeller with stator transmitter induction coil

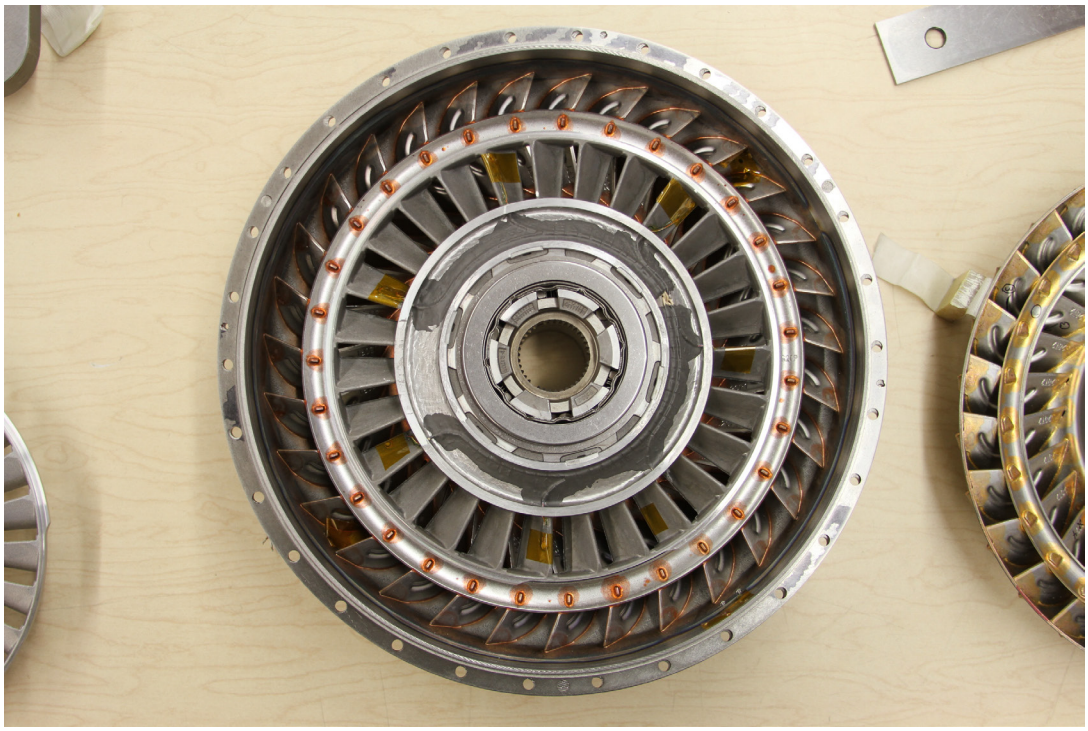


Figure I-12. Stator laying on top of impeller

www.manaraa.com

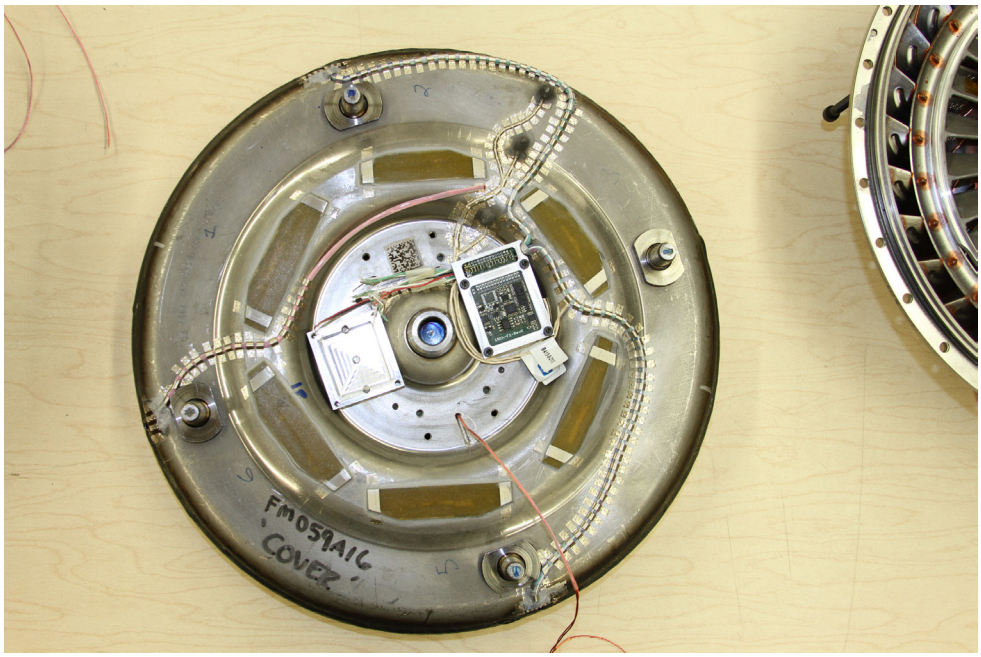


Figure I-13. Impeller transmitter hardware mounted to cover. Kevlar patches to allow turbine transmitter signal to escape the torque converter

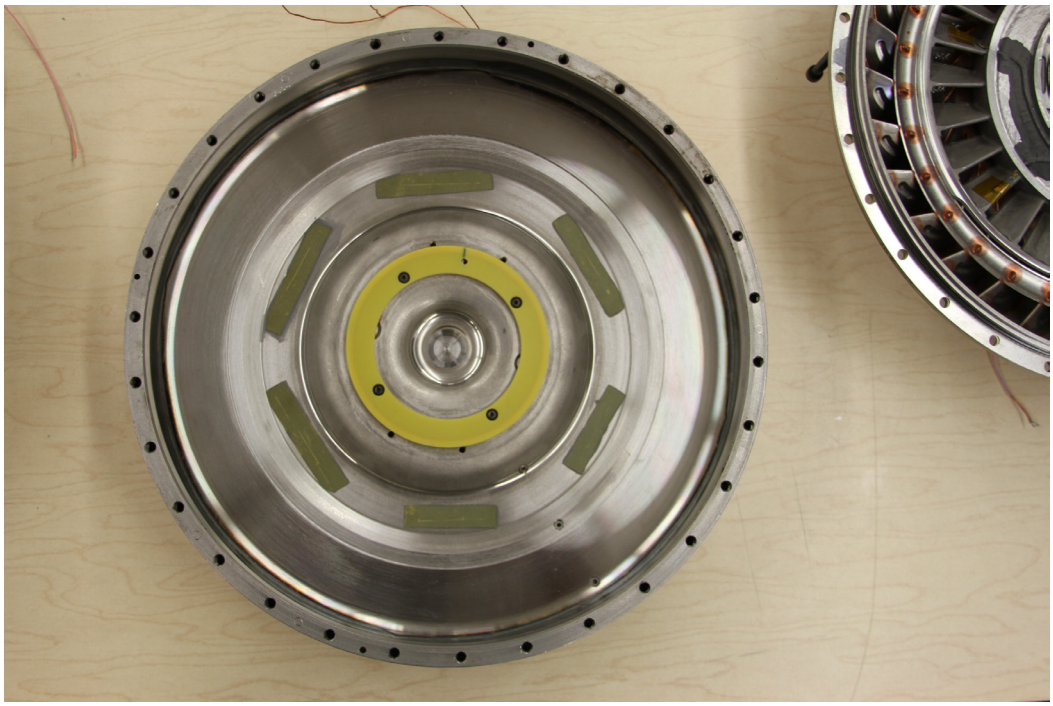


Figure I-14. Turbine transmitter induction coil and Kevlar patches on inside of cover

www.manaraa.com

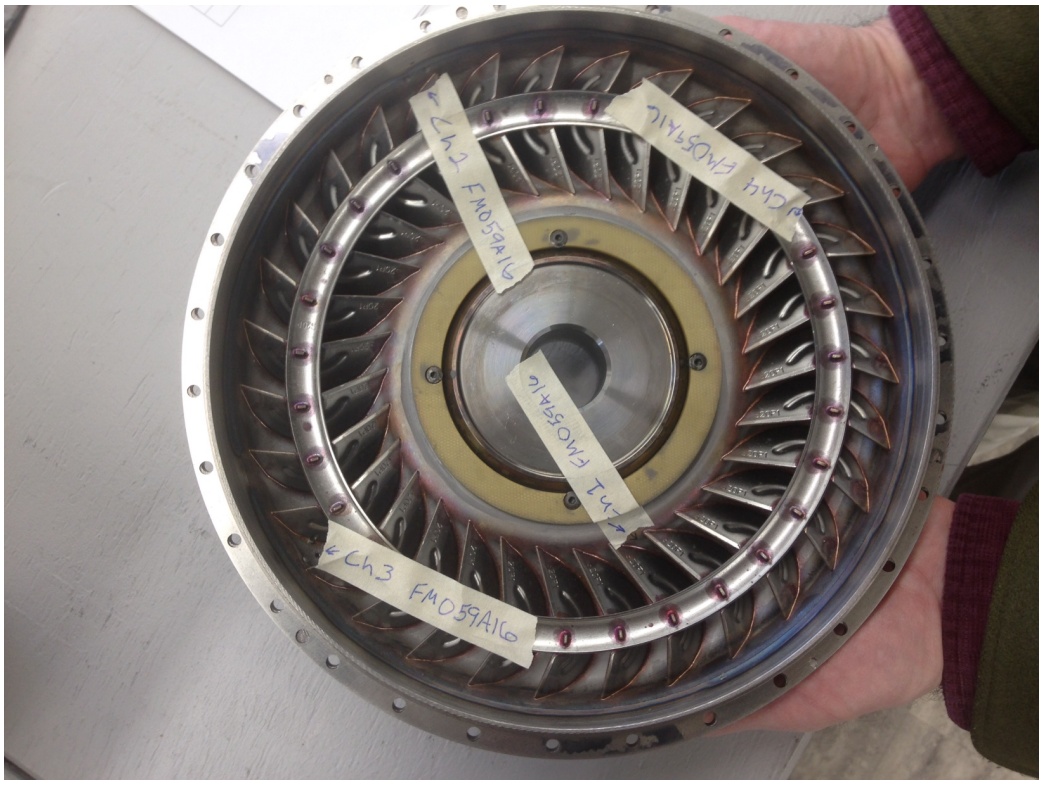


Figure I-15. Impeller torus transducer locations

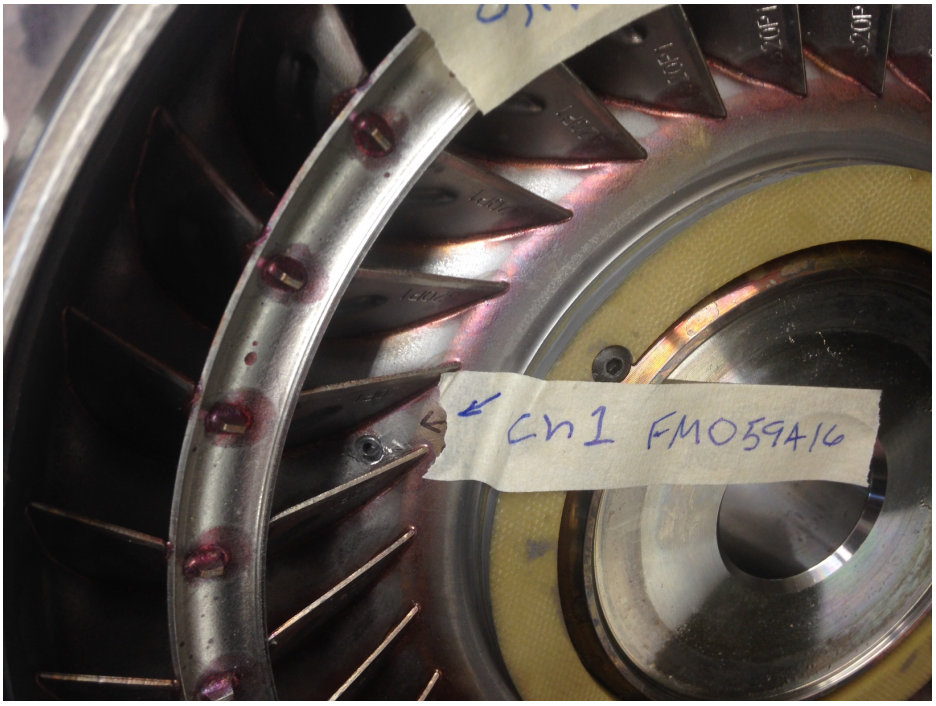


Figure I-16. Impeller channel 1 location, leading edge between blades

www.manaraa.com

Figure I-17. Impeller channel 2 location, between impeller and turbine

Figure I-18. Impeller channel 3 location, trailing edge between blades

www.manaraa.com

Figure I-19. Impeller channel 4 location, center between blades

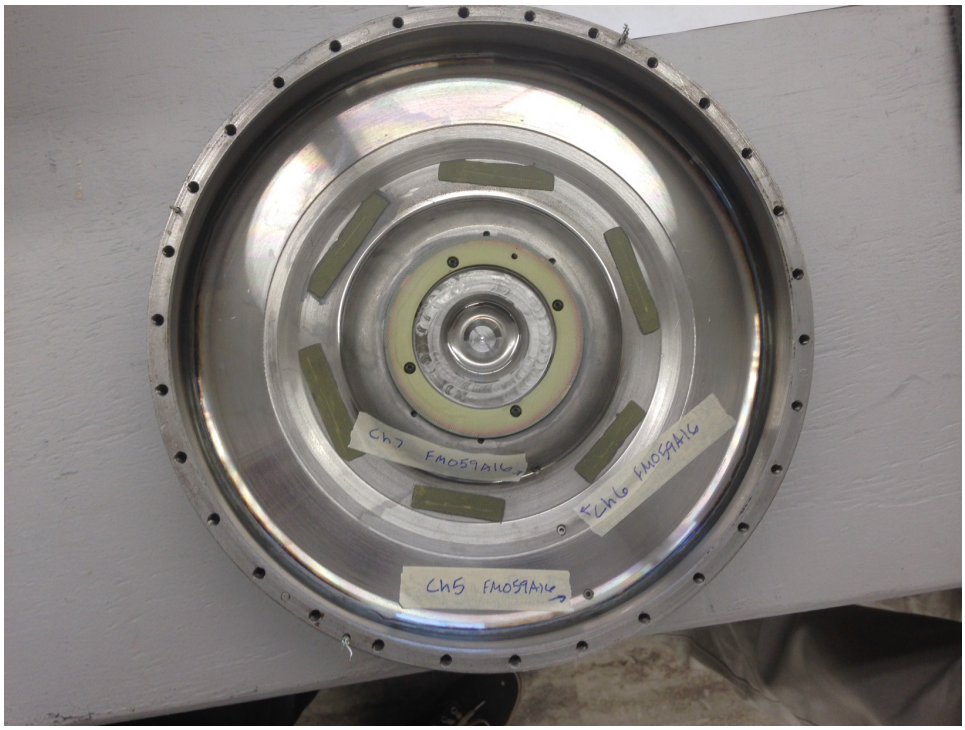


Figure I-20. Cover transducer locations

www.manaraa.com

Figure I-21. Cover channels 5-7 locations

Figure I-22. Stator transducer locations

www.manaraa.com

Figure I-23. Stator channel 1 location, leading edge/middle/pressure side

Figure I-24. Stator channel 2 location, trailing edge/middle/pressure side

www.manaraa.com

Figure I-25. Stator channel 3 location, middle of blade/shell/pressure side

Figure I-26. Stator channel 4 location, leading edge/core/pressure side

www.manaraa.com

Figure I-27. Stator channel 5 location, trailing edge/shell/pressure side

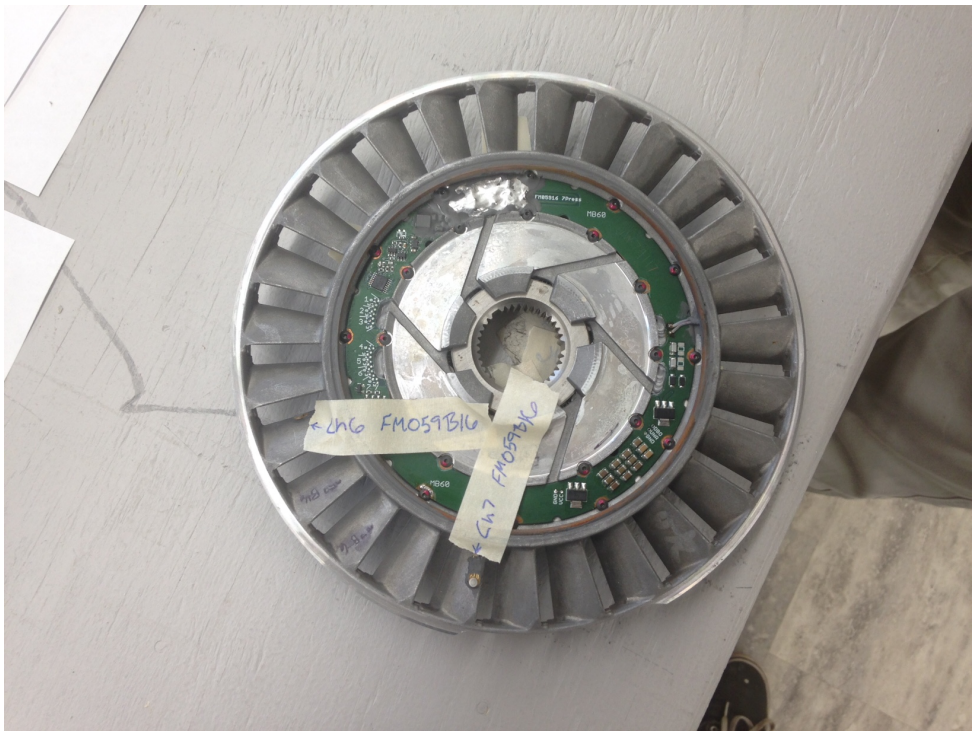


Figure I-28. Stator transducer locations

www.manaraa.com

Figure I-29. Stator channel 6 location, leading edge/middle/suction side

Figure I-30. Stator channel 7 location, trailing edge/middle/suction side

www.manaraa.com

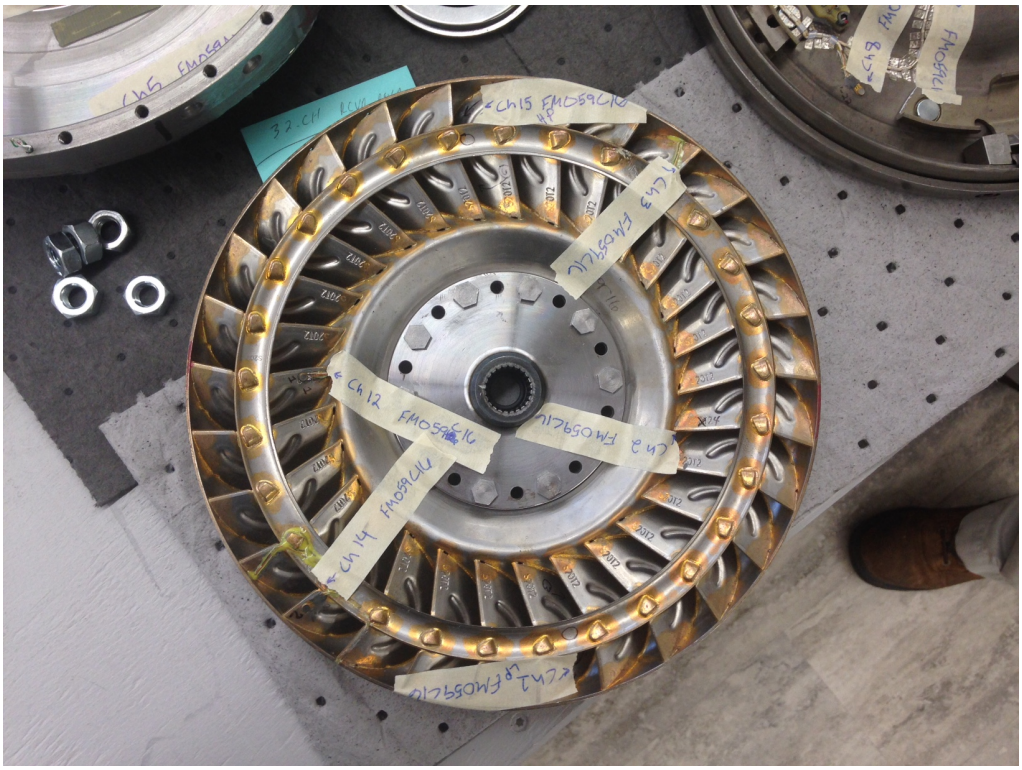


Figure I-31. Turbine transducer locations

Figure I-32. Turbine channel 1 location, middle of blade suction side

www.manaraa.com

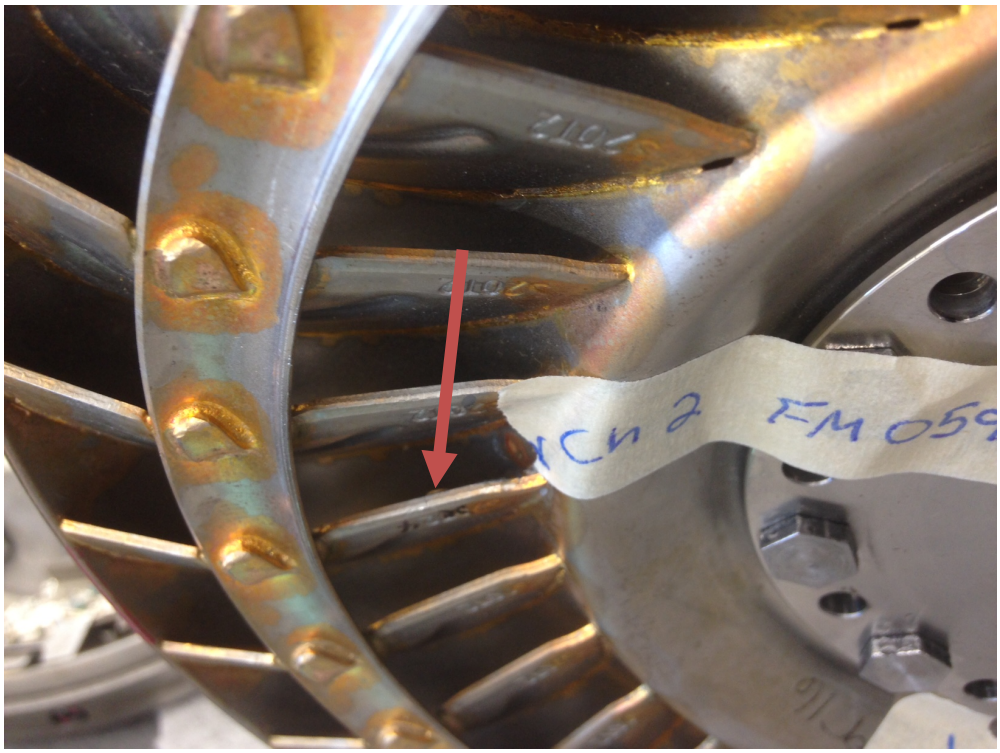


Figure I-33. Turbine channel 2 location, trailing edge pressure side

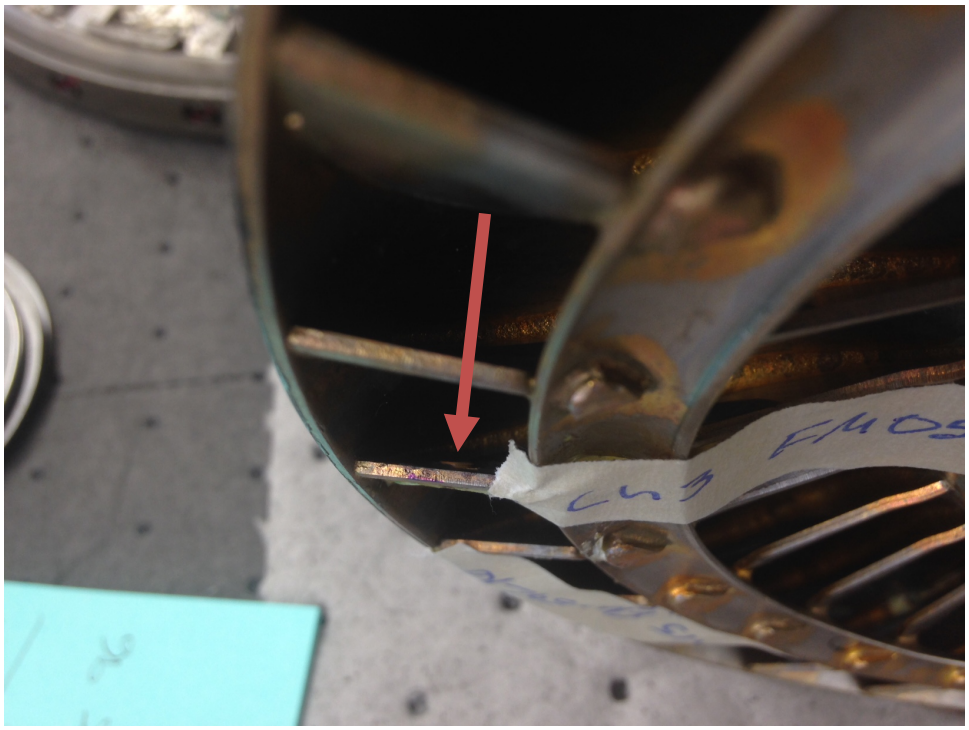


Figure I-34. Turbine channel 3 location, leading edge pressure side

www.manaraa.com

Figure I-35. Turbine channel 12 locations, trailing edge suction side

Figure I-36. Turbine channel 14 location, leading edge suction side

www.manaraa.com

Figure I-37. Turbine channel 15 location, middle blade pressure side

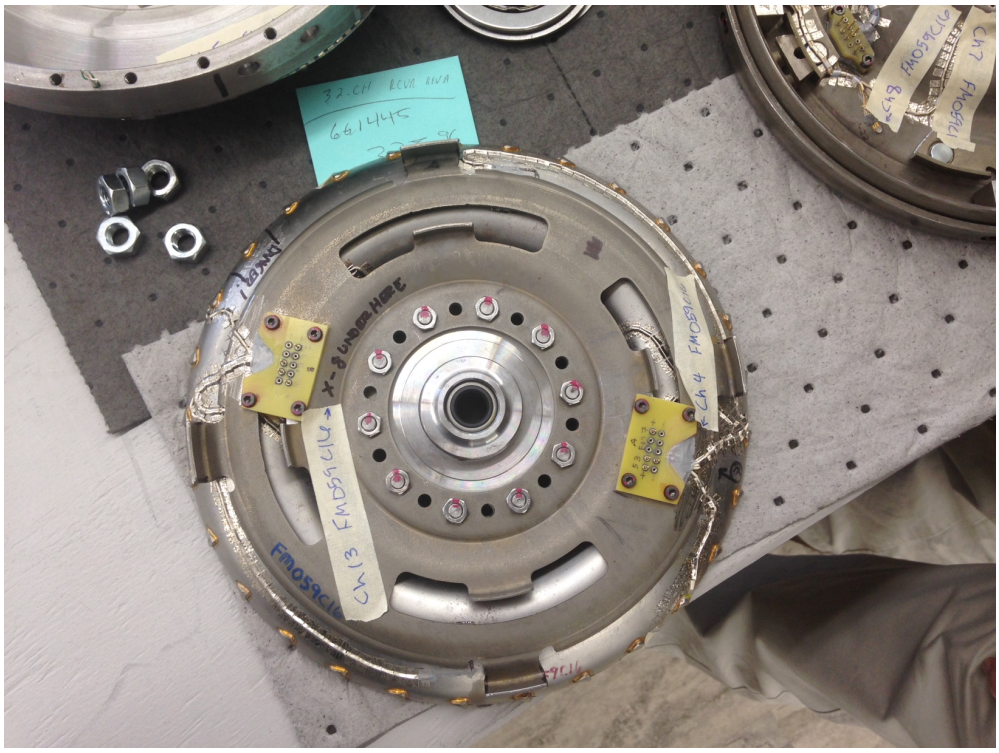


Figure I-38. Turbine channel 4 and 13 locations, back of turbine under plate

www.manaraa.com

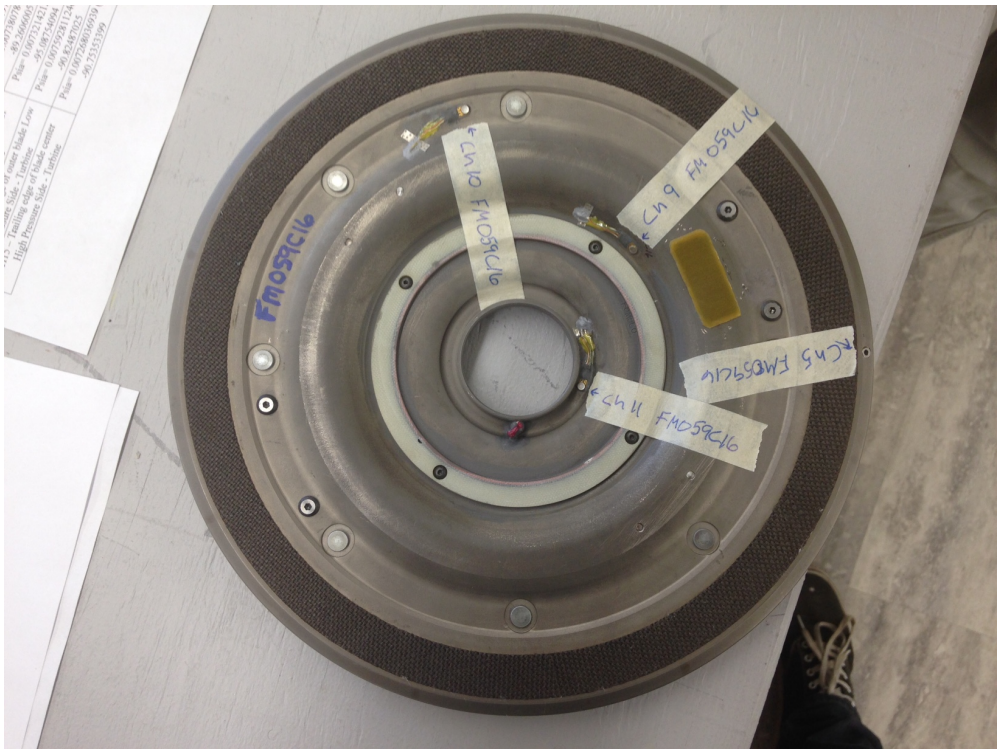


Figure I-39. Clutch transducer locations

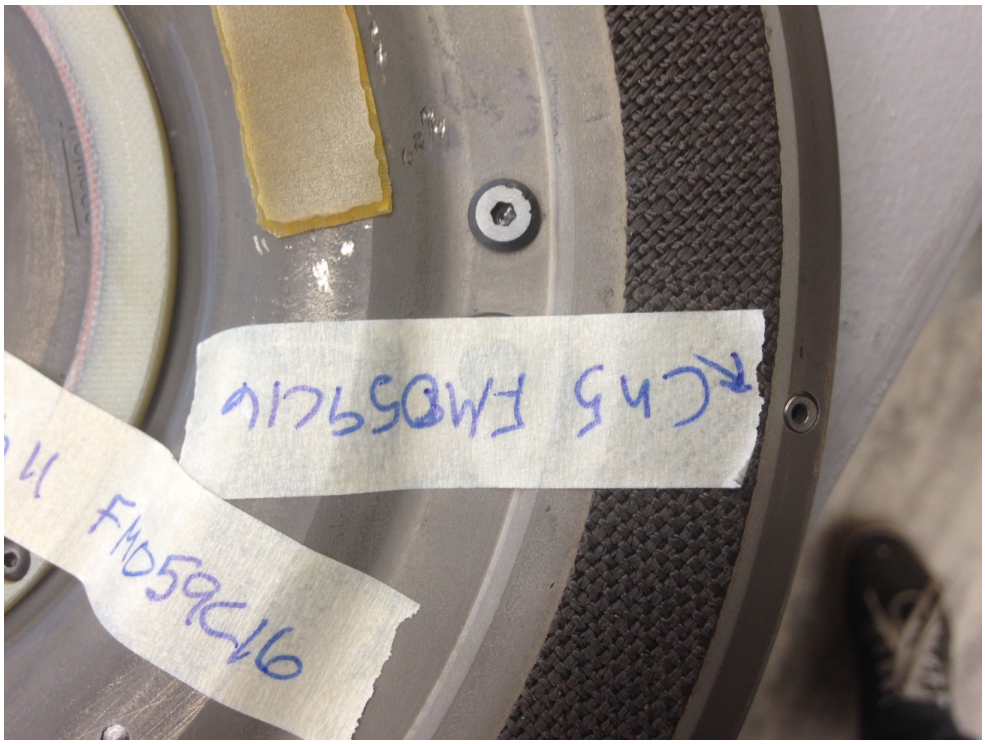


Figure I-40. Clutch channel 5 location, outer radius past friction material

www.manaraa.com

Figure I-41. Clutch channel 9 location, middle radius

Figure I-42. Clutch channel 10 location, outer radius before friction material

www.manaraa.com

Figure I-43. Clutch channel 11 location, inner radius

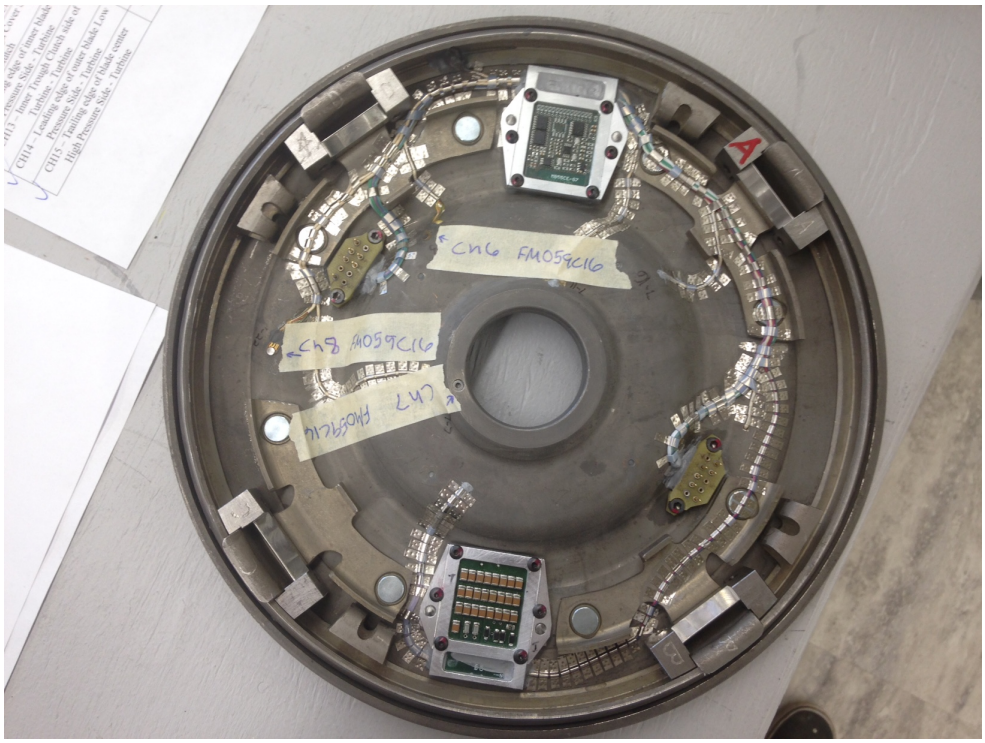


Figure I-44. Clutch plate transducer locations

www.manaraa.com

Figure I-45. Clutch channel 6 location, middle radius

Figure I-46. Clutch channel 7 and 8 locations, inner and outer radius respectively

www.manaraa.com

J Telemetry Setup Procedure

1. Connect extension cable from transmission to power supply on computer control stand outside and power on.

Figure I-1. Power supply for telemetry

2. Turn on the three receivers, one at a time, in the test cell.

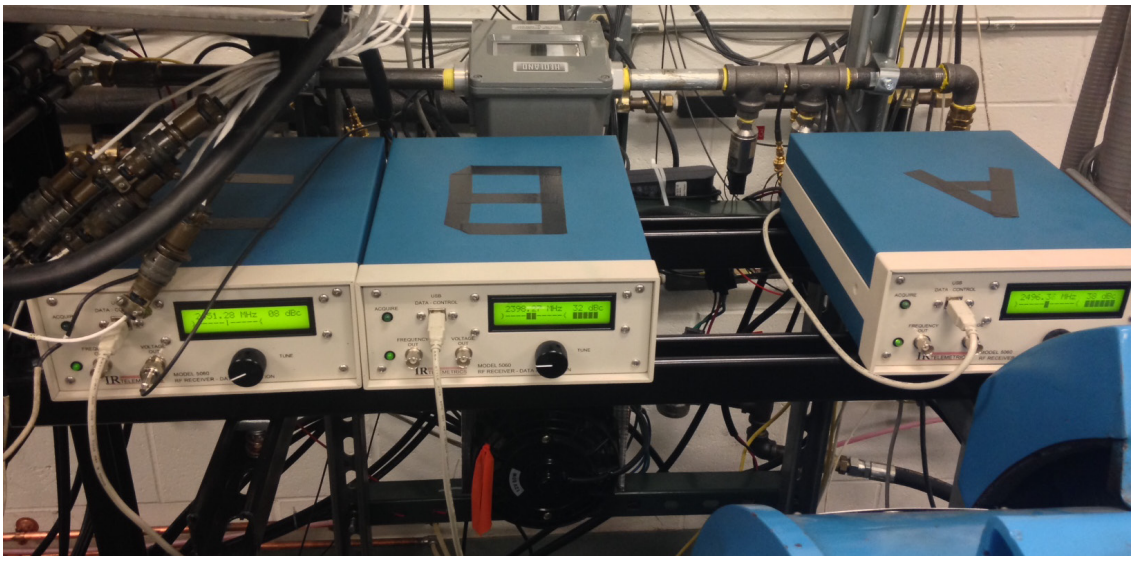


Figure I-2. Receivers for each transmitter

3. Open three Digital FV software windows.

www.manaraa.com

4. Connect the DFV 2 window to each of the receivers.

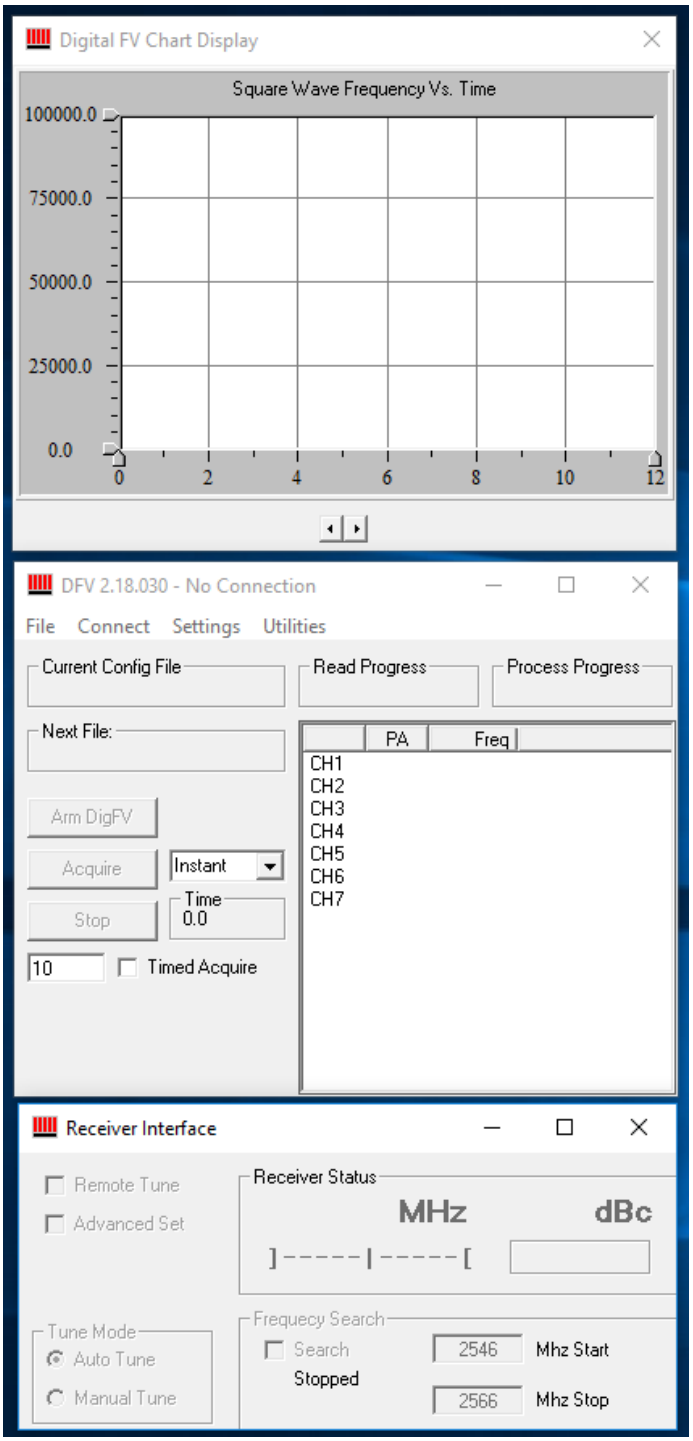


Figure I-3. Digital FV windows- chart display (top), receiver controller (middle), and receiver readout (bottom)

www.manaraa.com

5. Open configuration file associated with each receiver by selecting File > Open Configuration

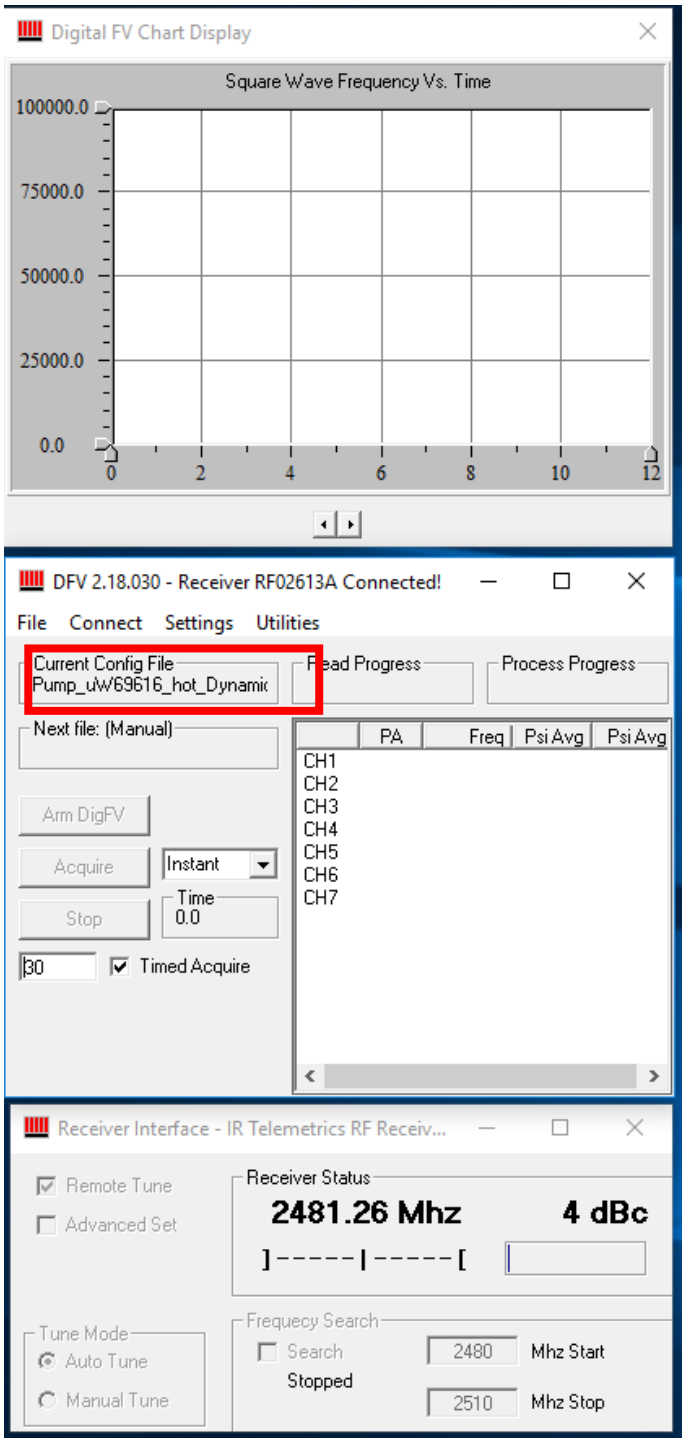


Figure I-4. Receiver connected

www.manaraa.com

6. Use dropdown menu and select streaming or on sync depending on test scenario. Streaming for steady state, On Sync for transient. Signal strength can be monitored on Receiver Interface window.

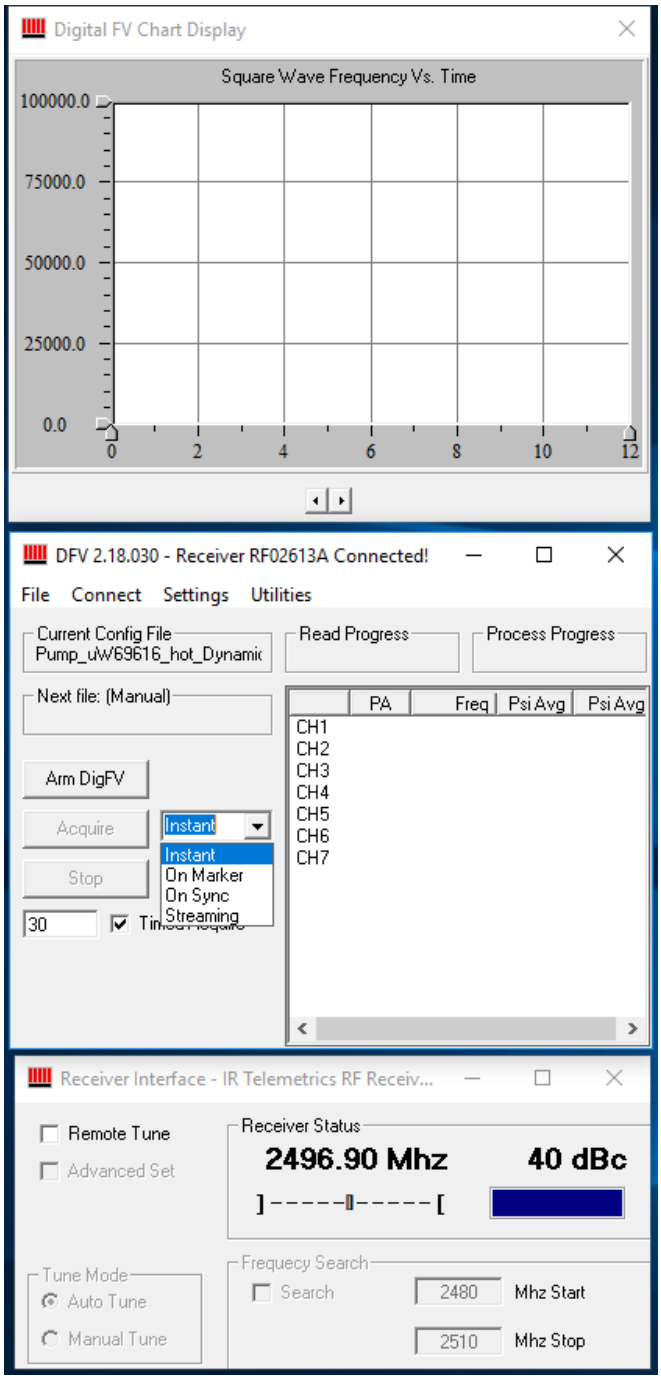


Figure I-5. Receiver showing signal strength and recording options

www.manaraa.com

7. Under Settings > File Options to set the filename to auto increment. Set record time to stop after specified time by checking Timed Acquire and typing the amount of times. Record telemetry data by pressing Arm DigFV and then Acquire.

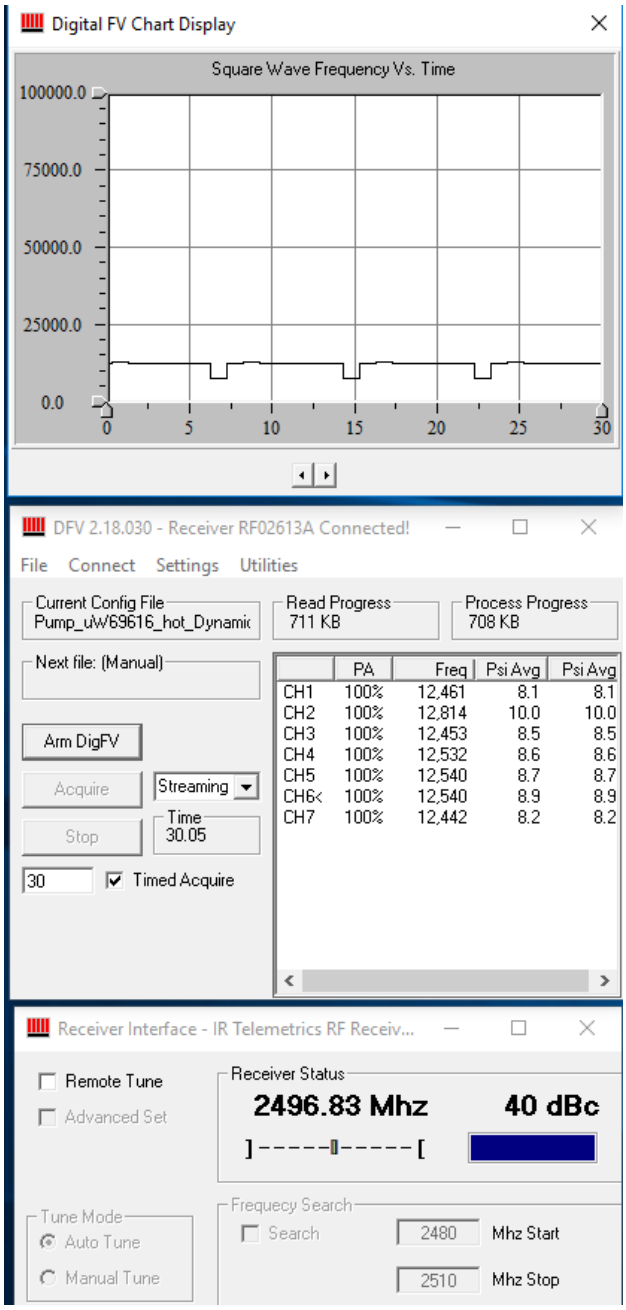


Figure I-6. Example of streamed data

www.manaraa.com

K Torque Converter Clutch Pressures

K.1 Raw Data for 6th Gear

Released TCC*

Output Speed [RPM]	Ch1 [PSI]	Ch2 [PSI]	Ch3 [PSI]	Ch4 [PSI]	Ch5 [PSI]	Ch6 [PSI]	Ch7 [PSI]	Ch8 [PSI]	Ch9 [PSI]	Ch10 [PSI]	Ch11 [PSI]	Ch12 [PSI]	Ch13 [PSI]	Ch14 [PSI]	Ch15 [PSI]	Charge Pressure [PSI]	Input Speed [RPM]	Input Torque [Nm]
527	8.6	6.8	13.9	11.2	18.1	6.1	4.9	11.3	6.4	11.2	5.0	5.6	5.7	11.8	12.1	56.4	1416	30
527	6.0	3.8	11.9	12.5	20.3	7.3	4.1	12.6	6.1	12.1	4.4	-0.3	6.7	2.1	17.5	57.8	1715	100
421	6.7	5.5	10.3	8.9	13.5	5.8	5.1	9.0	5.8	9.0	5.2	4.4	5.5	8.1	9.8	53.7	1164	30
421	2.0	1.8	6.4	10.4	16.4	6.9	4.1	10.3	5.3	10.0	4.1	-3.0	6.7	-4.9	16.9	58.3	1693	100
315	6.8	6.2	9.1	8.8	11.5	7.2	6.2	8.9	6.9	8.7	6.7	5.4	7.0	6.6	9.7	48.8	947	30
315	-2.8	-1.4	0.8	8.4	13.3	6.2	3.9	8.4	4.6	8.1	3.7	-6.0	6.5	-14.3	16.5	60.8	1789	100

Slip TCC*

Output Speed [RPM]	Ch1 [PSI]	Ch2 [PSI]	Ch3 [PSI]	Ch4 [PSI]	Ch5 [PSI]	Ch6 [PSI]	Ch7 [PSI]	Ch8 [PSI]	Ch9 [PSI]	Ch10 [PSI]	Ch11 [PSI]	Ch12 [PSI]	Ch13 [PSI]	Ch14 [PSI]	Ch15 [PSI]	Charge Pressure [PSI]	Input Speed [RPM]	Input Torque [Nm]
527	4.9	3.5	9.8	5.5	12.2	0.9	-20.0	5.7	-62.4	-56.7	-107.4	2.7	0.1	8.2	5.5	125.4	1315	31
527	3.7	2.3	8.7	4.4	10.8	-0.3	-2.8	4.6	-61.1	-55.3	-105.4	1.6	-0.9	7.1	4.5	124.0	1316	101
421	0.8	0.2	4.3	1.4	5.8	-1.3	-18.5	1.5	-65.2	-61.6	-107.1	-0.5	-2.0	2.7	1.3	124.6	1050	31
421	0.5	-0.1	3.9	1.0	5.3	-1.6	-4.2	1.2	-58.8	-55.1	-104.7	-0.6	-2.1	2.5	0.3	122.3	1052	101
315	-2.1	-2.0	0.2	-1.6	0.9	-2.7	-10.5	-1.3	-67.5	-65.4	-106.5	-2.6	-3.3	-1.3	-1.8	123.7	786	31
316	-3.3	-3.2	-1.0	-2.8	-0.4	-4.0	-5.7	-2.6	-65.7	-63.7	-104.6	-3.7	-4.6	-2.5	-6.8	121.9	786	102

Applied TCC*

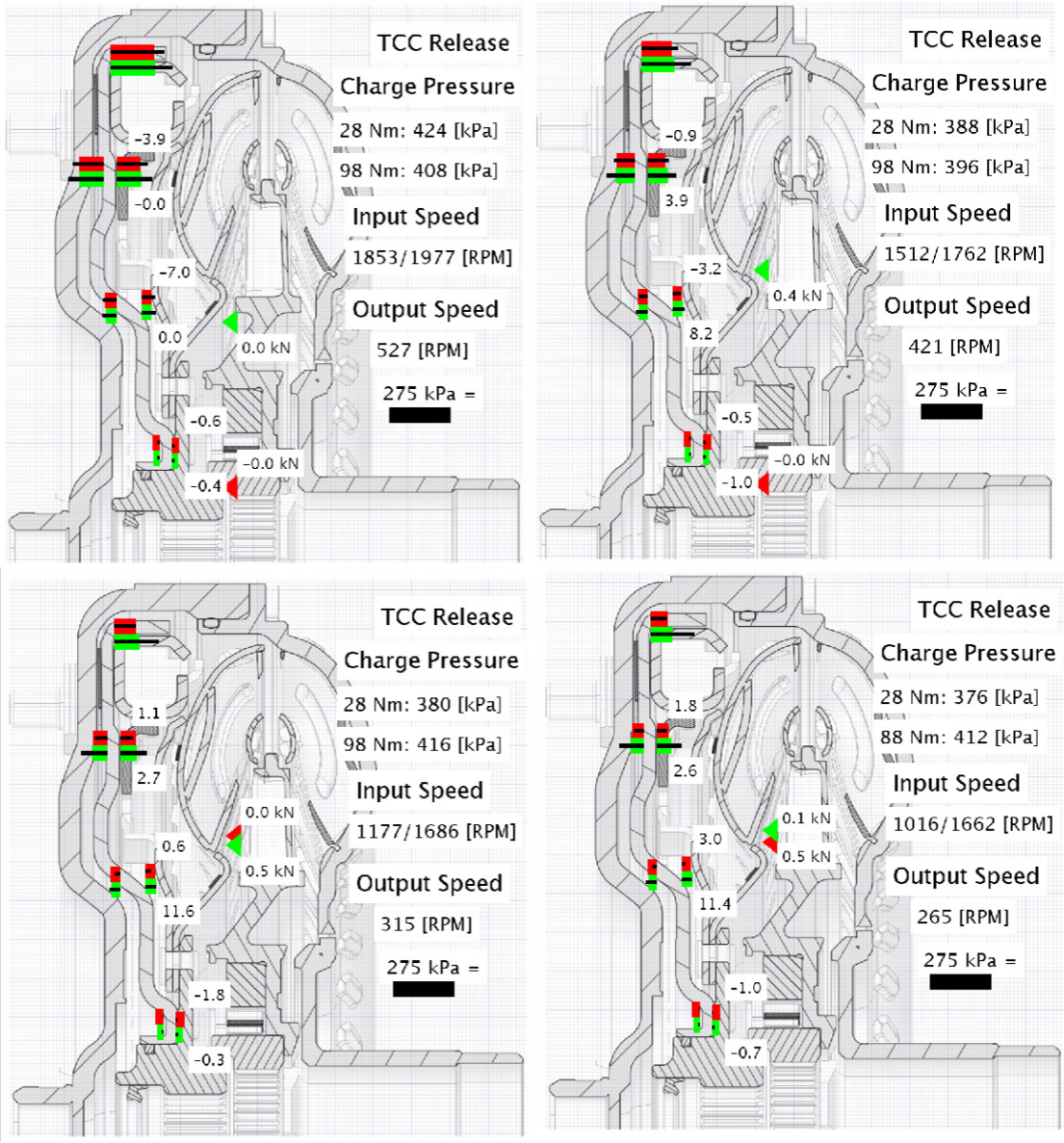
Output Speed [RPM]	Ch1 [PSI]	Ch2 [PSI]	Ch3 [PSI]	Ch4 [PSI]	Ch5 [PSI]	Ch6 [PSI]	Ch7 [PSI]	Ch8 [PSI]	Ch9 [PSI]	Ch10 [PSI]	Ch11 [PSI]	Ch12 [PSI]	Ch13 [PSI]	Ch14 [PSI]	Ch15 [PSI]	Charge Pressure [PSI]	Input Speed [RPM]	Input Torque [Nm]
527	14.3	11.9	18.6	15.2	21.2	9.6	6.2	15.1	4.1	9.8	0.9	12.0	9.3	18.2	15.6	15.5	1339	30
527	12.5	10.7	17.2	13.3	20.0	8.3	4.8	13.5	-13.8	-8.3	-21.0	10.3	8.2	16.6	14.0	37.7	1341	101
421	11.0	9.6	13.8	11.6	15.4	8.3	5.8	11.8	2.6	6.2	0.3	9.2	8.0	13.3	11.6	15.6	1071	30
421	9.0	7.9	12.2	9.7	13.8	6.5	4.3	9.8	-15.6	-12.1	-21.9	7.6	6.5	11.5	10.0	38.3	1075	101
315	8.6	7.8	10.4	9.0	11.2	7.2	5.8	9.1	2.0	4.0	0.6	7.6	7.2	10.0	10.4	15.1	823	30
316	6.6	6.2	8.6	7.2	9.4	5.6	4.2	7.2	-16.5	-13.9	-21.8	5.8	5.4	7.9	7.3	37.7	803	101

***(Pressure values are Sensor – Charge Pressure)**

www.manaraa.com

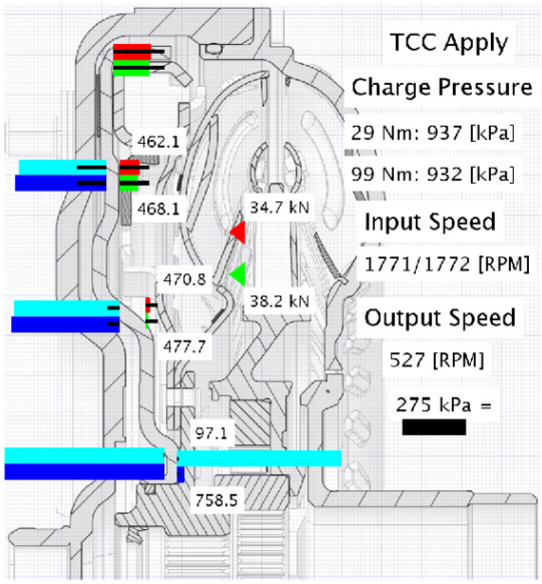
K.2 5th Gear TCC Pressure Graphics

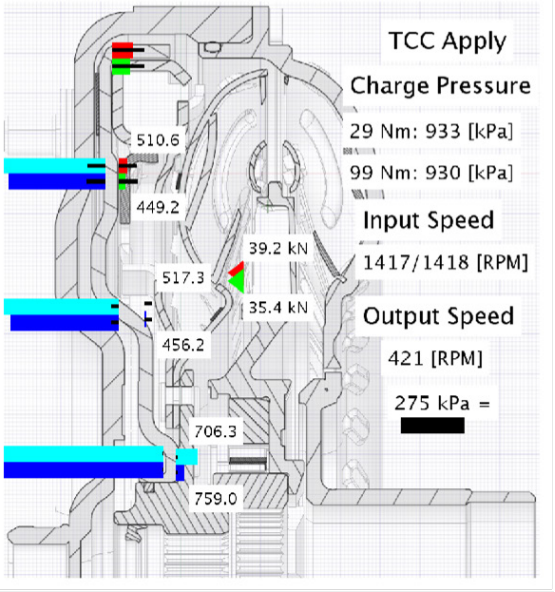
K.2.1 TCC Released

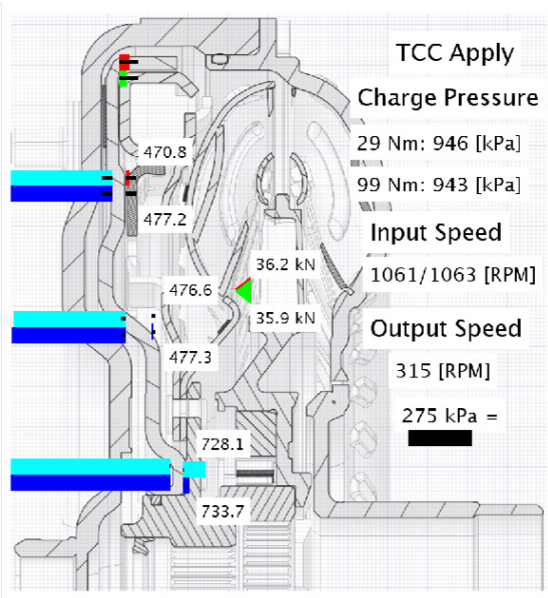


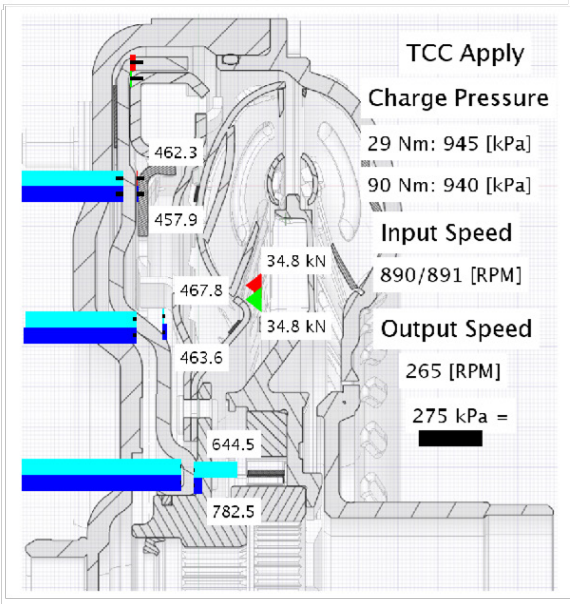
www.manaraa.com

K.2.2 TCC Applied



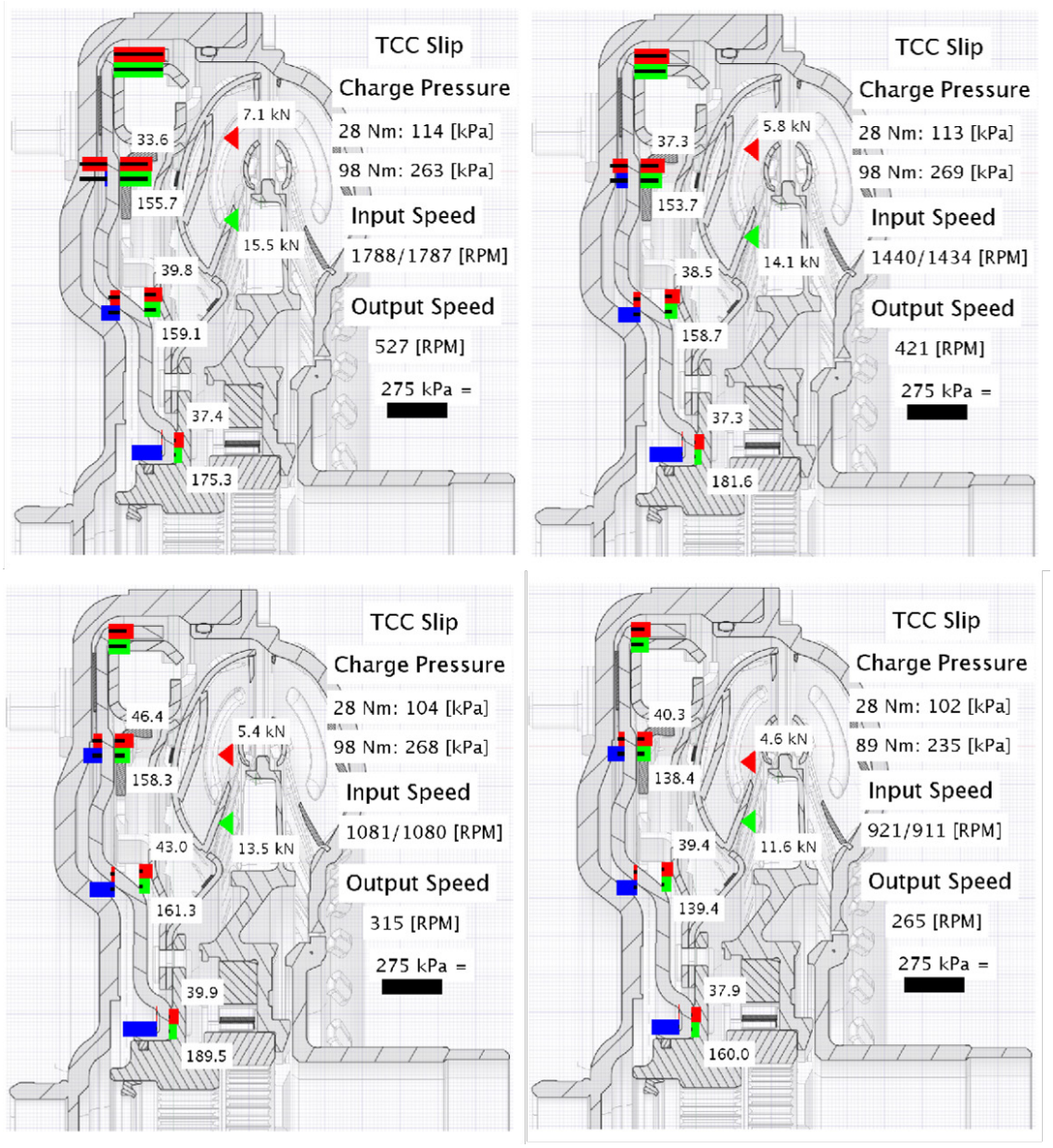






www.manaraa.com

K.2.3 TCC Slip



www.manaraa.com

K.3 Raw Data for 5th Gear

Released TCC*

Output Speed [RPM]	Ch1 [PSI]	Ch2 [PSI]	Ch3 [PSI]	Ch4 [PSI]	Ch5 [PSI]	Ch6 [PSI]	Ch7 [PSI]	Ch8 [PSI]	Ch9 [PSI]	Ch10 [PSI]	Ch11 [PSI]	Ch12 [PSI]	Ch13 [PSI]	Ch14 [PSI]	Ch15 [PSI]	Charge Pressure [PSI]	Input Speed [RPM]	Input Torque [Nm]
527	13.1	9.6	21.9	16.0	28.4	6.4	4.5	15.7	7.4	16.3	4.6	8.4	6.0	19.9	17.2	61.5	1853	28
527	9.7	5.5	19.1	16.4	29.0	7.0	3.8	16.3	7.0	16.3	3.9	1.6	5.9	11.9	19.8	59.2	1977	98
421	9.1	6.9	15.0	11.6	19.6	5.8	4.6	11.7	6.3	11.9	4.7	5.8	5.4	12.9	12.6	56.2	1512	28
421	6.9	3.9	13.3	12.8	21.6	6.9	3.8	13.0	5.7	12.4	3.9	0.0	6.3	3.9	17.3	57.4	1762	98
315	7.4	6.3	11.0	9.6	14.3	6.5	5.5	9.9	6.4	9.7	5.8	5.2	6.1	8.8	10.7	55.2	1177	28
315	2.4	2.2	6.9	10.8	16.7	7.4	4.2	10.7	5.7	10.3	4.3	-2.5	6.8	-4.3	17.3	60.3	1686	98
265	6.1	5.3	8.8	8.0	11.4	5.9	5.2	8.2	5.5	7.9	5.3	4.1	5.5	6.4	9.0	54.6	1016	28
265	0.5	1.3	4.2	9.6	14.6	7.0	4.5	9.5	5.4	9.1	4.6	-3.1	7.0	-7.3	16.3	59.8	1662	88

Slip TCC*

Output Speed [RPM]	Ch1 [PSI]	Ch2 [PSI]	Ch3 [PSI]	Ch4 [PSI]	Ch5 [PSI]	Ch6 [PSI]	Ch7 [PSI]	Ch8 [PSI]	Ch9 [PSI]	Ch10 [PSI]	Ch11 [PSI]	Ch12 [PSI]	Ch13 [PSI]	Ch14 [PSI]	Ch15 [PSI]	Charge Pressure [PSI]	Input Speed [RPM]	Input Torque [Nm]
527	21.0	17.2	28.5	22.0	33.7	12.0	6.2	21.6	6.2	16.7	0.8	16.9	11.8	28.8	22.5	16.5	1788	28
527	19.6	15.8	27.7	20.4	32.2	10.9	5.1	20.6	-12.2	-2.0	-20.3	15.6	10.9	27.0	21.3	38.2	1787	98
421	15.0	12.6	20.5	15.9	23.1	9.8	5.9	15.8	4.3	10.4	0.5	12.2	9.9	19.6	16.4	16.4	1440	28
421	13.6	11.3	18.8	14.3	21.8	8.4	4.5	14.4	-14.6	-7.8	-21.9	11.1	8.3	18.2	14.9	39.0	1434	98
315	12.4	10.2	14.4	12.2	16.5	8.6	6.2	12.9	2.4	6.1	0.4	10.3	8.5	15.0	12.2	15.1	1081	28
315	9.7	8.6	12.7	10.2	14.3	7.0	4.7	10.4	-16.4	-12.6	-22.8	8.4	6.9	12.3	10.7	38.9	1080	98
265	9.5	8.7	11.9	10.1	12.7	7.9	6.1	10.4	2.2	4.5	0.6	8.8	7.7	11.8	10.7	14.8	921	28
265	8.4	7.7	10.5	8.8	11.7	6.6	4.9	8.8	-13.6	-11.3	-18.3	7.5	6.5	10.3	9.2	34.1	911	89

Applied TCC*

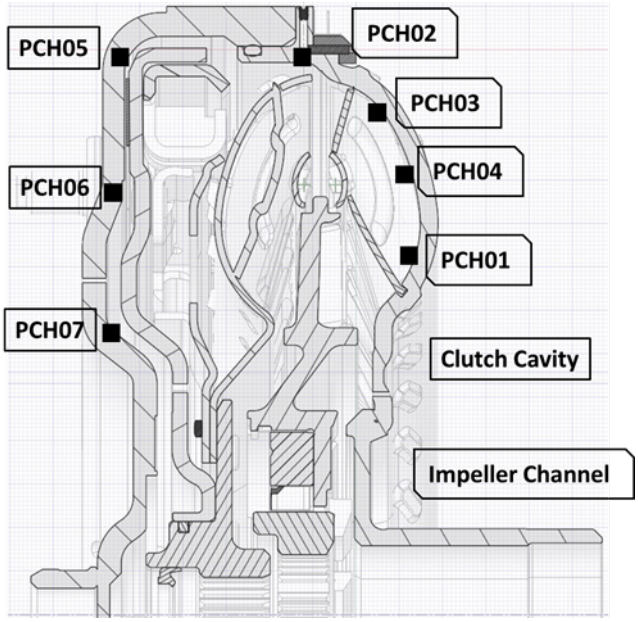
Output Speed [RPM]	Ch1 [PSI]	Ch2 [PSI]	Ch3 [PSI]	Ch4 [PSI]	Ch5 [PSI]	Ch6 [PSI]	Ch7 [PSI]	Ch8 [PSI]	Ch9 [PSI]	Ch10 [PSI]	Ch11 [PSI]	Ch12 [PSI]	Ch13 [PSI]	Ch14 [PSI]	Ch15 [PSI]	Charge Pressure [PSI]	Input Speed [RPM]	Input Torque [Nm]
527	11.0	7.8	19.3	12.0	24.1	3.1	-101.8	12.3	-65.2	-54.7	-115.9	7.5	2.6	18.1	12.8	135.9	1771	29
527	9.9	6.7	18.1	10.8	22.7	2.0	-4.4	11.1	-67.3	-56.8	-114.4	6.4	1.6	17.0	11.7	135.1	1772	99
421	4.0	2.4	9.8	4.9	12.6	-0.4	-13.2	5.3	-75.4	-68.7	-115.6	2.2	-0.7	8.7	5.6	135.3	1417	29
421	3.3	1.7	9.1	4.2	11.0	-1.0	-5.3	4.6	-67.2	-60.6	-115.4	1.6	-1.3	8.0	4.9	134.9	1418	99
315	1.6	1.2	5.3	2.4	6.8	-0.1	-14.1	2.8	-69.2	-65.5	-119.7	0.9	-0.7	4.0	2.9	137.2	1061	29
315	0.1	-0.1	3.6	0.8	5.0	-1.7	-4.0	0.0	-71.0	-69.3	-110.4	0.0	-2.2	3.2	1.1	136.8	1063	99
265	-0.4	-0.3	2.5	0.4	3.7	-1.1	-26.6	0.8	-68.9	-66.3	-120.1	-0.6	-1.6	1.4	0.8	137.0	890	29
265	-2.4	-2.4	0.5	-1.7	1.4	-3.1	-5.2	-1.3	-70.4	-67.7	-118.7	-2.6	-3.5	-0.7	-1.3	136.4	891	90

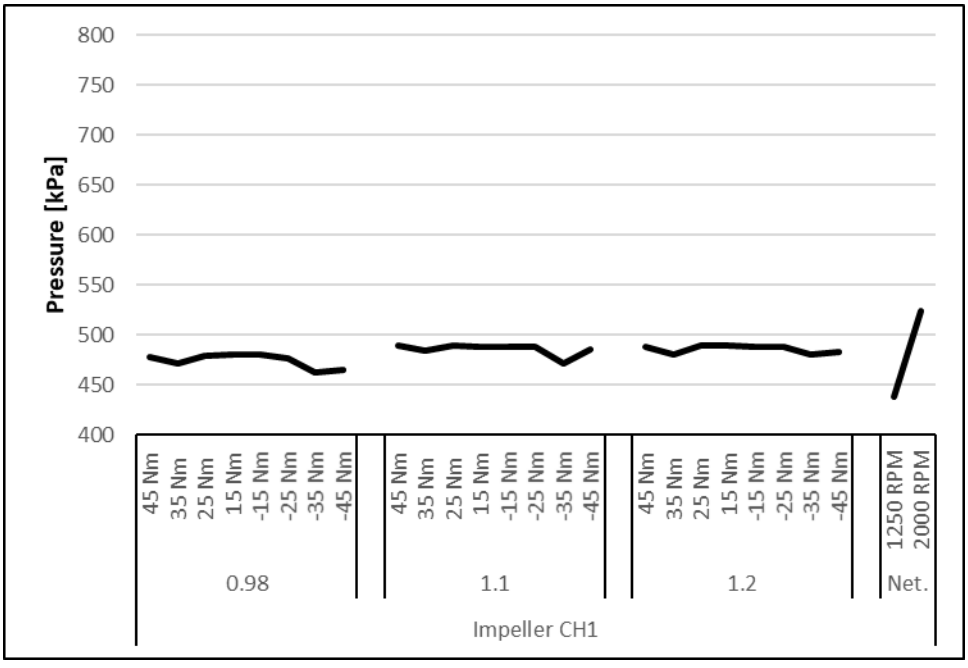
***(Pressure values are Sensor – Charge Pressure)**

www.manaraa.com

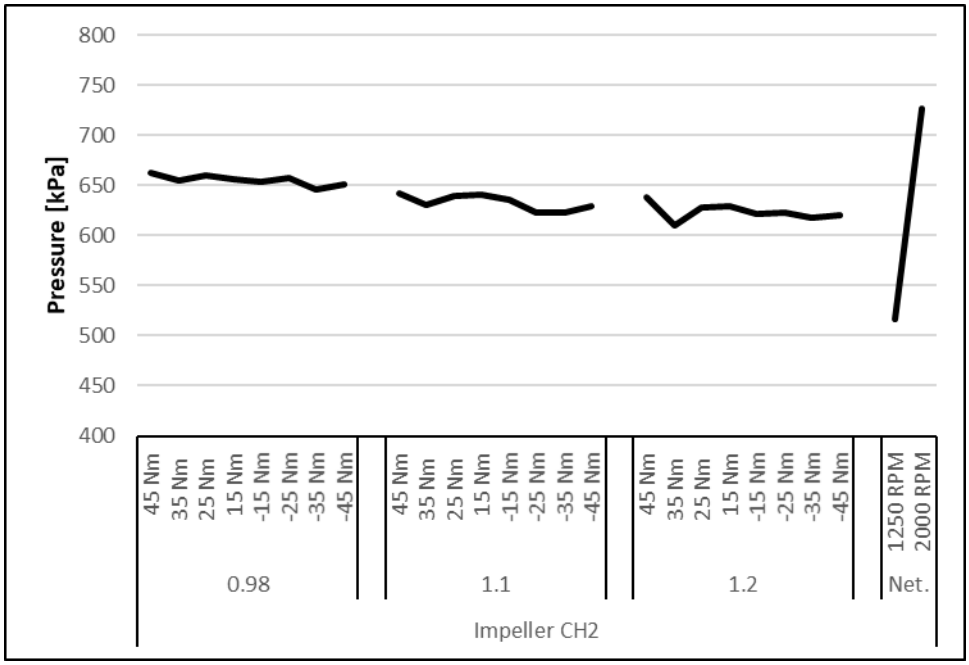
L Back Drive Pressure Results

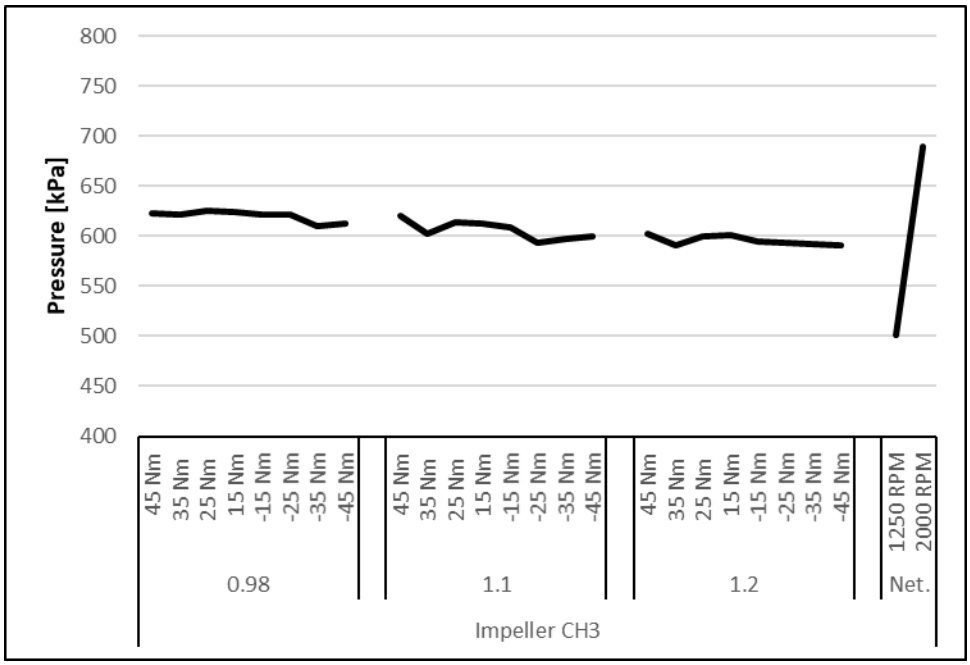
L.1 Impeller Results



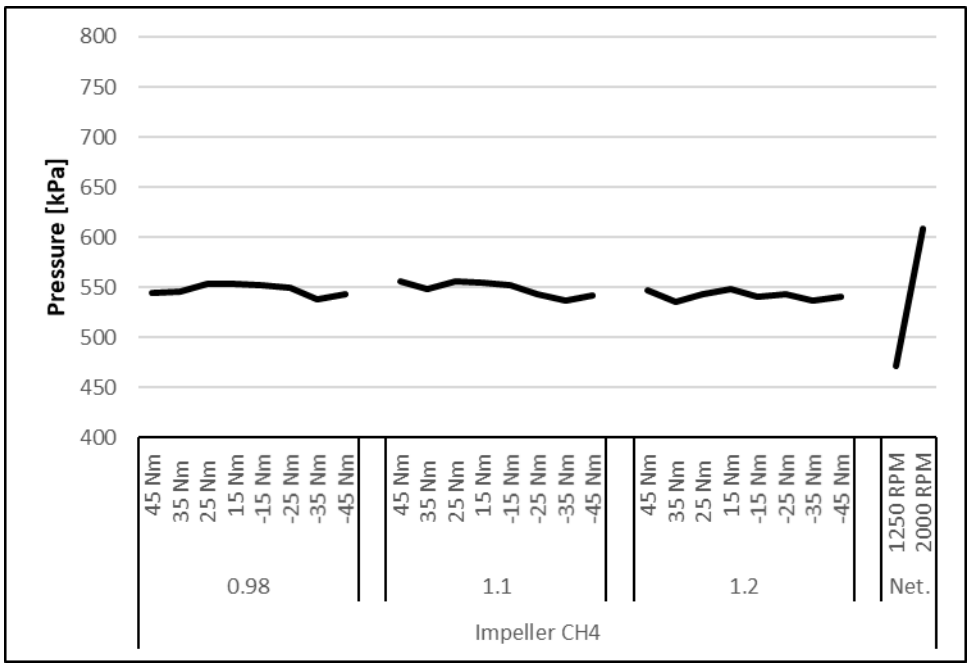


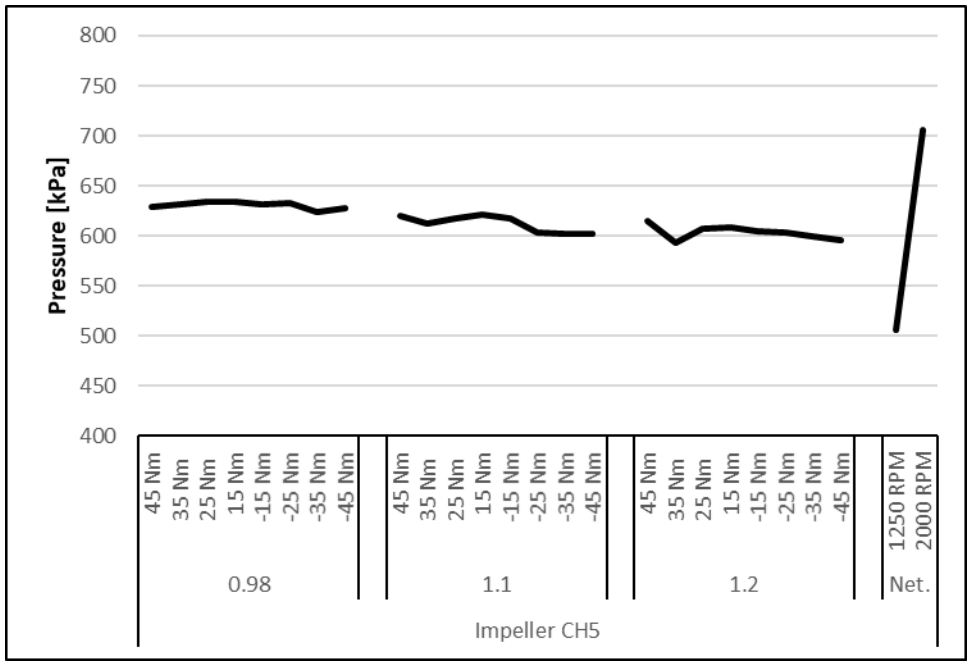
www.manaraa.com



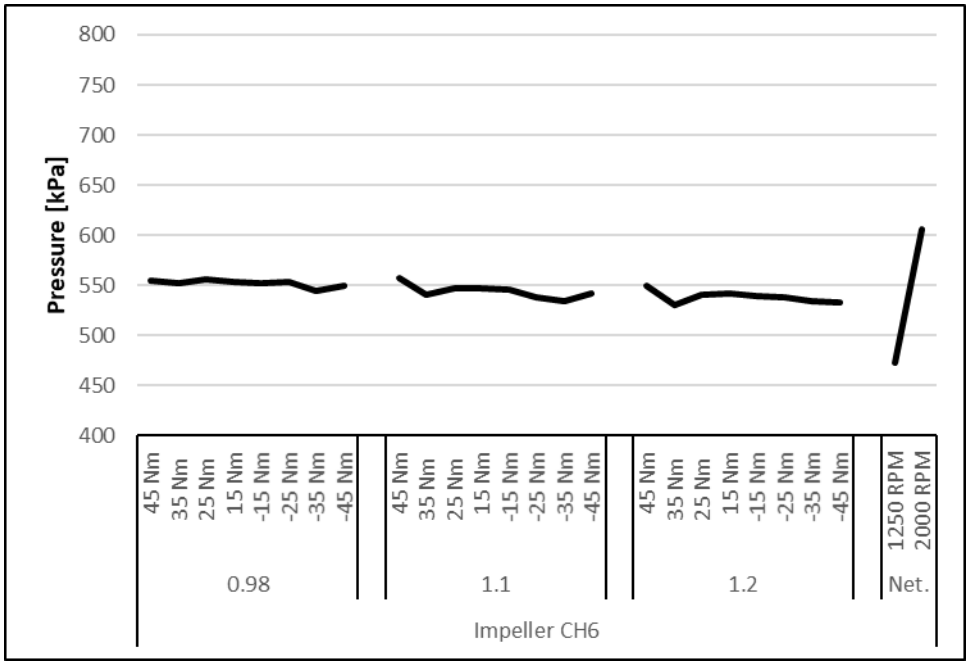


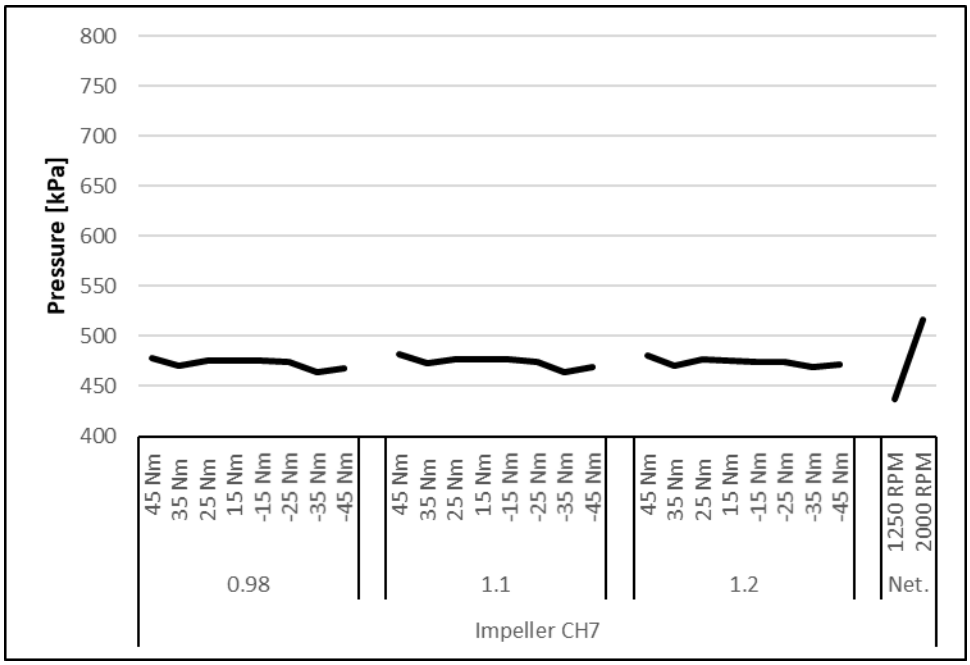
www.manaraa.com





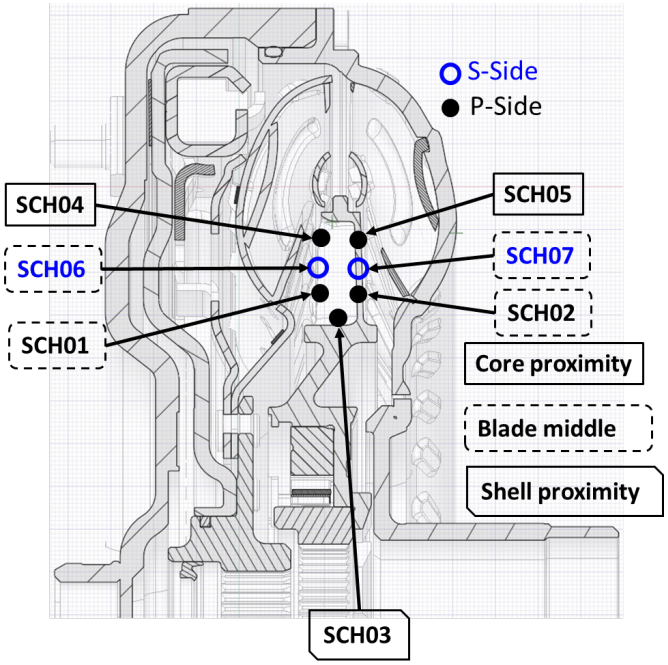
www.manaraa.com

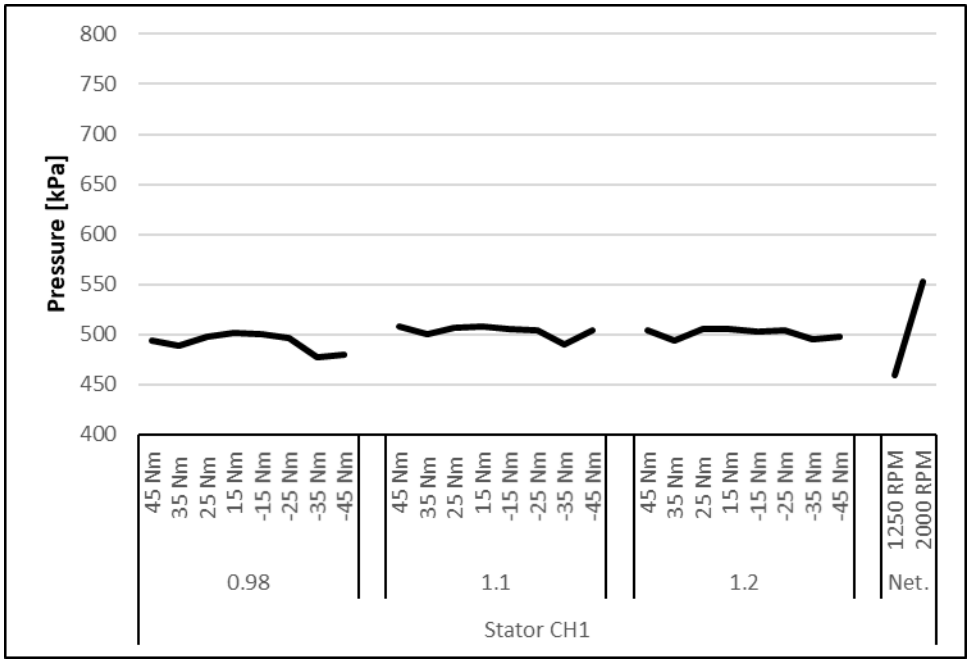




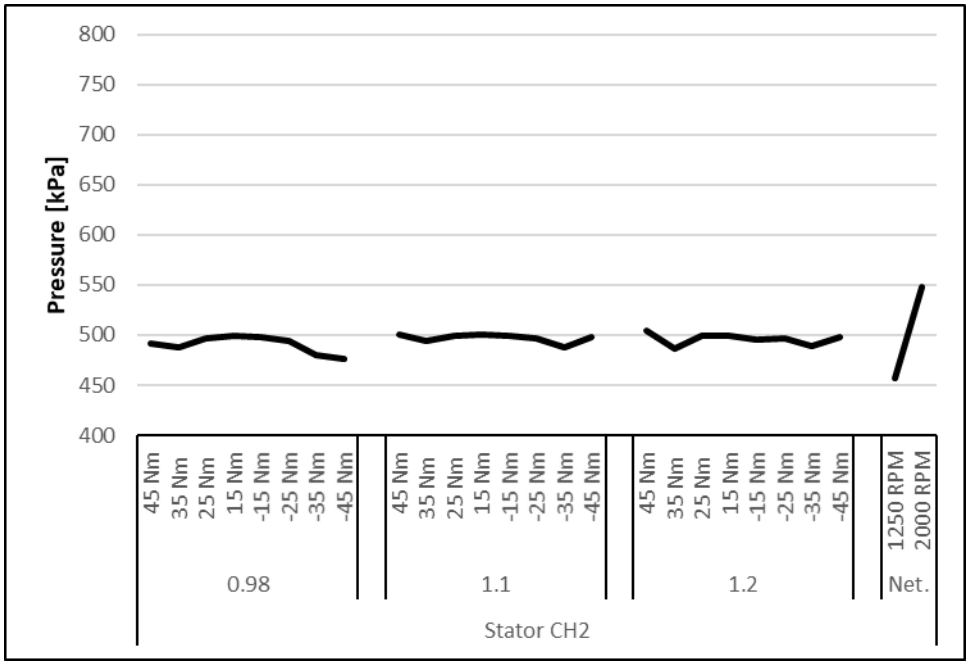
www.manaraa.com

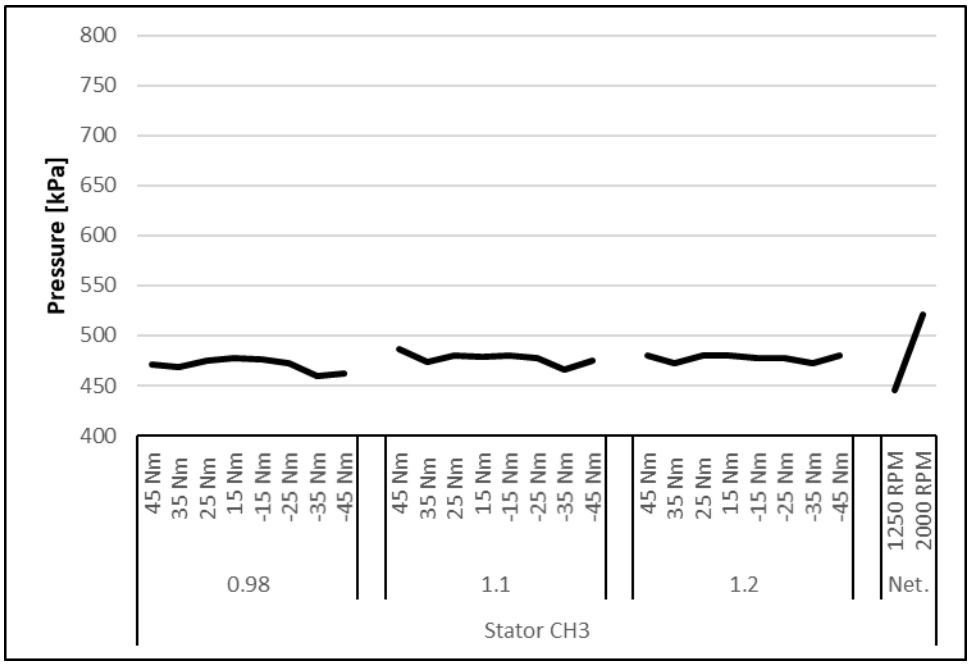
L.2 Stator Results



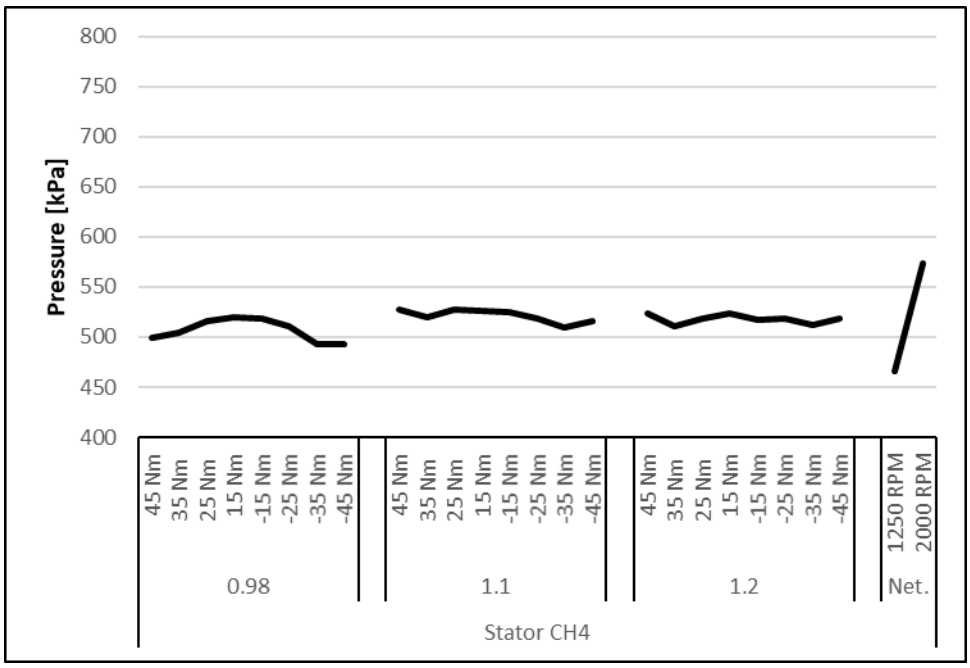


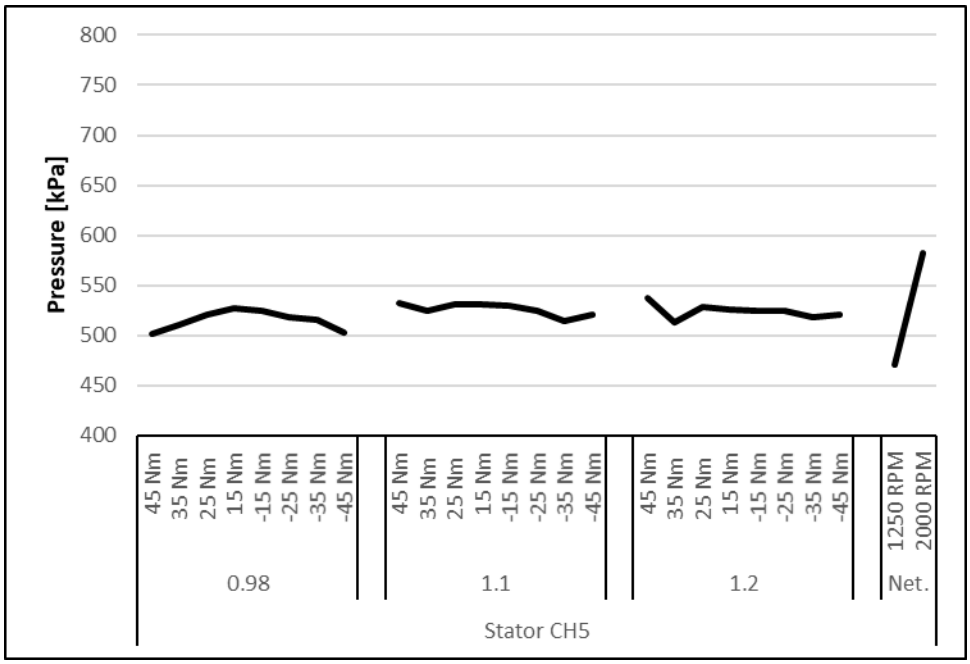
www.manaraa.com



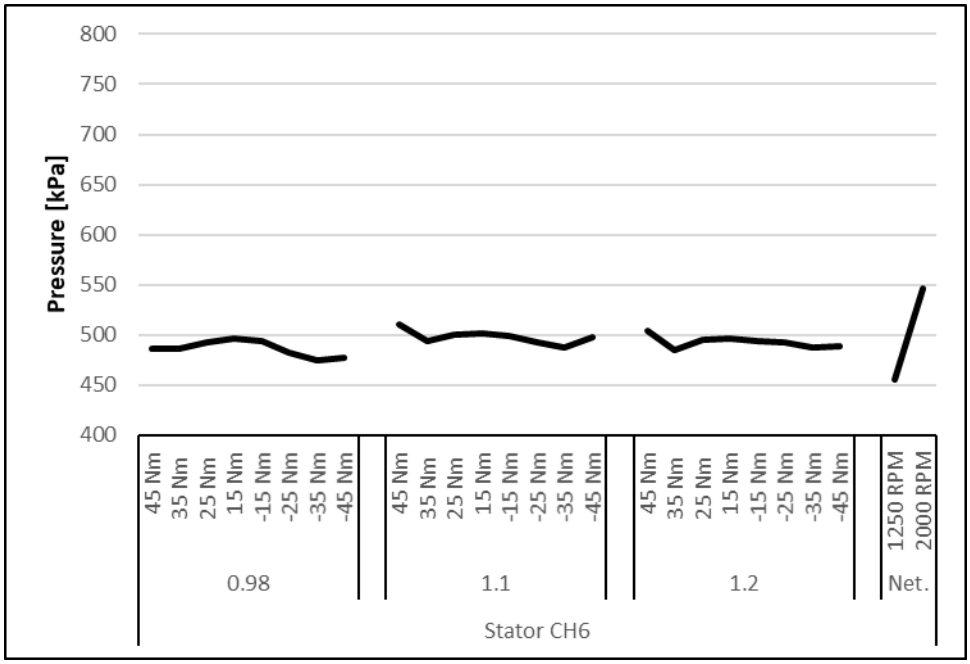


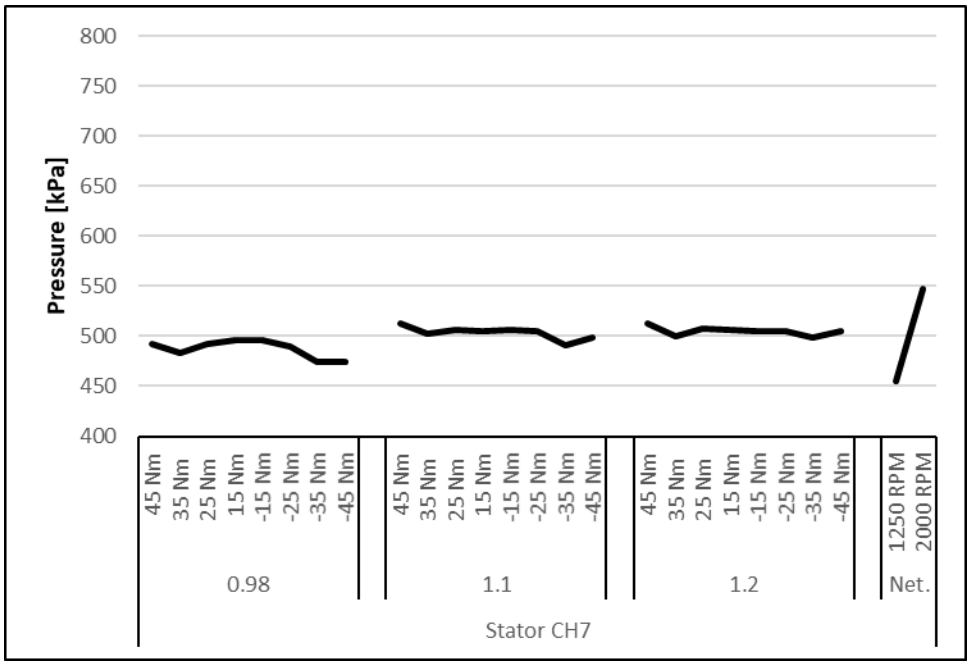
www.manaraa.com





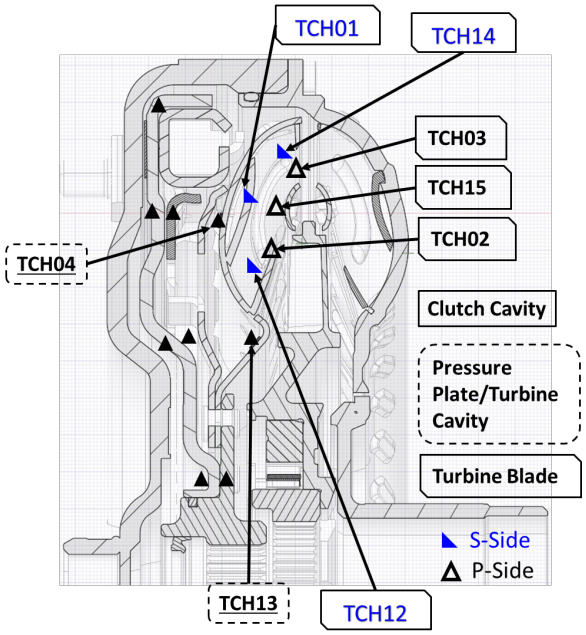
www.manaraa.com

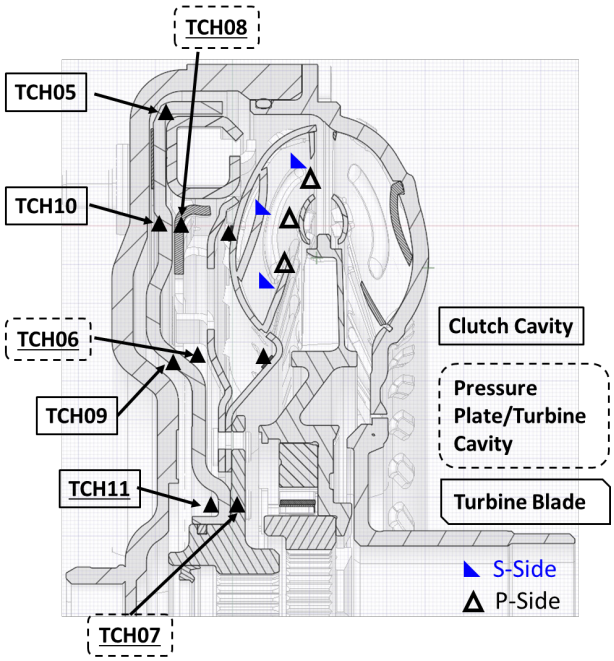




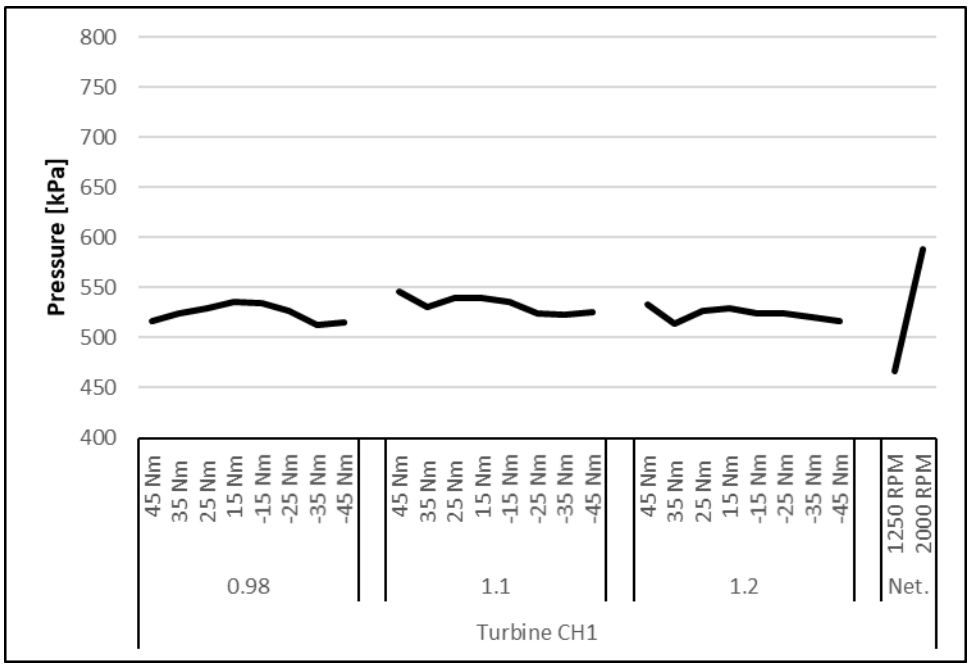
www.manaraa.com

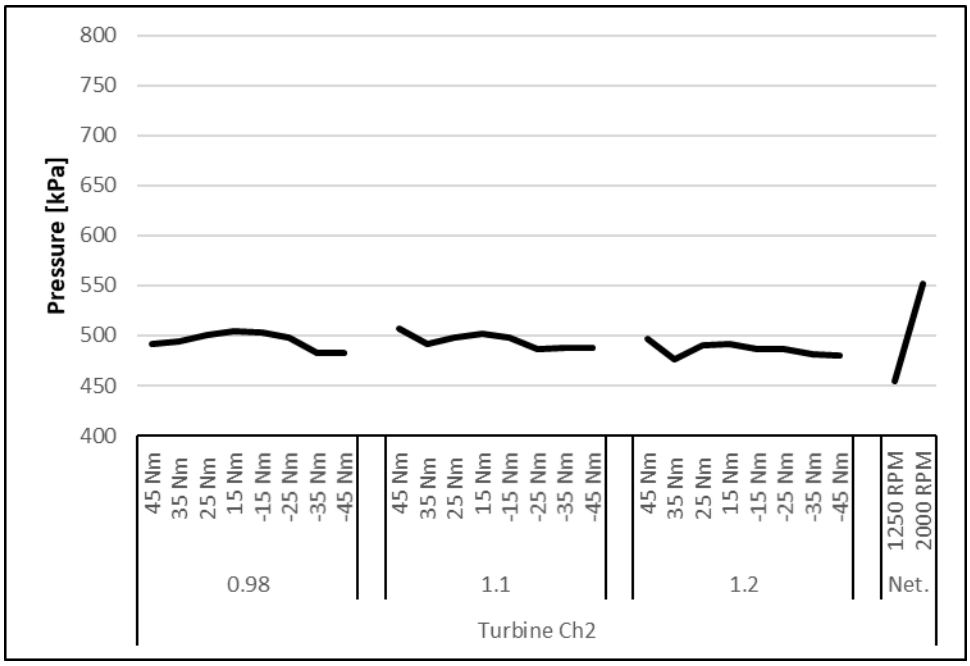
L.3 Turbine Results



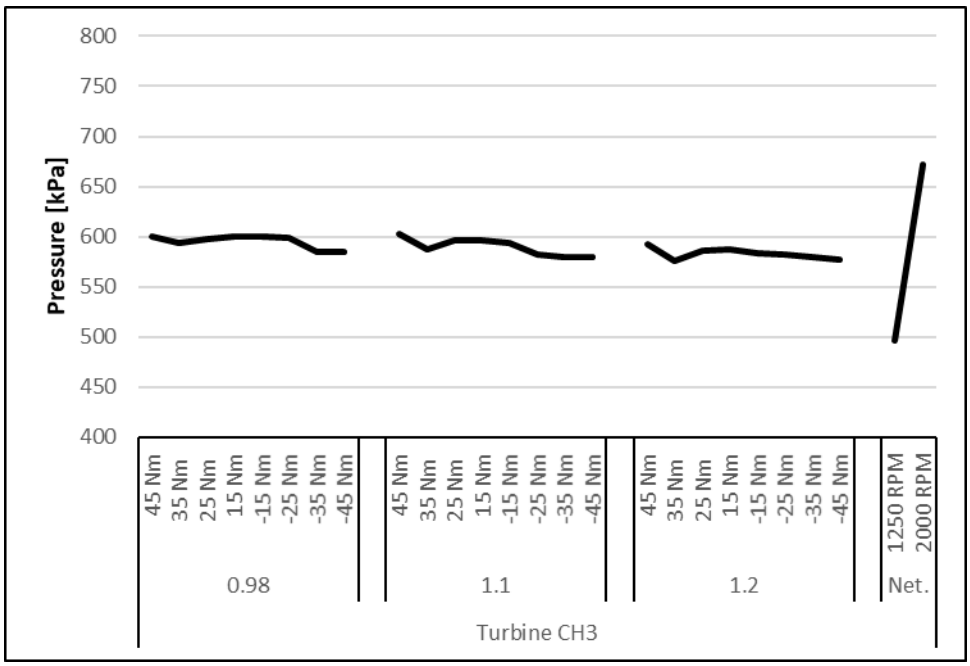


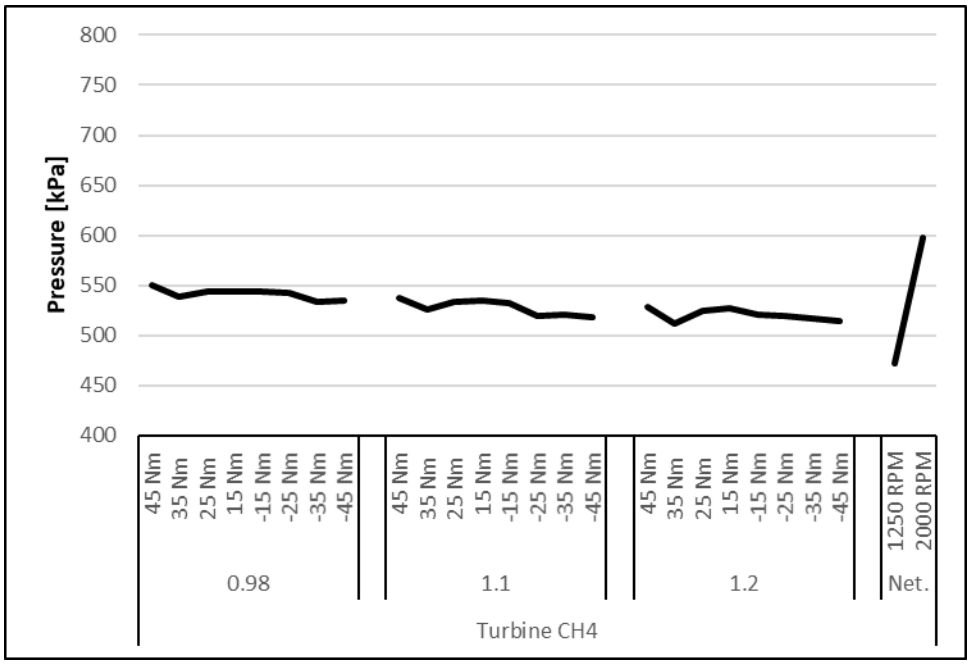
www.manaraa.com



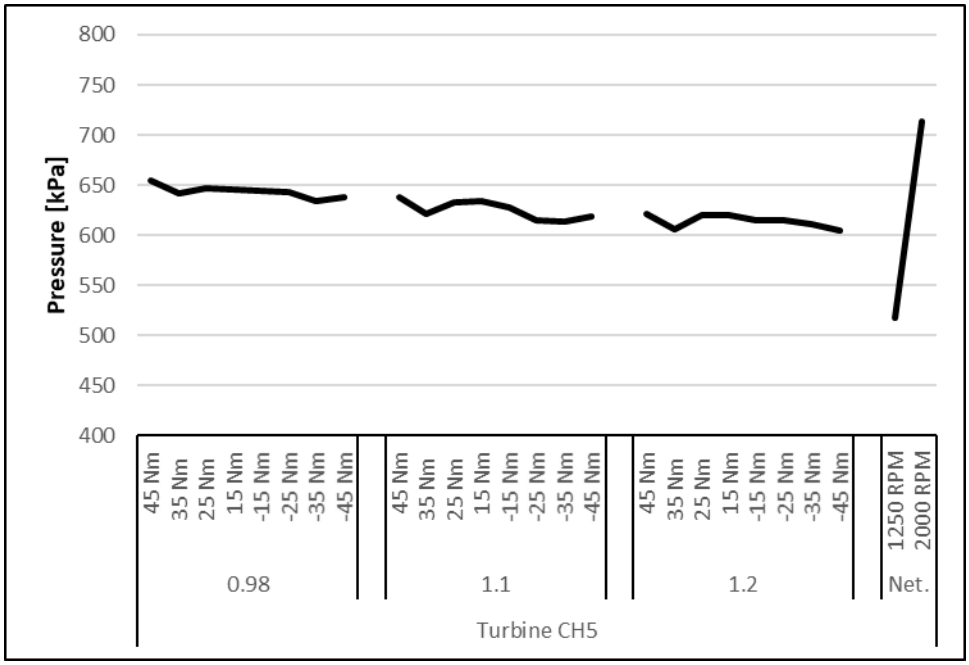


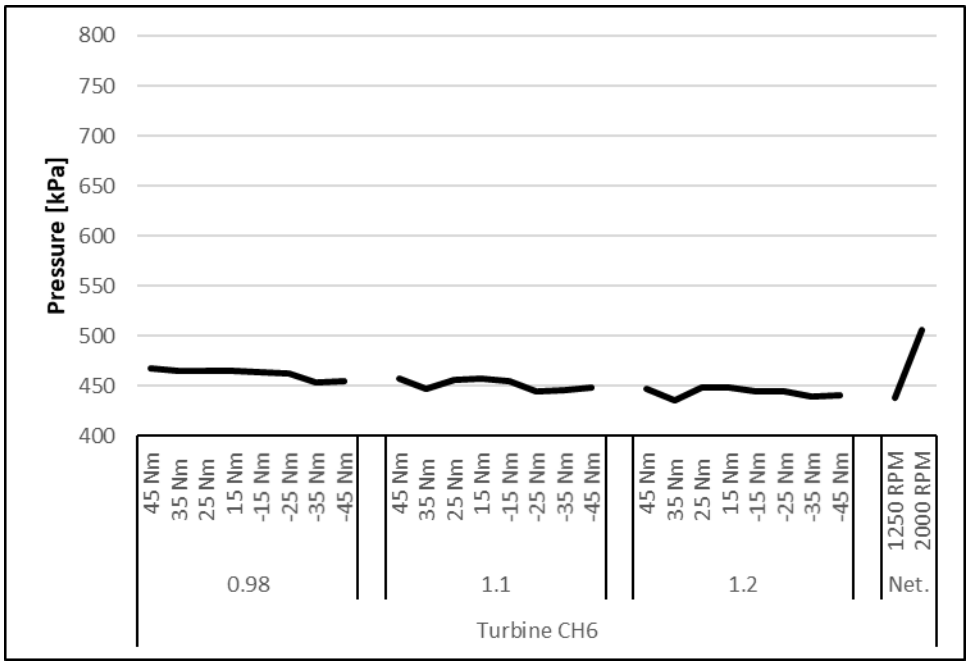
www.manaraa.com



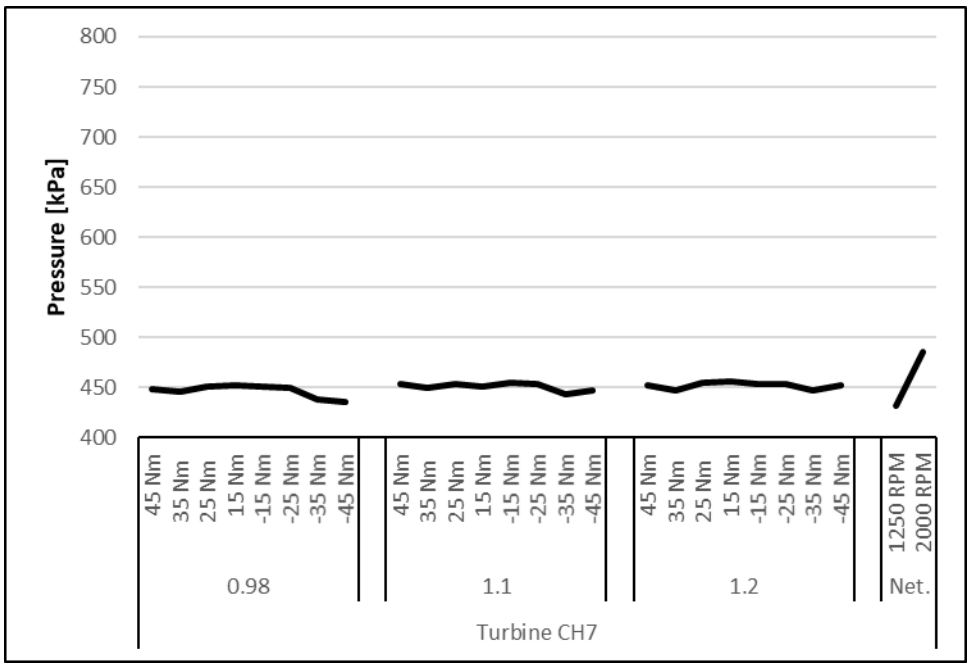


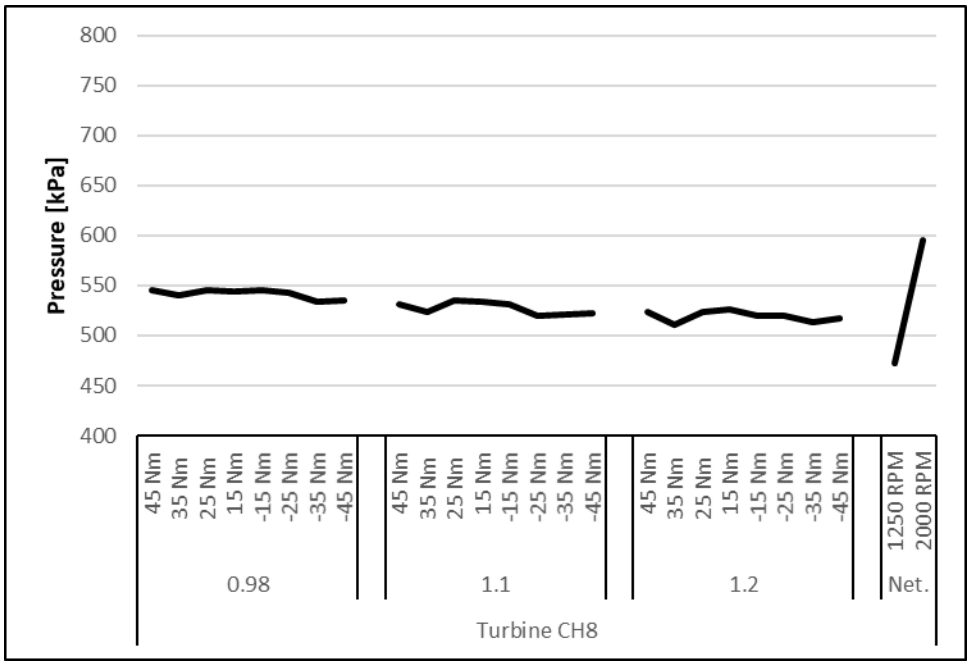
www.manaraa.com



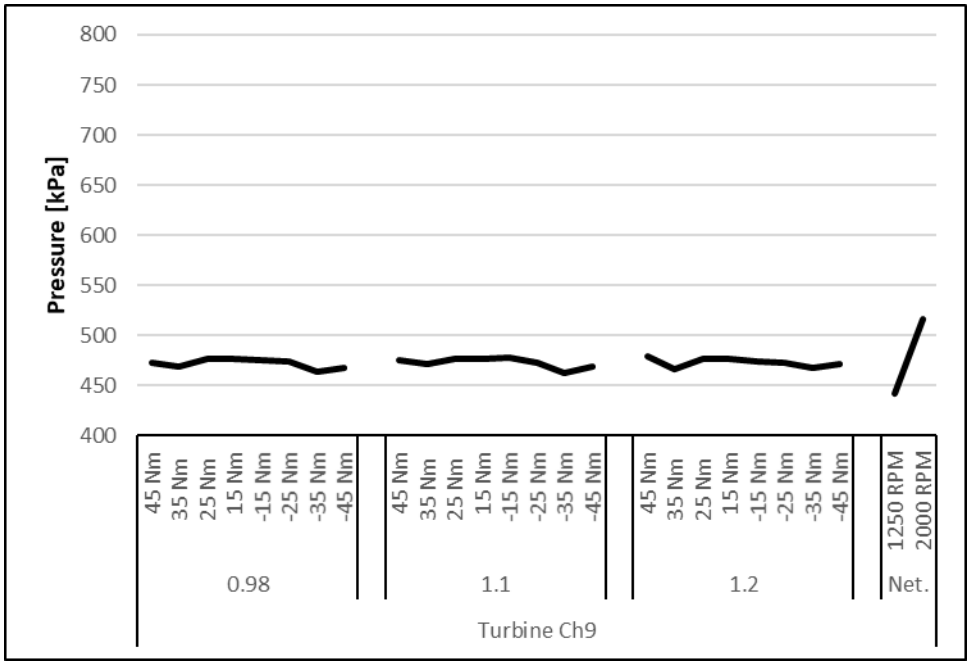


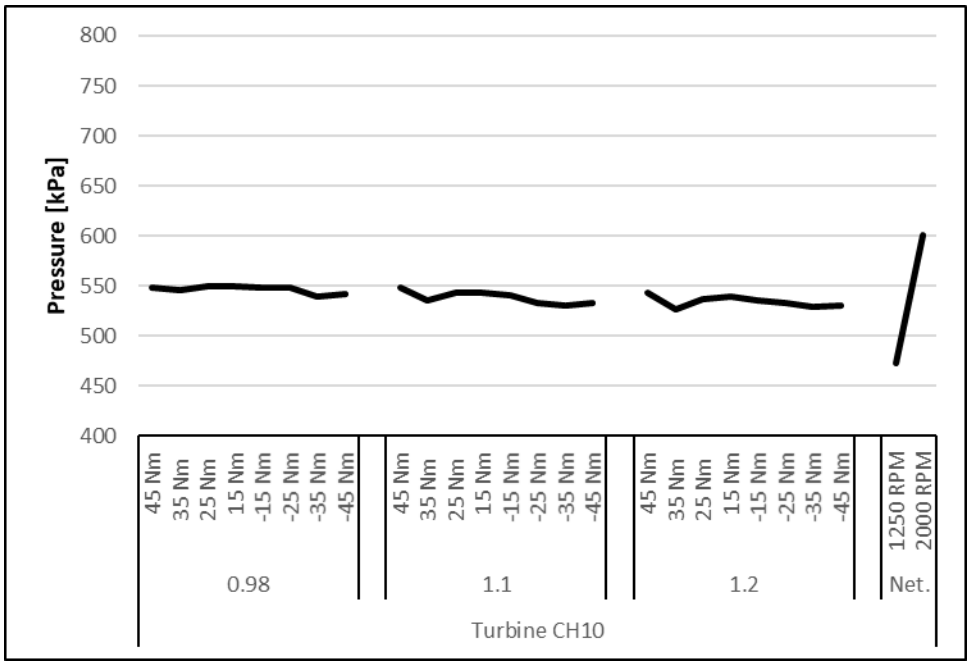
www.manaraa.com



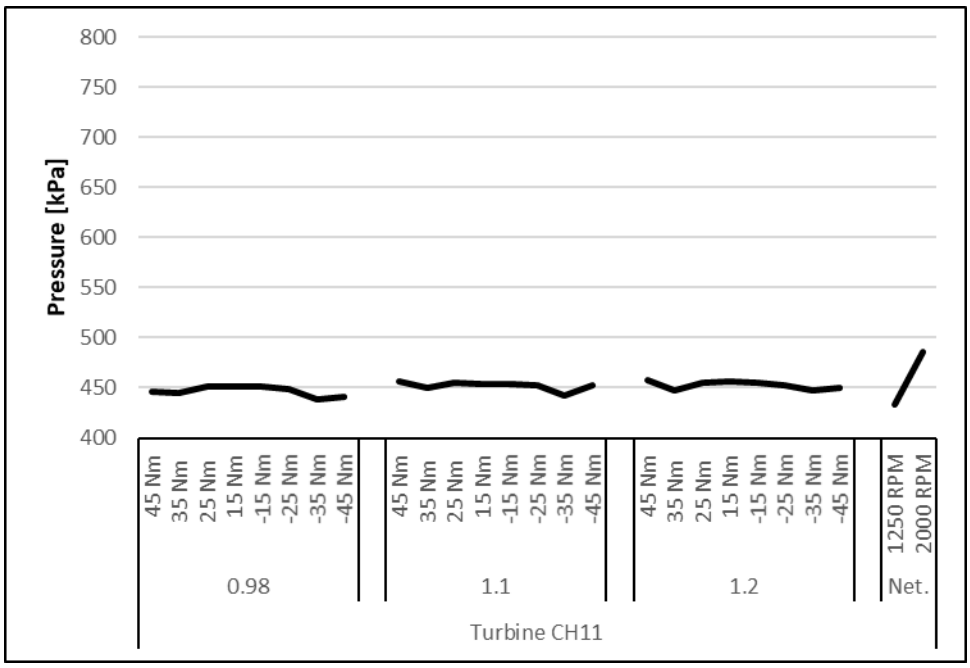


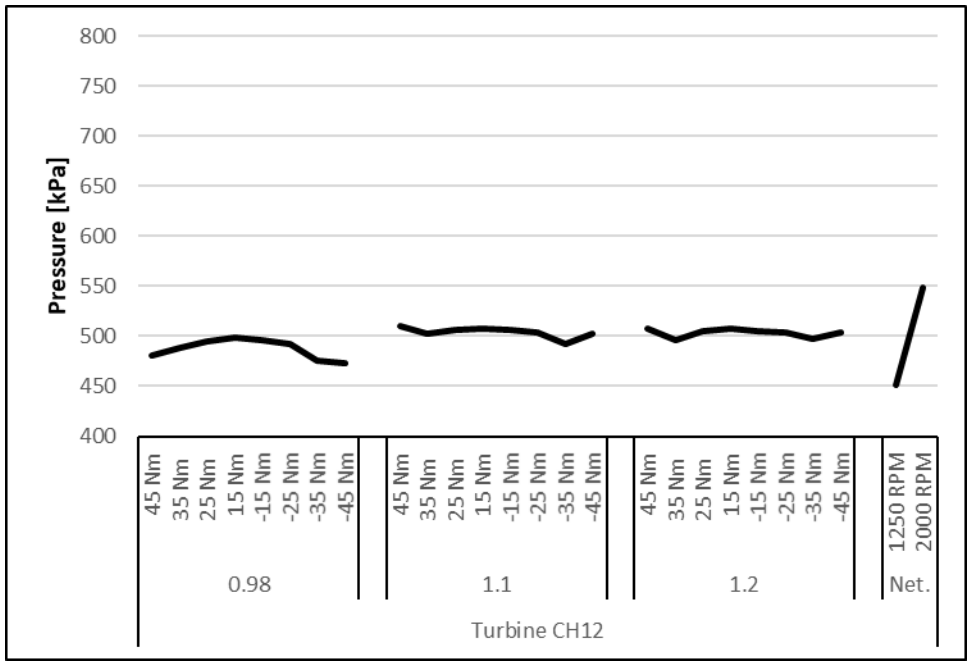
www.manaraa.com



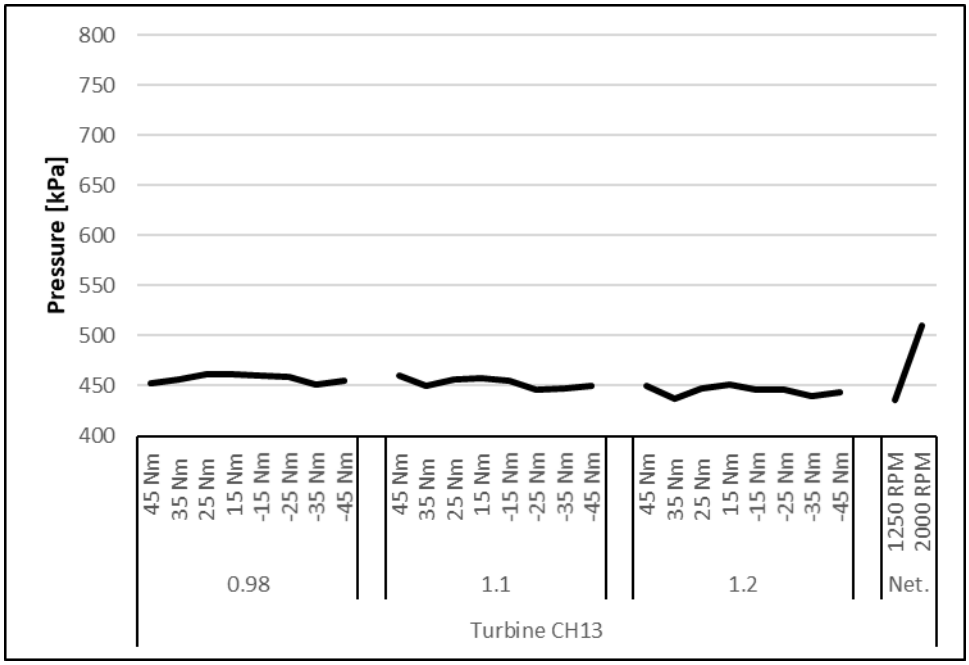


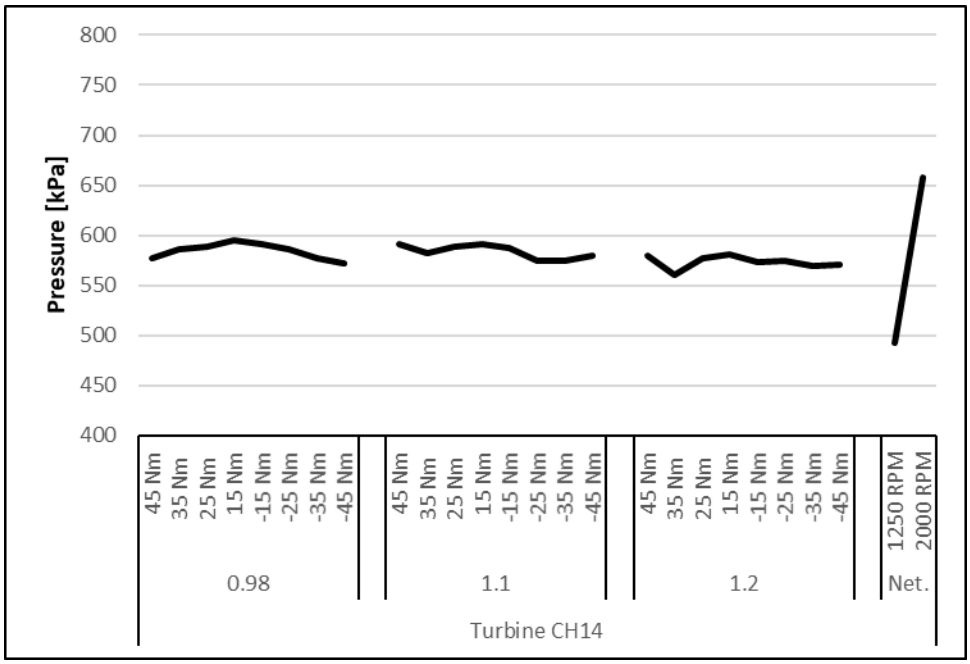
www.manaraa.com



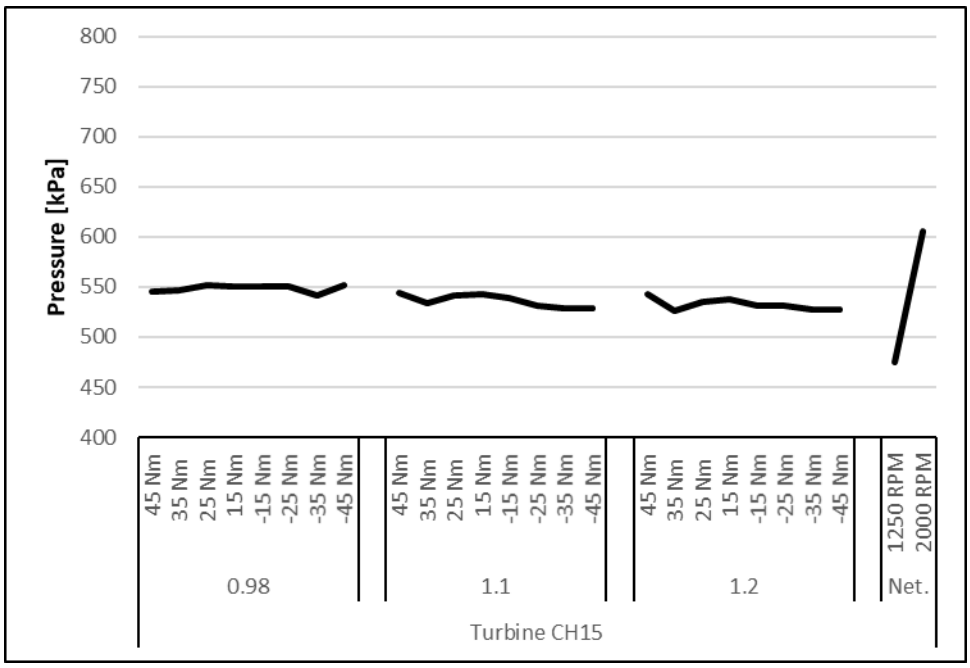


www.manaraa.com





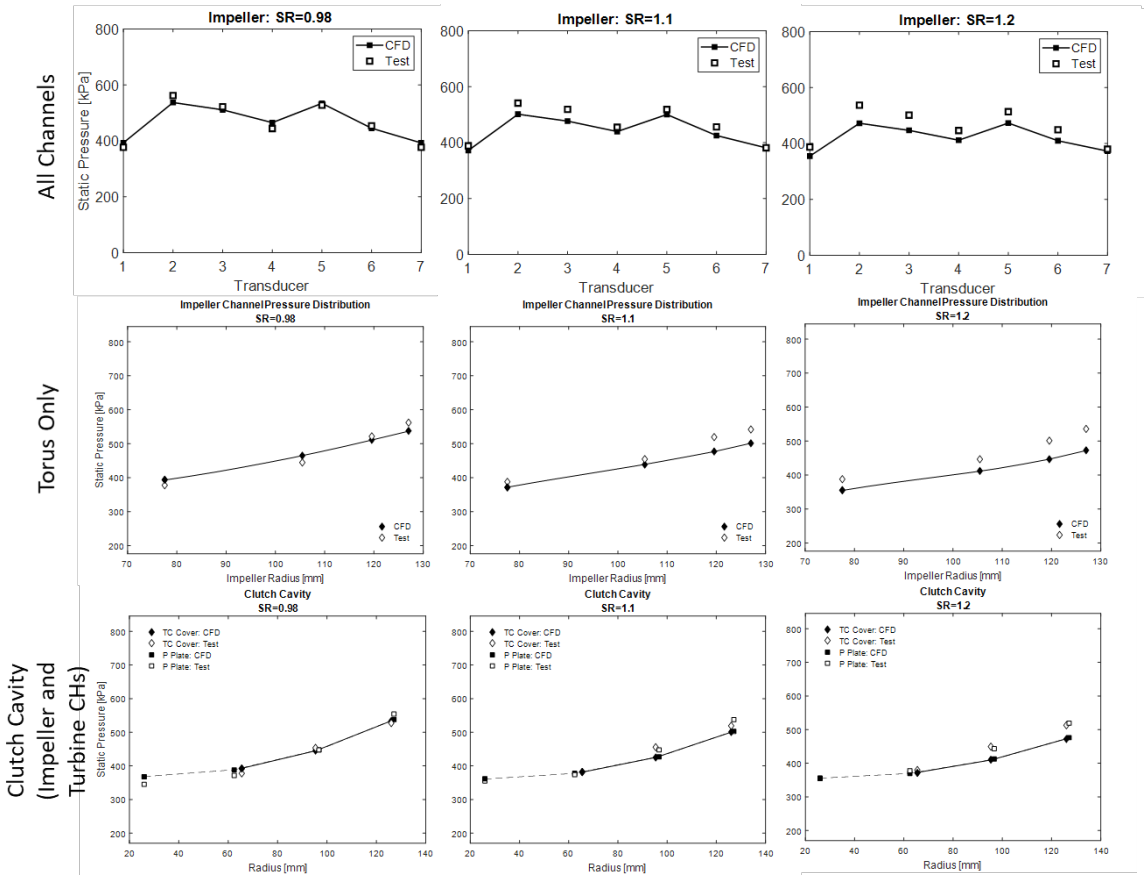
www.manaraa.com



www.manaraa.com

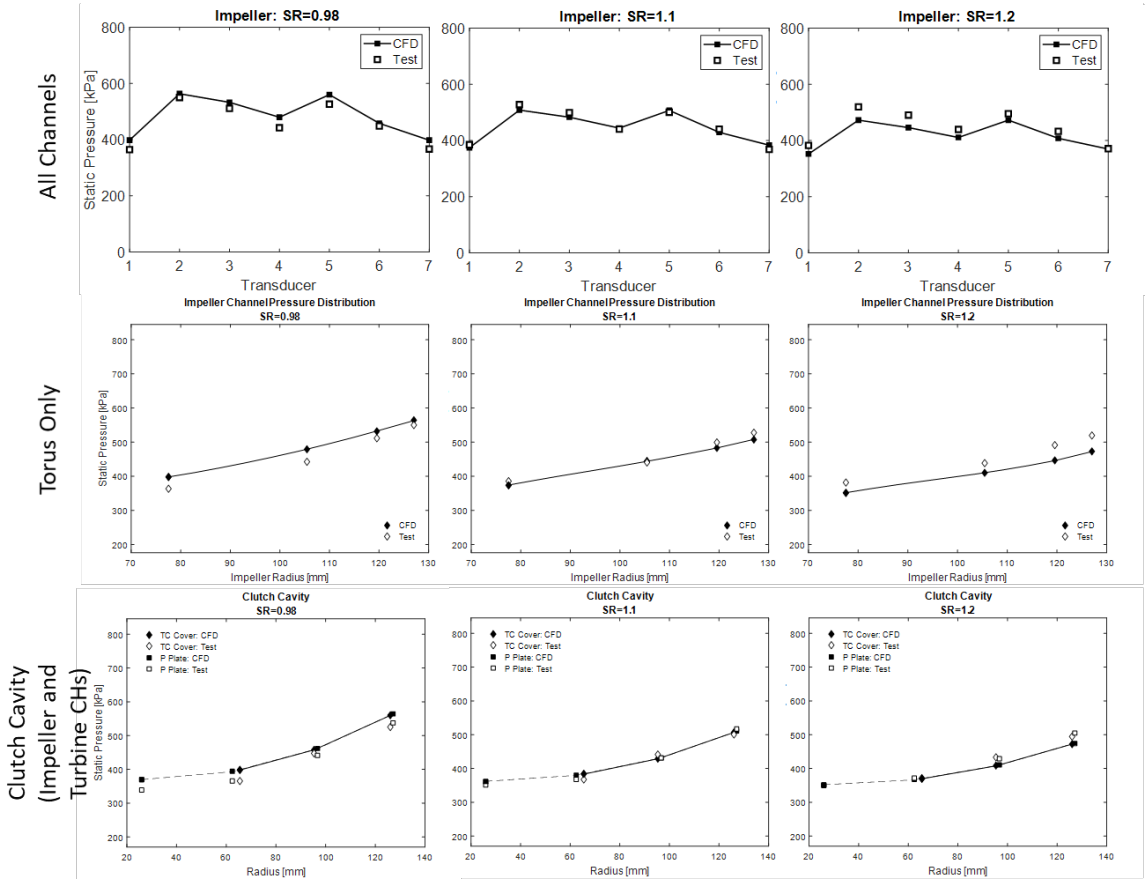
M Back Drive CFD Comparison

M.1 Impeller +45 Nm CFD Comparison



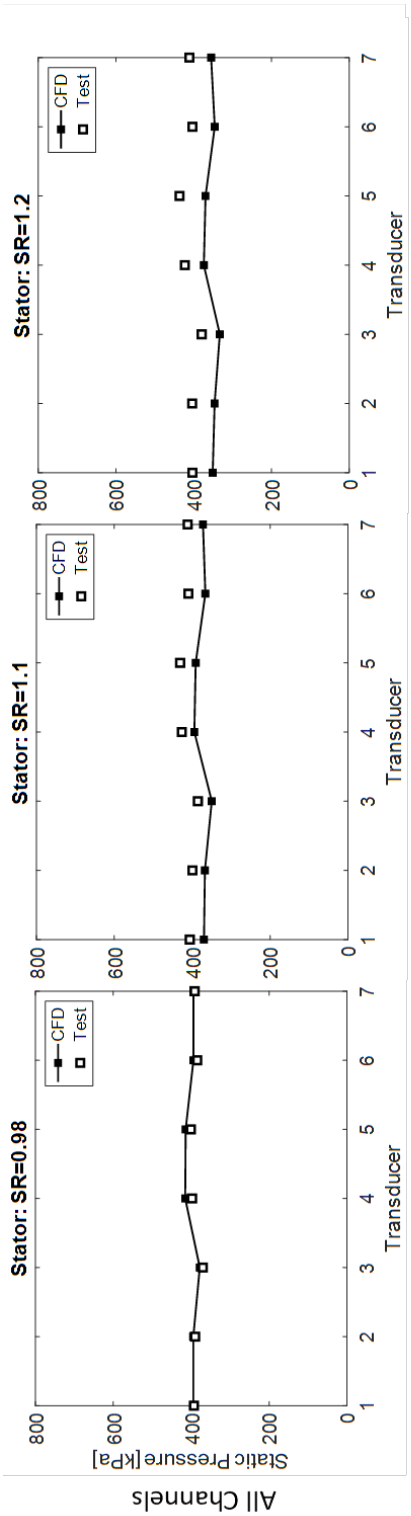
www.manaraa.com

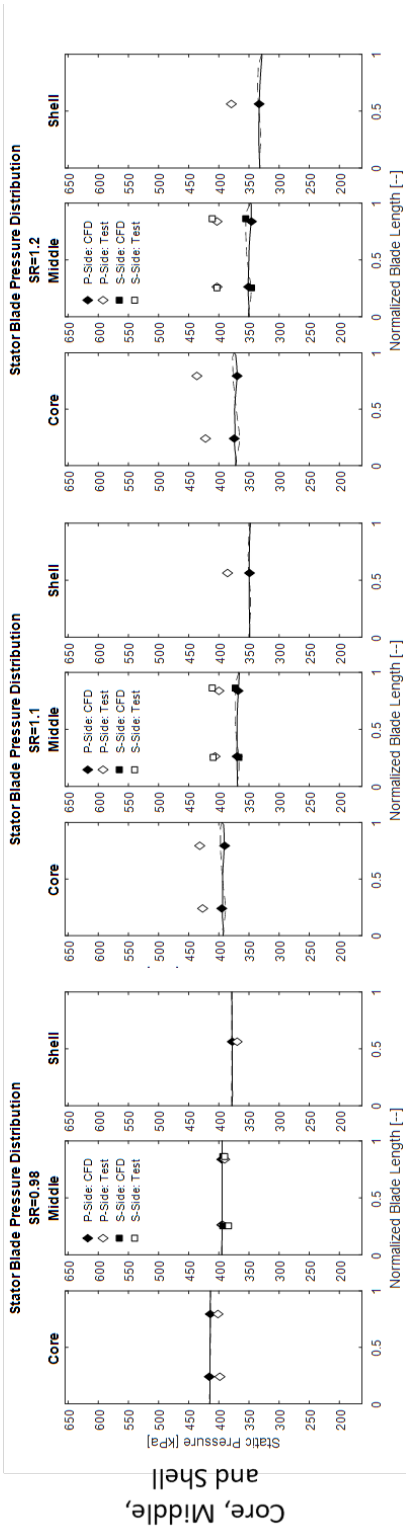
M.2 Impeller -45 Nm CFD Comparison



www.manaraa.com

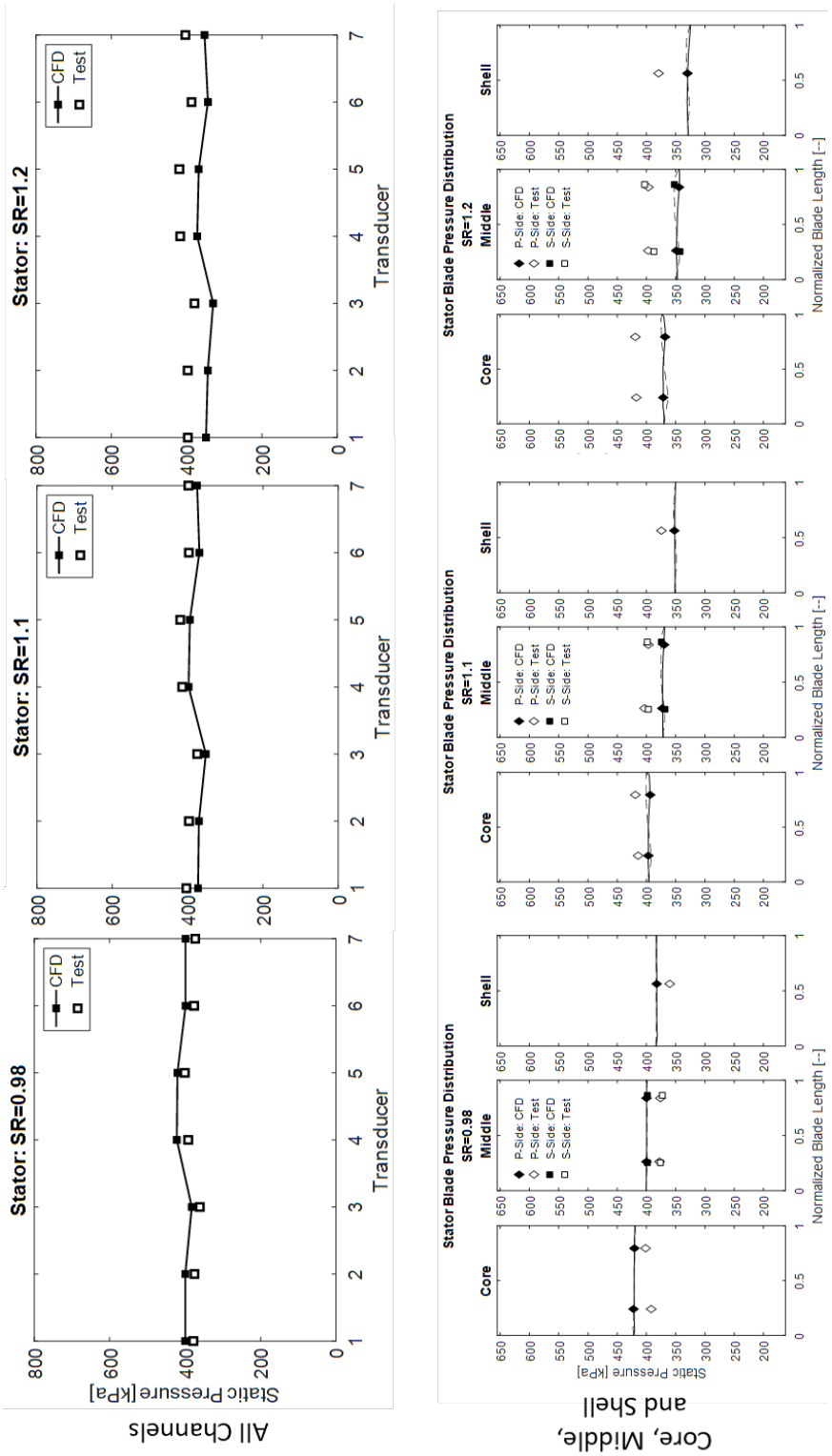
M.3 Stator +45 Nm CFD Comparison





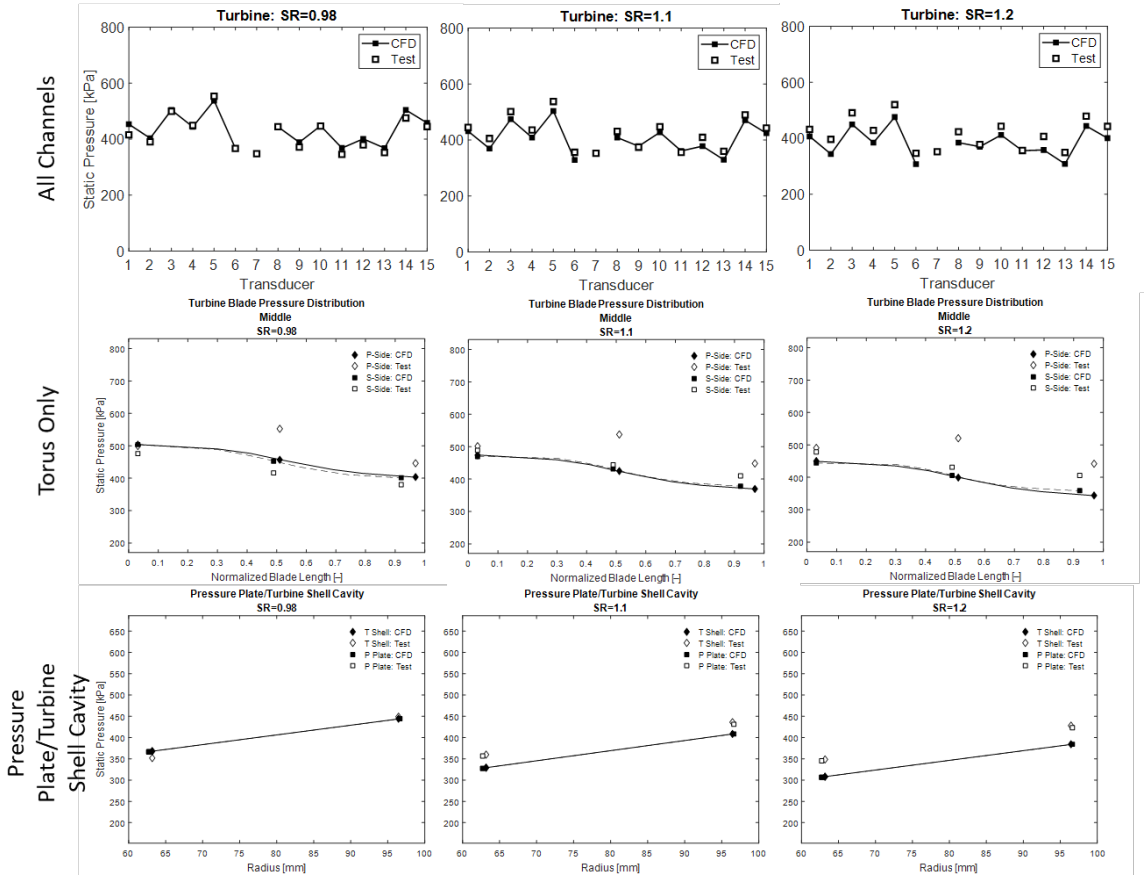
www.manaraa.com

M.4 Stator -45 Nm CFD Comparison



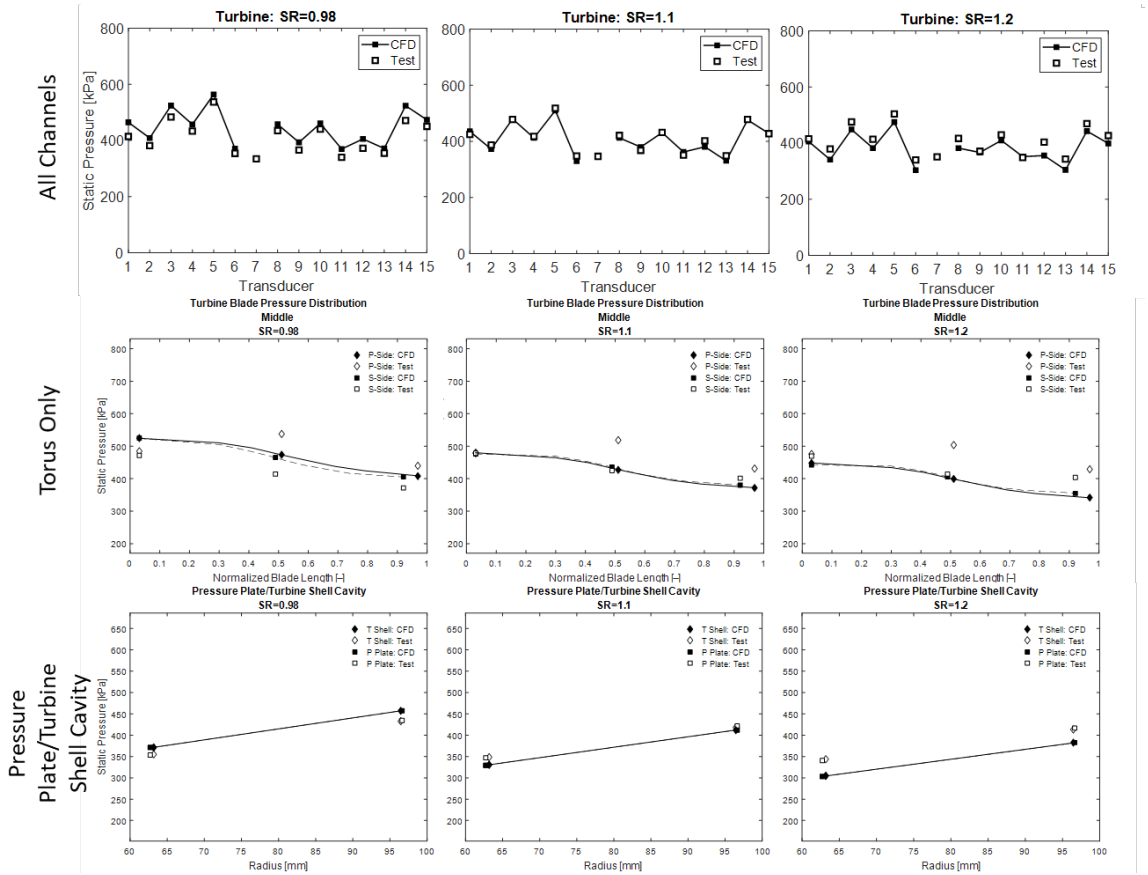
www.manaraa.com

M.5 Turbine +45Nm CFD Comparison



www.manaraa.com

M.6 Turbine -45 Nm CFD Comparison

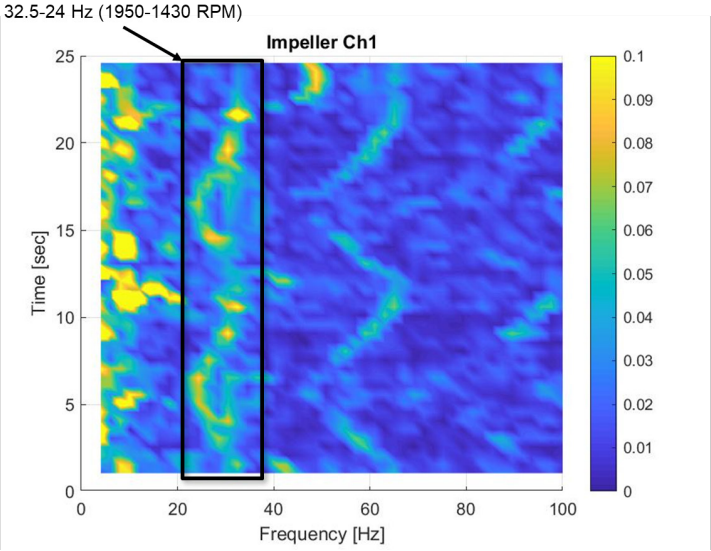


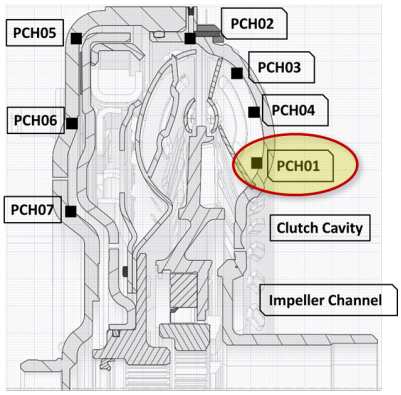
www.manaraa.com

N Back Drive FFT Color Maps

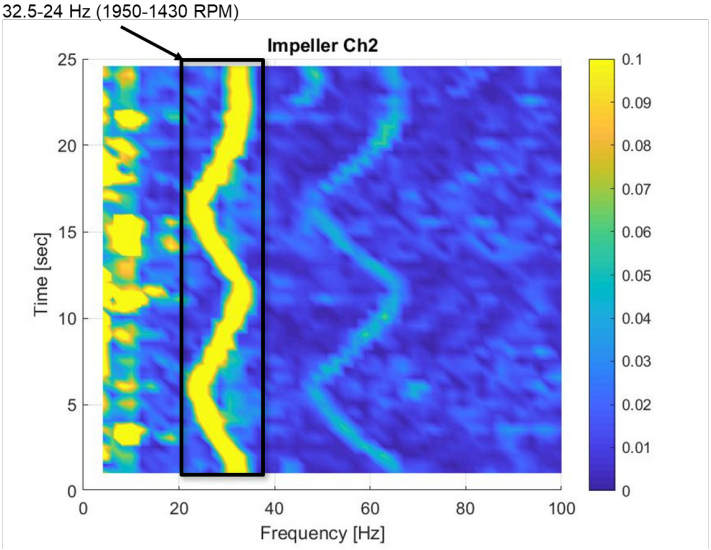
N.1 Impeller Color Maps

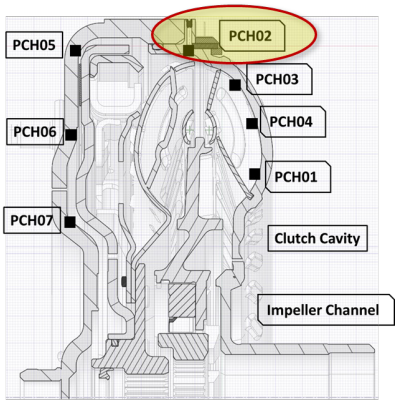
Impeller Primary Frequency
32.5-24 Hz (1950-1430 RPM)



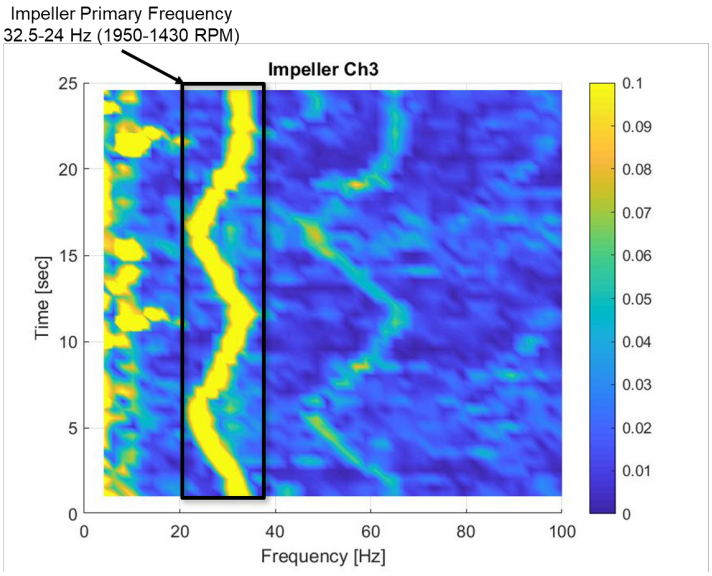


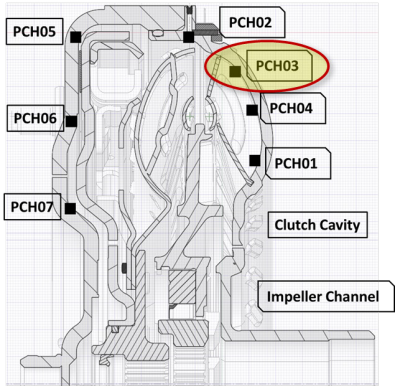
Impeller Primary Frequency
32.5-24 Hz (1950-1430 RPM)

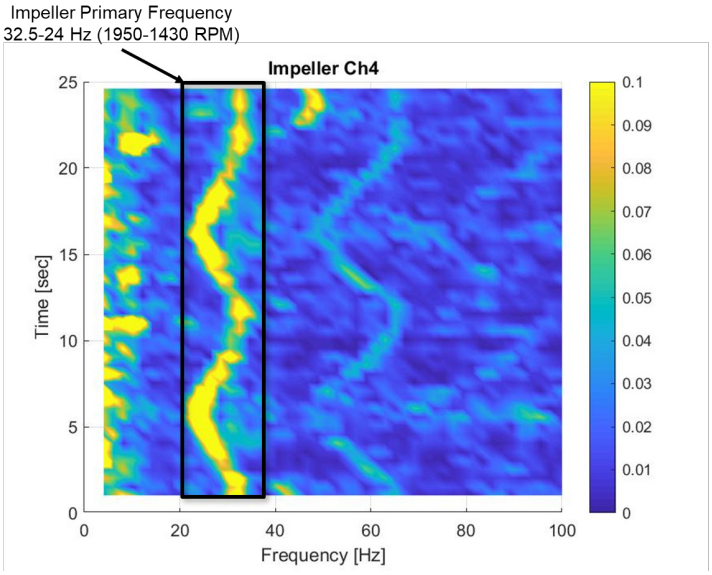


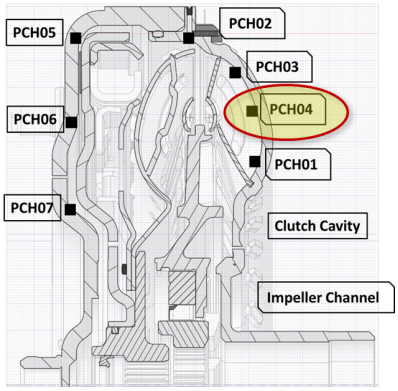


www.manaraa.com



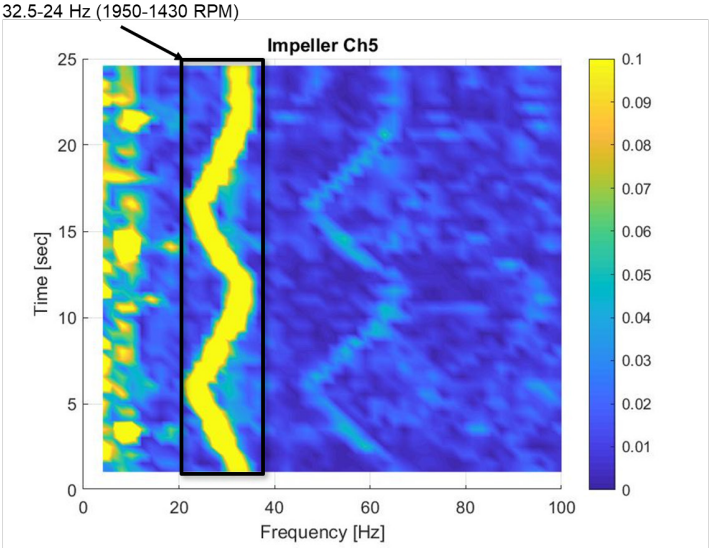


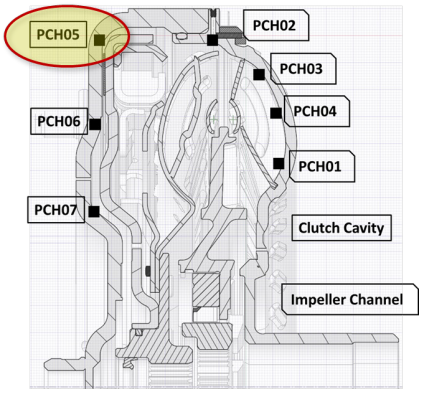




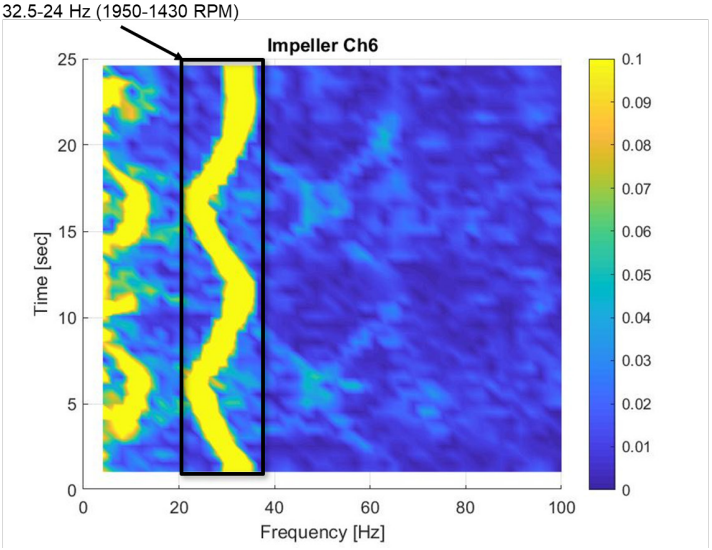
www.manaraa.com

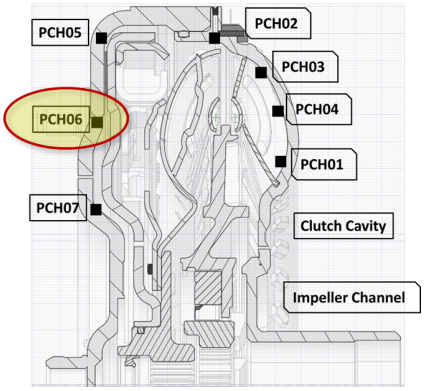
Impeller Primary Frequency
32.5-24 Hz (1950-1430 RPM)



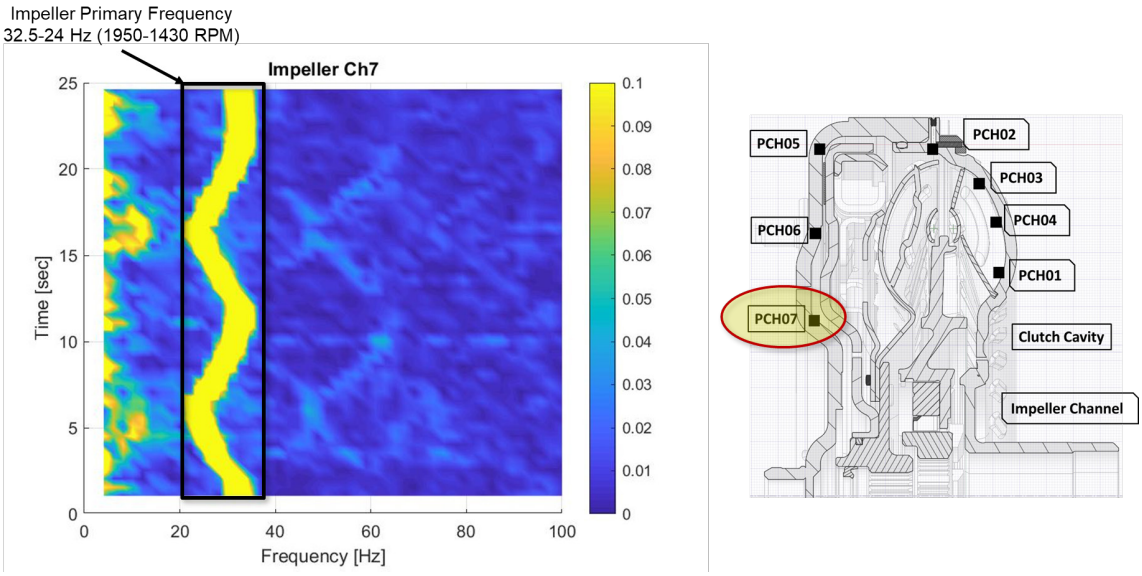


Impeller Primary Frequency
32.5-24 Hz (1950-1430 RPM)

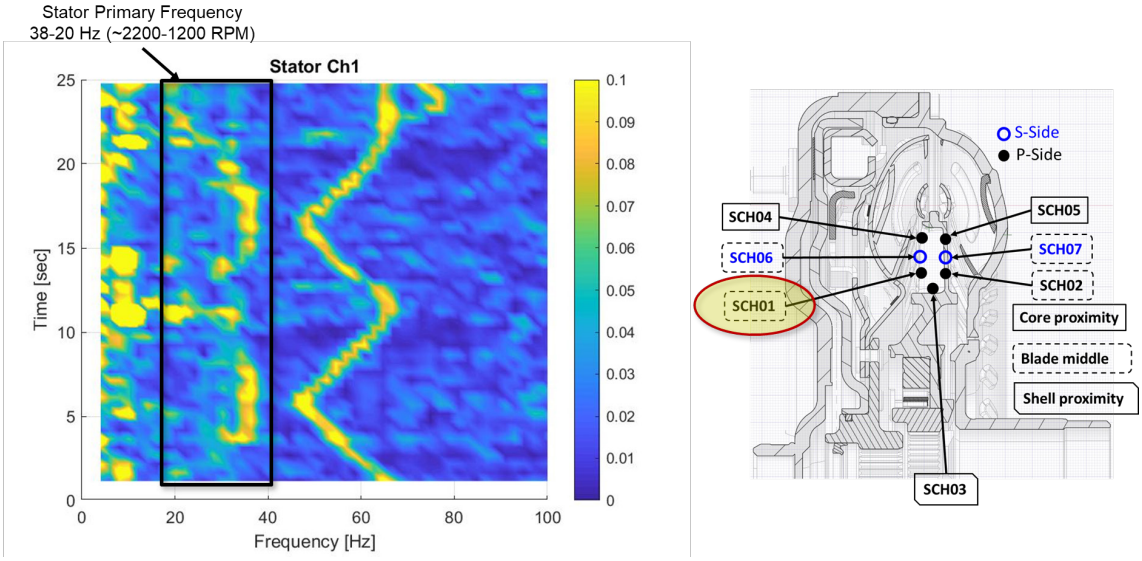




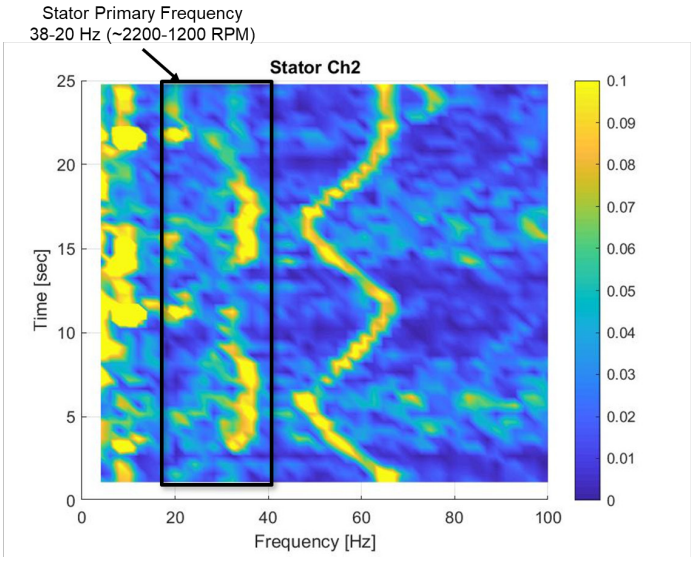
www.manaraa.com

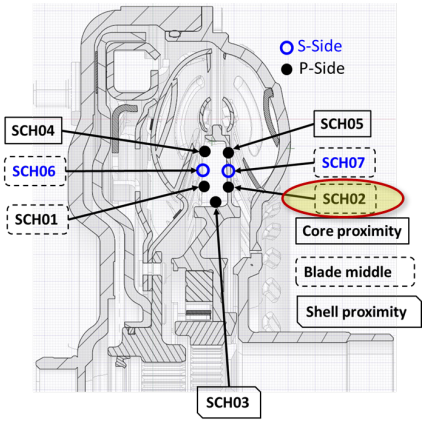


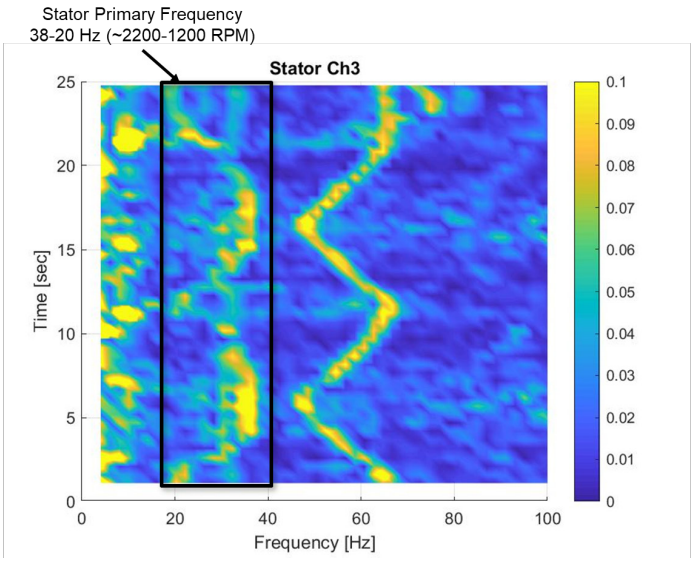
N.2 Stator Color Maps

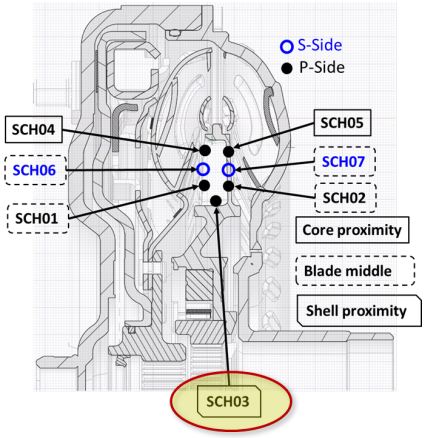


www.manaraa.com

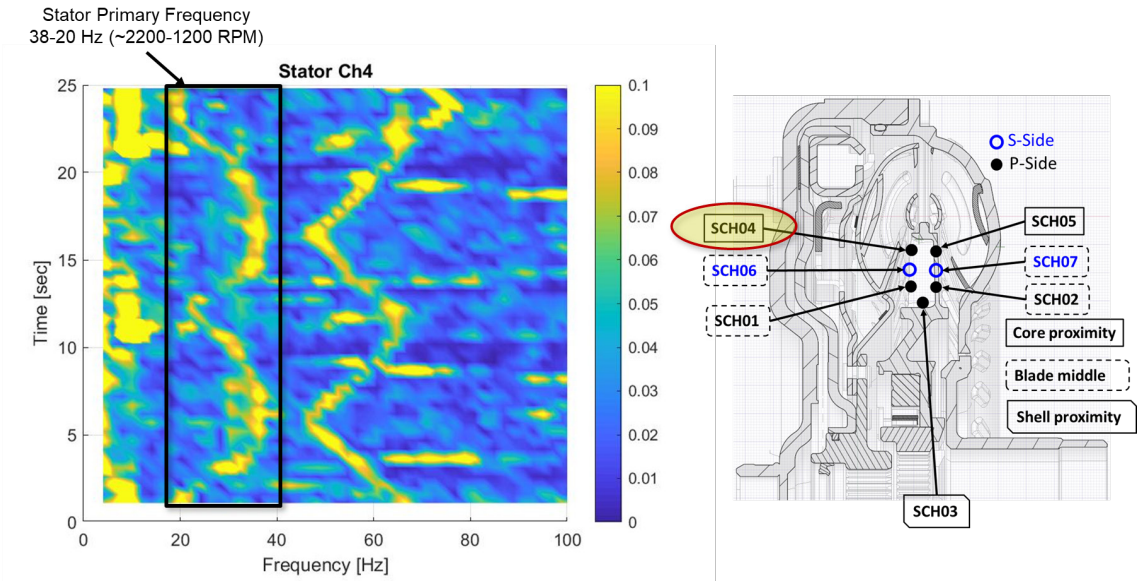


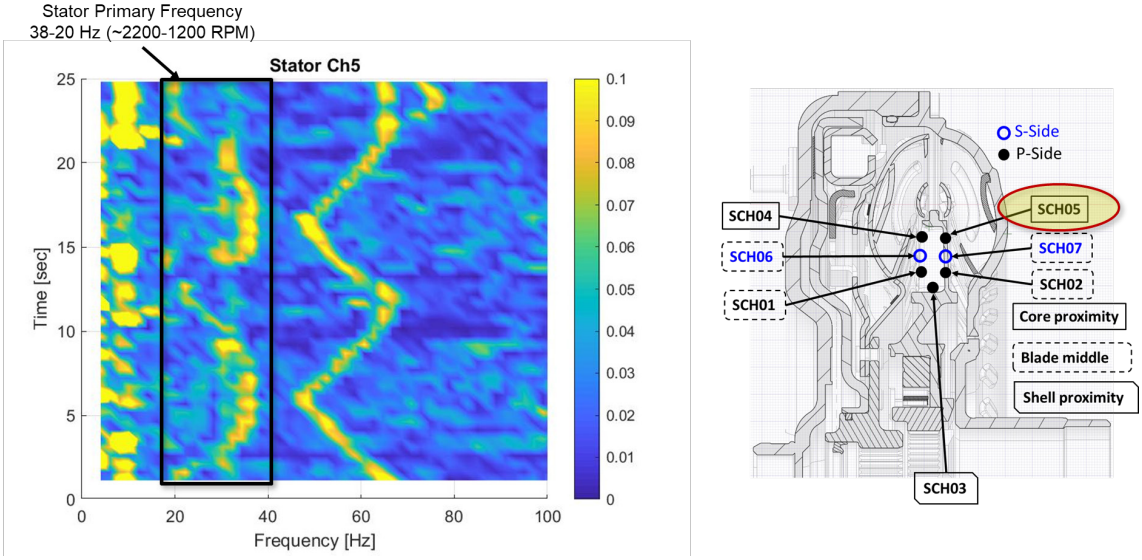




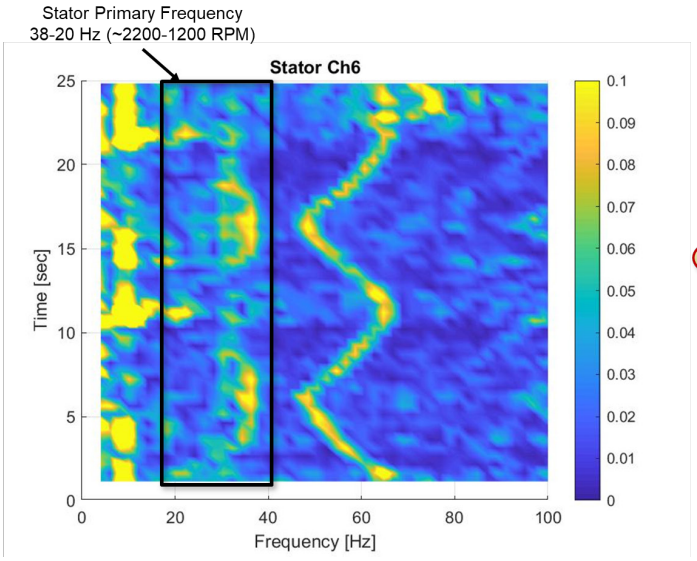


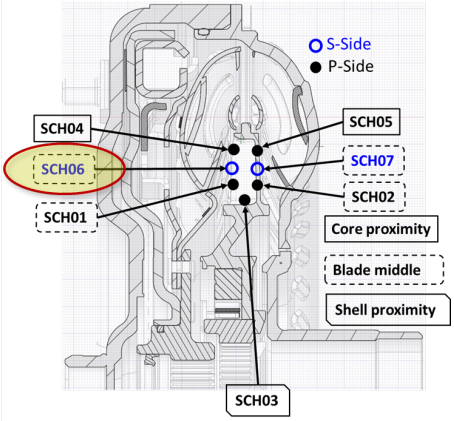
www.manaraa.com

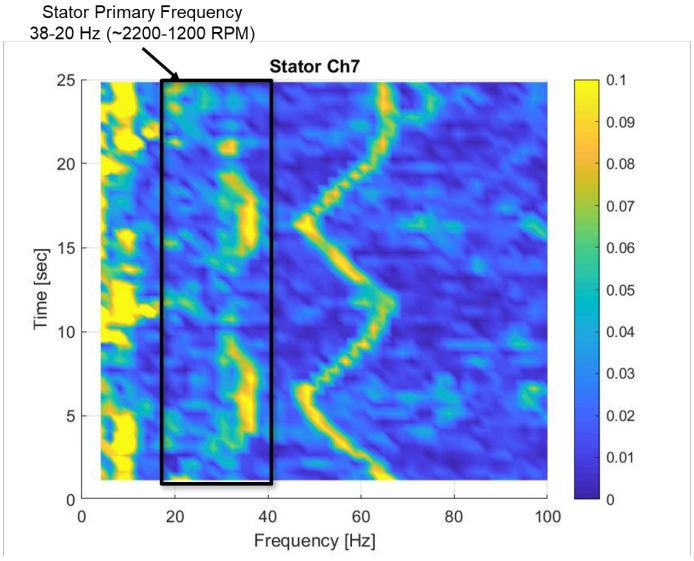


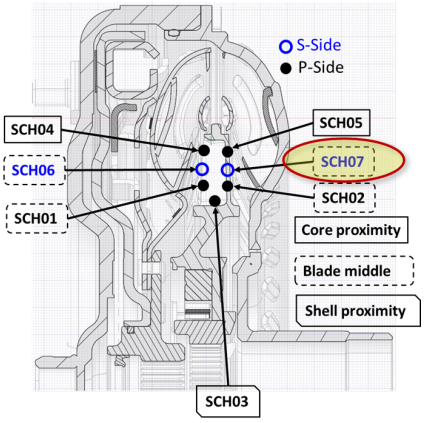


www.manaraa.com



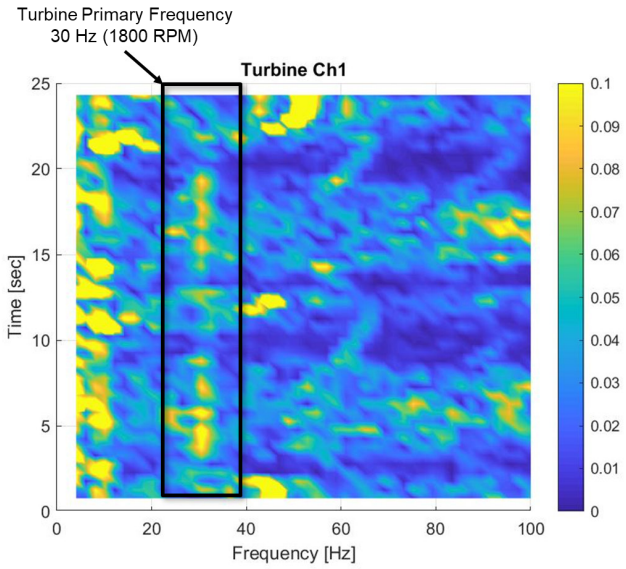


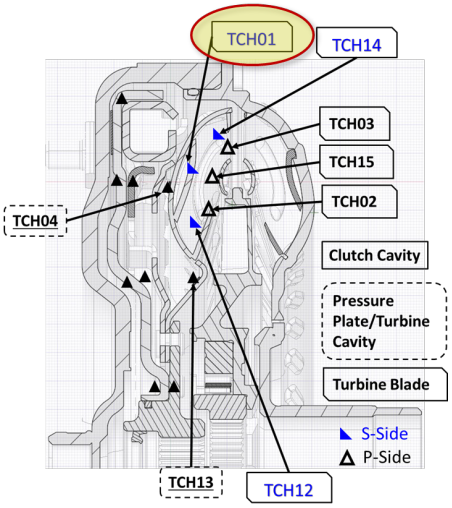


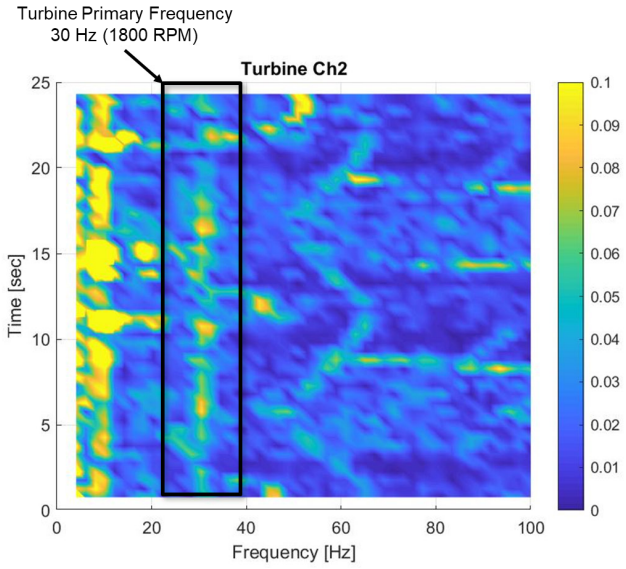


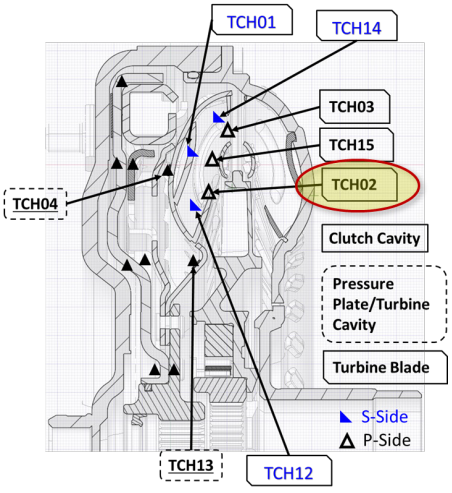
www.manaraa.com

N.3 Turbine Color Maps

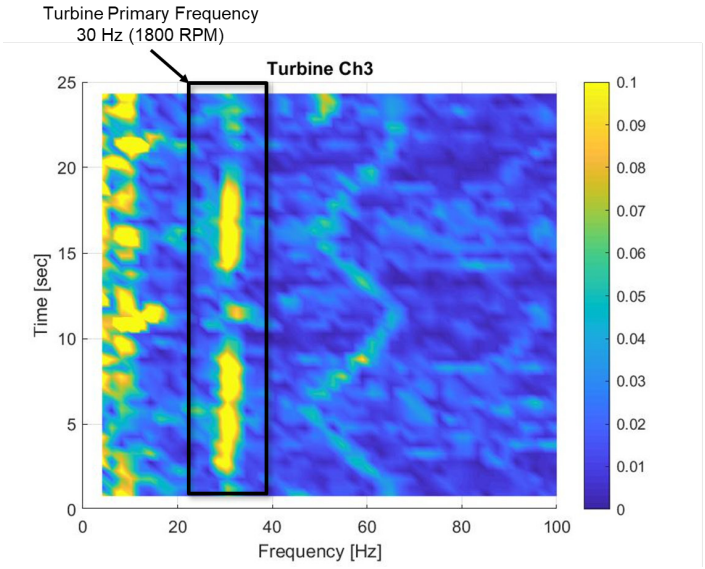


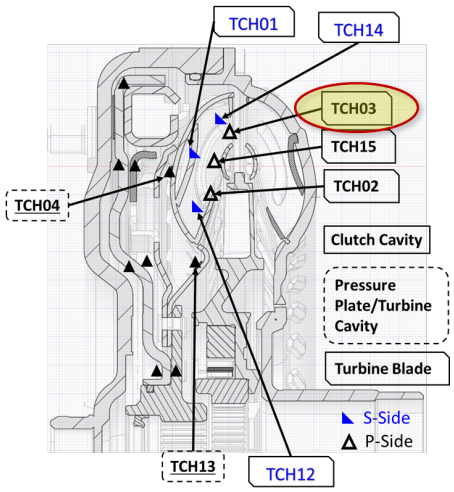


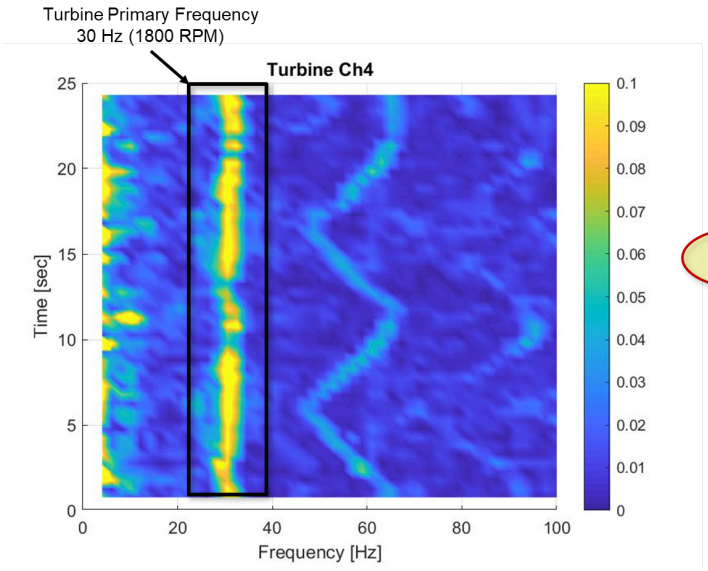


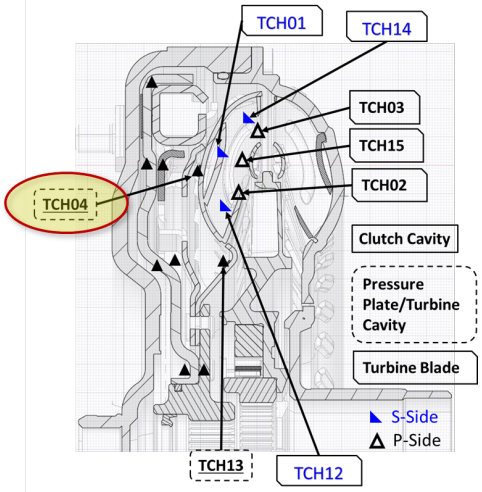


www.manaraa.com

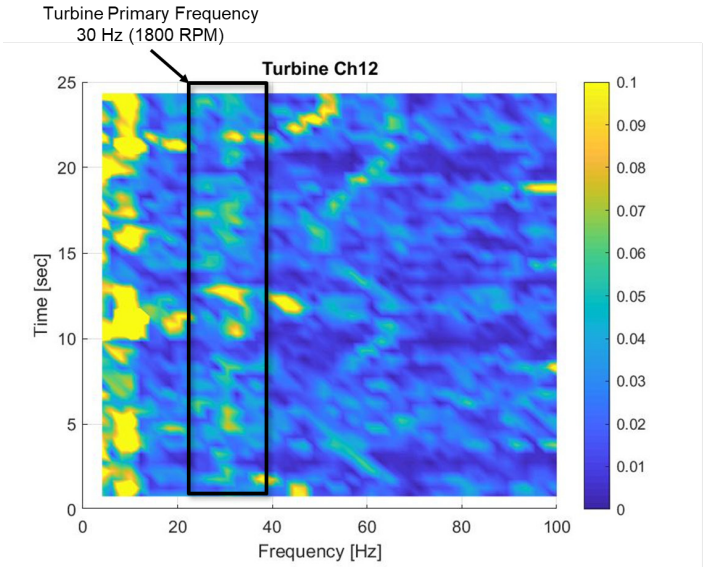


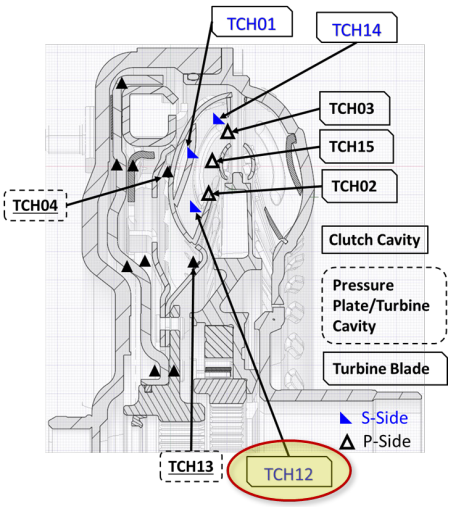


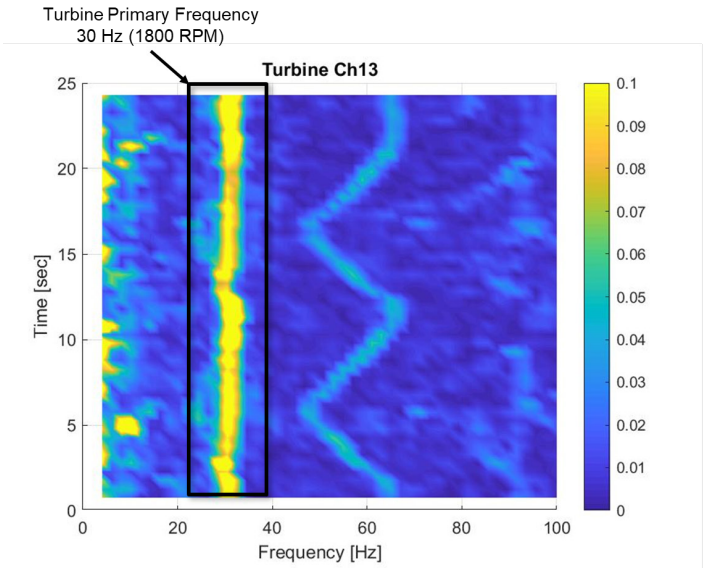


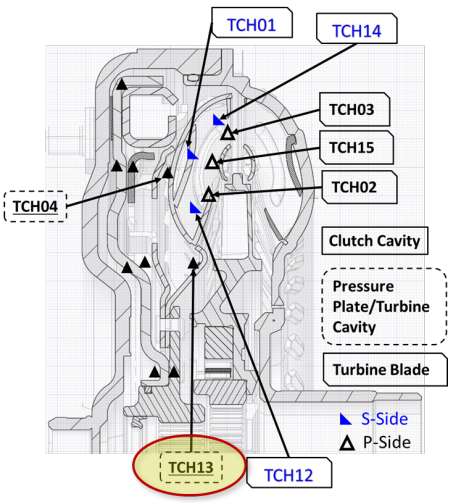


www.manaraa.com

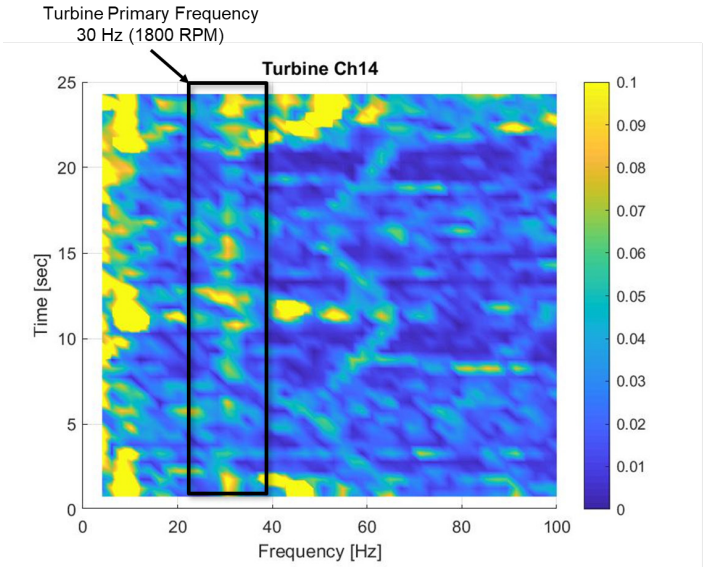


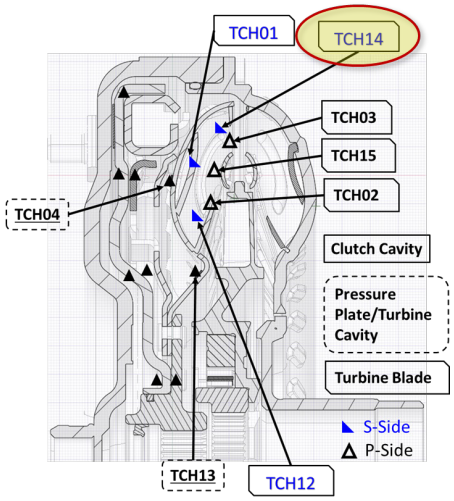


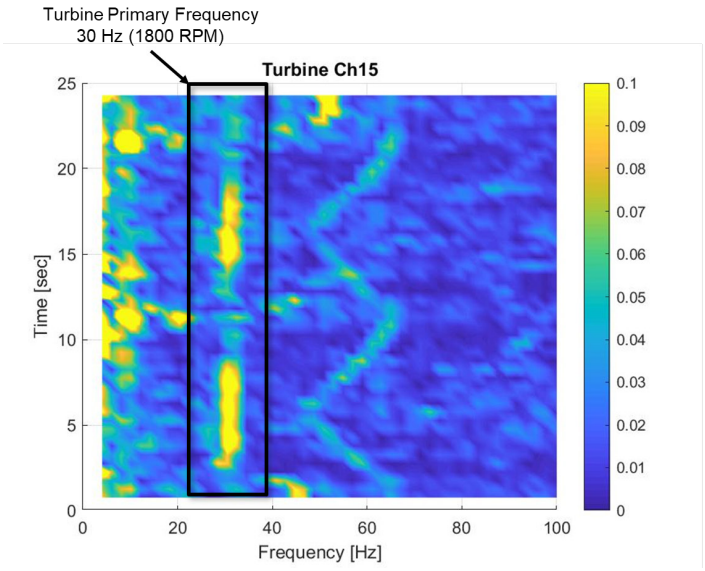


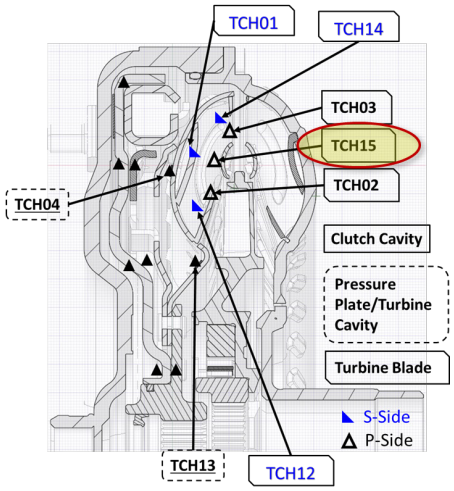


www.manaraa.com

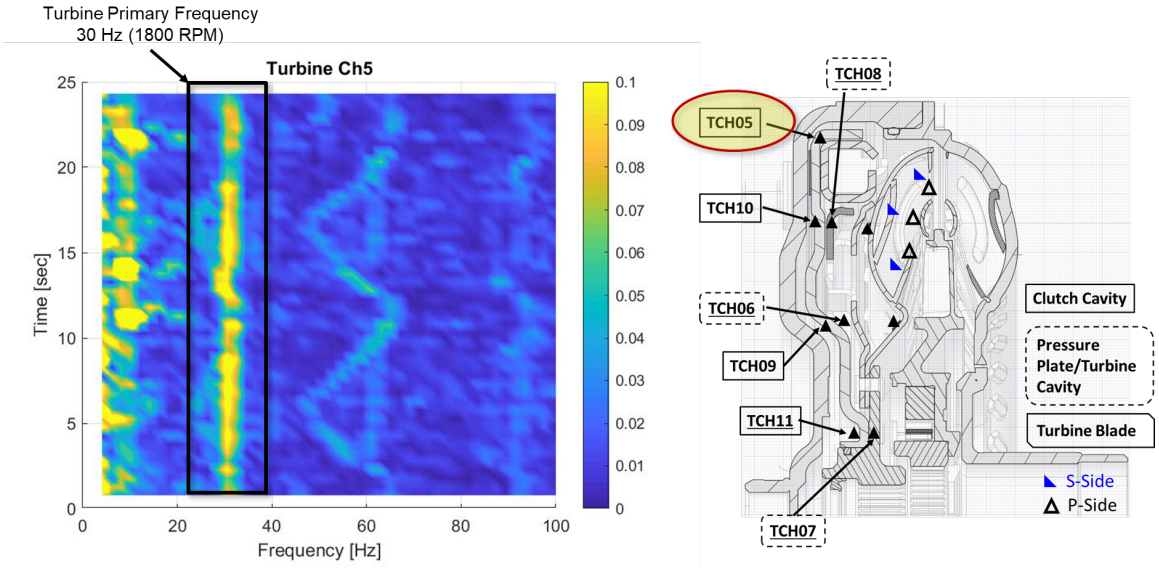


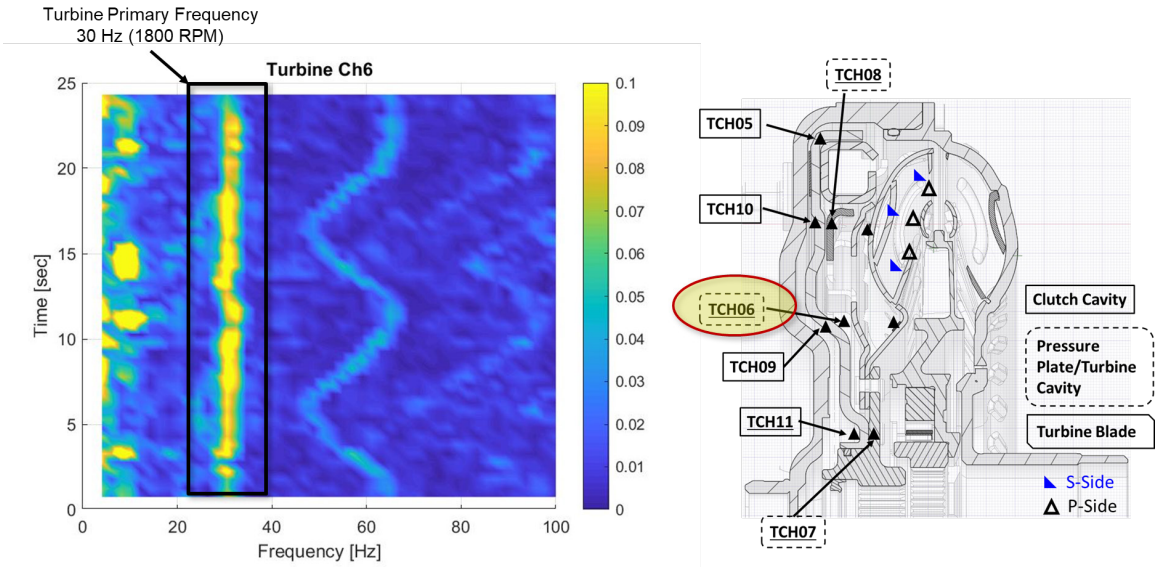




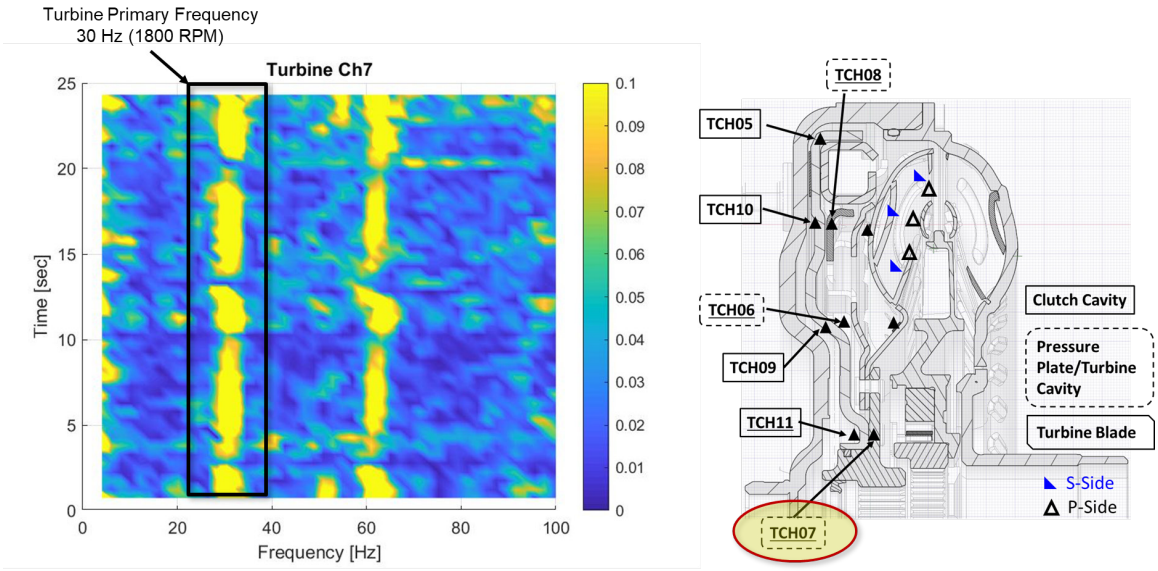


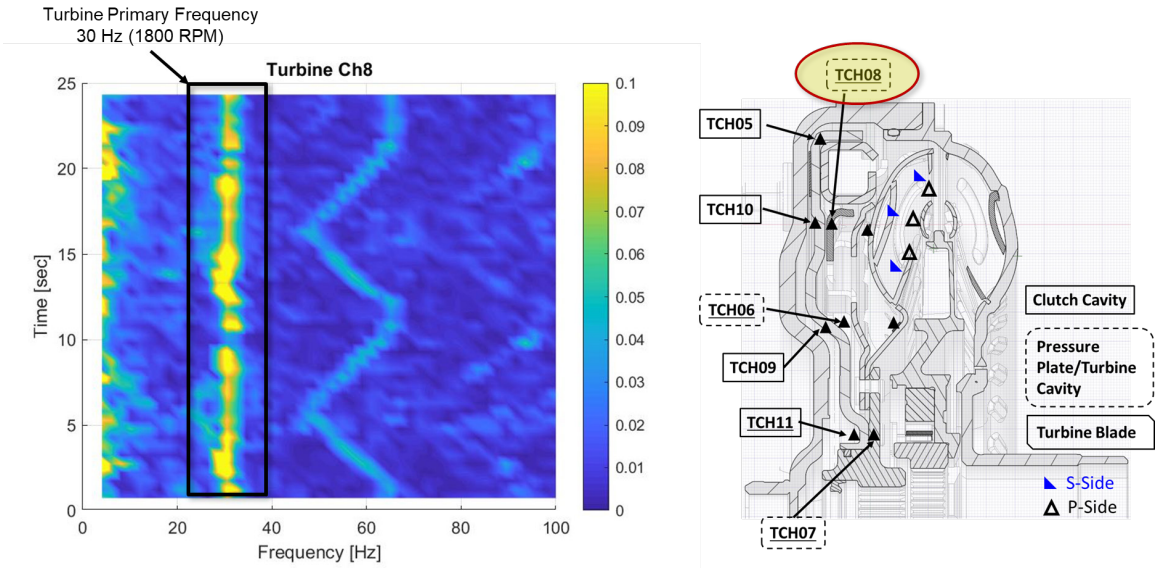
www.manaraa.com



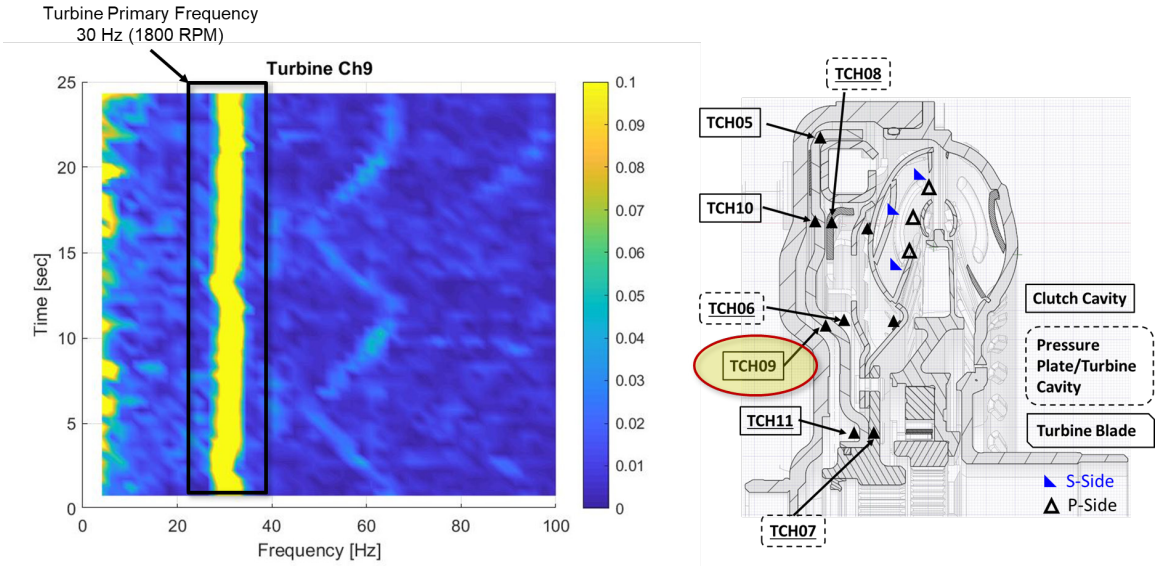


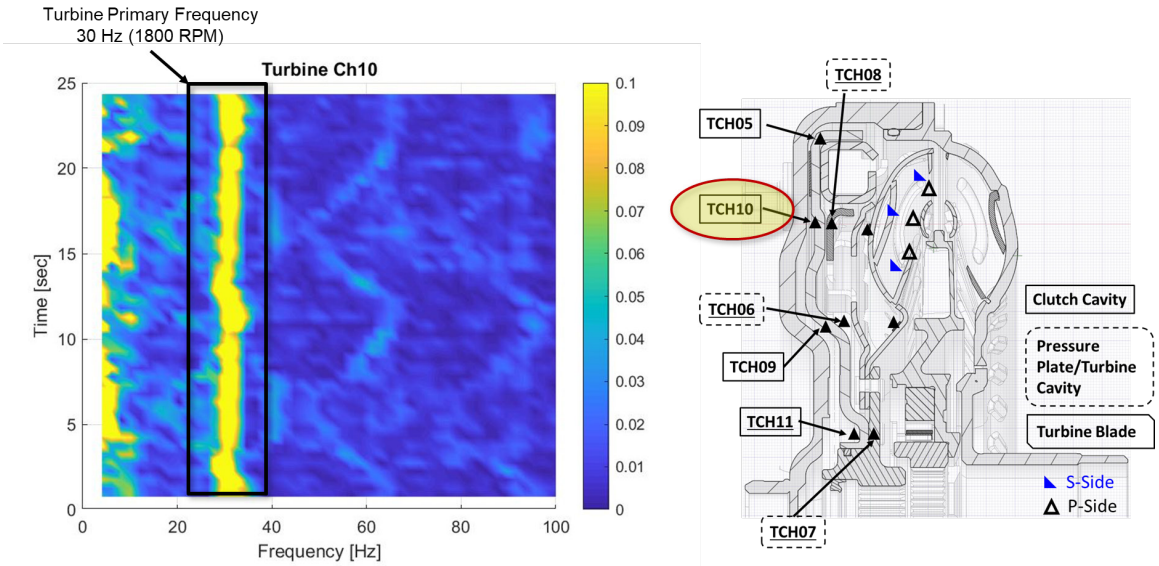
www.manaraa.com



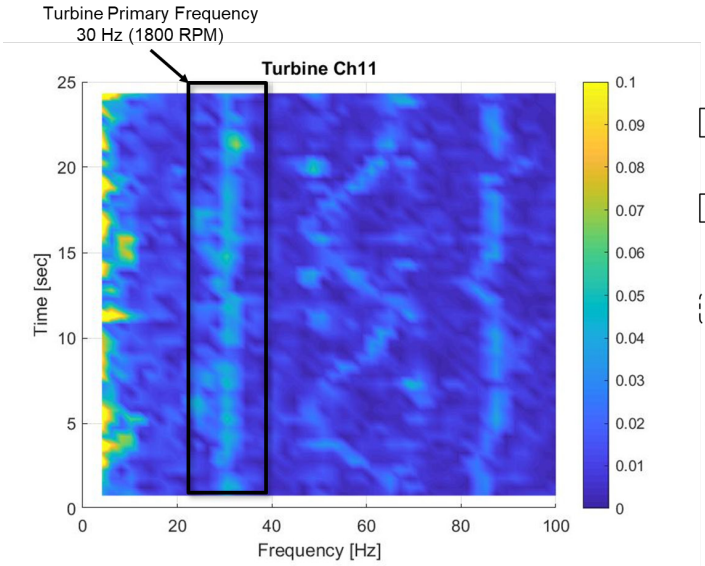


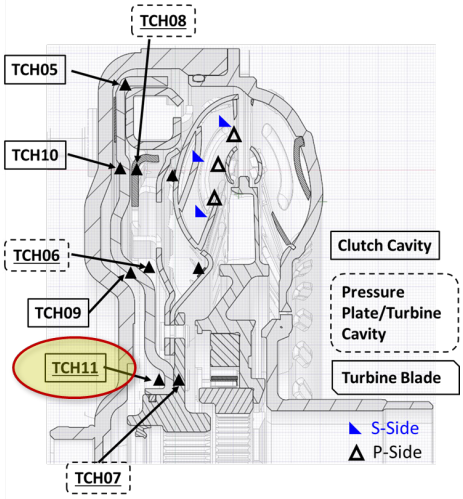
www.manaraa.com





www.manaraa.com





www.manaraa.com

O Key Analysis Tools

LMS Data to Matlab

```
function LMS_Data_to_Matlab(varargin)
% Required Format:
% NO INPUTS - will ask user to select path and file location
% path- 1st input: path to file
% file- 2nd input: file name
%
% OUTPUTS - Test lab channel names with respective data
%
% Purpose of Code:
% Takes a Test lab Throughput that was exported to matlab and adds all
% channels to workspace with proper names and respective data

if isempty(varargin)
    % User Interface to ask for file location
    answer = questdlg('Choose LMS Matlab File',...
        'Data File Selection',...
        'Browse','Cancel','Cancel');
    % Handle Response
    switch answer
        case 'Browse'
            selection = 1;
        case 'Cancel'
            selection = 0;
    end
    if selection == 1
        [file,path] = uigetfile('*');
    else
        return
    end

    % Saving file to a know structure name
    combined = load(fullfile(path,file));

else
    % Saving file to a know structure name
    combined = load(fullfile(varargin{1},varargin{2}));
end

% Identifing number of signal channels in data file and storing structure
% information
nameField = fieldnames(combined);

% Pulling first structure from combined structure
struct_1 = getfield(combined,cell2mat(nameField(1)));

% Caculating Time vector for all signals
dt = struct_1.x_values.increment;
```


www.manaraa.com

```
Time = (0:dt:(struct_1.x_values.number_of_values-1)*dt)';
assignin('base','Time',Time)

for ii = 1:length(nameField)
    % extracting current field to pull variables from
    struct_curr = getfield(combined,cell2mat(nameField(ii)));

    % Pulling channel names and data
    Names = struct_curr.function_record.name;
    Ch_Matrix = struct_curr.y_values.values;

    if ischar(Names)
        % Clearing previous interations
        New_name_raw = [47];
        % Split the Names up from the channel numbers
        New_name_raw(1,:) = strtrim(strsplit((Names)',':'));

        % Assisning data to variable names
        assignin('base',cell2mat(New_name_raw(1,2:end)),Ch_Matrix(:,1))
    else
        for jj = 1:length(Names)
            % Split the Names up from the channel numbers
            New_name(jj,:) = strtrim(strsplit(cell2mat(Names(jj))',':'));

            % Assisning data to variable names
            assignin('base',cell2mat(New_name(jj,2)),Ch_Matrix(:,jj))
        end
    end
end
end
```

Published with MATLAB® R2018a

O.1 Telemetry Average Pressure

Data files 222

Loop for each test run 223


```
% Purpose of Code:
% Takes .csv output files from telemetry and averages all the same test run
% values and output an .xlsx file with pressures, channel name, and run
% name
```

Data files

```
clear
clc

% Selecting file with data to be processed
```


www.manaraa.com

```
answer = questdlg('Select .csv Files In Folder to be Processed',...
    'Data File Selection',...
    'Browse','Cancel','Cancel');
% Handle Response
switch answer
    case 'Browse'
        selection = 1;
    case 'Cancel'
        selection = 0;
end
if selection == 1
    [file,path] = uigetfile('*.*','Select One or More Files',...
                            'MultiSelect','on');
else
    return
end

% Selecting Impeller, Turbine, or Stator for channel naming
list = {'Impeller' 'Stator' 'Turbine'};
Names = (listdlg('PromptString','Select test location:', 'SelectionMode',...
        'single','ListString',list));

% Defines number of channels
if Names == 3
    Ch = 15;
else
    Ch = 7;
end
```

Loop for each test run

```
delete Telemetry_Pressure_Averaged_Results.xlsx  % Deletes file to ensure no data is from
old processing

% Splits each file name apart and determines number of test runs completed
A = cell(3,length(file));
for ii = 1:length(file)
    A(:,ii) = split(file{ii},'_');
end
B = unique(A(1,:));

% Organizing each test into the proper column
test_run = cell(1,length(B));
count = 1;
for jj = 1:length(B)
    for ii = 1:length(file)
        if isequal(A(1,ii),B(jj))
            test_run(count,jj) = file(ii);
            count = count + 1;
        else
            count = 1;
```


www.manaraa.com

```
        end
    end
end

Pressure_Average = zeros(length(test_run(1,:)),Ch);
count = 1;
offset = 0;
for jj = 1:length(test_run(1,:))
    % finds the number of runs for each test excluding zero cells from
    % total
    x = sum(~cellfun(@isempty,test_run(:,jj)));

    Holder = zeros(x,Ch);
    for ii = (1+offset):(x+offset)
        % Loading CSV data file
        test = importdata(fullfile(path,file{ii}));

        Average = nanmean(hampel(test.data,100));
        Average = reshape(Average,3,[]);
        Holder(ii-offset,:) = Average(2,:);

        disp(['Processed Run ', num2str(count), ' of ', num2str(length(file))])
        count = count + 1;
    end
    offset = offset + x;
    Pressure_Average(jj,:) = mean(Holder,1);


xlswrite('Telemetry_Pressure_Averaged_Results.xlsx',test_run(1,jj),strcat('A',num2str(jj+
1),':A',num2str(jj+1)));
end
xlswrite('Telemetry_Pressure_Averaged_Results.xlsx',Pressure_Average,1,'B2');


if Names == 1
    Titles = {'Run Name', 'Ch1 Inlet [PSI]', 'Ch2 Impeller-Turbine OD [PSI]', 'Ch3 Exit
[PSI]', 'Ch4 Middle [PSI]',...
        'Ch5 Cover OD [PSI]', 'Ch6 Cover Middle [PSI]', 'Ch7 Cover ID [PSI]'};
elseif Names == 2
    Titles = {'Run Name', 'Ch1 Pside Lead Mid [PSI]', 'Ch2 Pside Trail Mid [PSI]', 'Ch3
Pside Mid Shell [PSI]', 'Ch4 Pside Lead Core [PSI]',...
        'Ch5 Pside Trail Core [PSI]', 'Ch6 Sside Lead Mid [PSI]', 'Ch7 Sside Trail Mid
[PSI]'};
else
    Titles = {'Run Name', 'Ch1 Sside Mid Mid [PSI]', 'Ch2 Pside Trail Mid [PSI]', 'Ch3
Pside Lead Mid [PSI]', 'Ch4 Shell Outer OD [PSI]',...
        'Ch5 Clutch Side OD Past Friction Material [PSI]', 'Ch6 Turbine Side Middle
[PSI]', 'Ch7 Turbine Side ID [PSI]',...
        'Ch8 Turbine Side OD [PSI]', 'Ch9 Clutch Side Middle [PSI]', 'Ch10 Clutch Side OD
Before Friction Material [PSI]',...
        'Ch11 Turbine Side ID [PSI]', 'Ch12 Sside Trail Mid [PSI]', 'Ch13 Shell Outer ID
```


www.manaraa.com

```
[PSI]', 'Ch14 Sside Lead Mid [PSI]',...
        'Ch15 Pside Mid Mid [PSI]'};
end

xlswrite('Telemetry_Pressure_Averaged_Results.xlsx',Titles);
disp('Processing Completed')
```

Published with MATLAB® R2018a

O.2 Telemetry Stitcher

Asking User to Define File Location 225

Asking User to Define Impeller, Stator, or Turbine Data..... 226

Data Processing 226

Sorting Time and Pressure Data 227


```
function [Time_Stitched,Pressure_Stitched,Sync] = Telemetry_Stitcher

% Required Format:
% Time- 1st input: 3D time matrix associated with the pressure matrix
% Pressure- 2nd input: 3D pressure matrix
% Time_Stitched- 1st output: Time vector for each channel
% Pressure_Stitched- 2nd output: Pressure vector for each channel
%
% Purpose of Code:
% Takes each channel from a set of tests and stitches the data into a
% single time trace for each channel
```

Asking User to Define File Location

```
answer = questdlg('Select Telemetry Files to be Processed',...
    'Data Folder Selection',...
    'Browse','Cancel','Cancel');
% Handle Response
switch answer
    case 'Browse'
        selection = 1;
    case 'Cancel'
        selection = 0;
end
if selection == 1
    [file,path] = uigetfile('*','Select One or More Files',...
                            'MultiSelect','on');
else
    return
end
```


www.manaraa.com

Asking User to Define Impeller, Stator, or Turbine Data

List dialog to define what data set

```
list = {'Impeller' 'Stator' 'Turbine'};
Set = (listdlg('PromptString','Select a Data Set', 'SelectionMode',...
        'single','ListString',list));

% Defines the number of channels to expect in the data sets
if Set == 3
    Ch_num = 15;
else
    Ch_num = 7;
end

% Checking if there are multiple files and to load the files properly
% depending on the variable type (string vs cell)
if ischar(file)
    file_length = 1;
else
    file_length = length(file);
end
```

Data Processing

```
Sync = zeros(file_length,1);
for ii = 1:file_length
    % Loads each file that was selected in the user dialog
    % Checking if there are multiple files and to load the files properly
    % depending on the variable type (string vs cell)
    if ischar(file)
        Data = csvread(fullfile(path,file),1,0);
    else
        Data = csvread(fullfile(path,cell2mat(file(ii))),1,0);
    end

    fs = 52000;                                                    % [Hz]
desired sampling frequency for the data to be resampled at
    t = 0:1/fs:30;                                                 % [sec] time
vector that Pressure will be mapped too
    % Commanding subroutine to remove dropouts and resample the data set
    [ty,y] = Dropout_Resample(Data(:,1),Data(:,2),fs);

    % Commanding subroutine to organize the data by channels and 3D matrix
    [Time,Frequency] = Telemetry_Organizer(ty,y,Ch_num);

%     %temp
%     Time_order(:,:,ii)= Time;
%     Frequency_order(:,:,ii)= Frequency;

    % Commanind subroutine to calibrate each of the channels
```


www.manaraa.com

```
    Pressure = Telemetry_Calibration(Frequency,Set);

    % Clearing the holder variables for new information of a different size
    if ii == 1
    else
        clear Time_holder Pressure_holder
    end

    % Adding a zero layer to pressure to match time 3D matrix
    if length(Pressure(1,1,:)) < length(Time(1,1,:))
        Pressure(:,:,end+1) = zeros(size(Time(:,:,1)));
    end

    % Looping through each channel and gathering all channel info
    Time_save = zeros(length(Time)*length(Time(1,1,:)),Ch_num);
    Pressure_save = zeros(length(Pressure)*length(Pressure(1,1,:)),Ch_num);
    for jj = 1:Ch_num
        Time_holder = squeeze(Time(:,jj,:));
        Pressure_holder = squeeze(Pressure(:,jj,:));
        Time_holder = reshape(Time_holder,[],1);
        Pressure_holder = reshape(Pressure_holder,[],1);
        Time_save(:,jj) = Time_holder;
        Pressure_save(:,jj) = Pressure_holder;
    end
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
    % Placing the held information from every file together
    if ii == 1
        Time_Stitched = Time_save;
        Pressure_Stitched = Pressure_save;
    else
        Time_Stitched = vertcat(Time_Stitched,Time_save);
        Pressure_Stitched = vertcat(Pressure_Stitched,Pressure_save);
    end

    % Sync average from each test run
    ss = find(Data(:,3)== 5000,1);
    Sync(ii) = Data(ss,1);

    disp(['Processed Run ', num2str(ii), ' of ', num2str(file_length)])
end

Sync = mean(Sync);
```

Sorting Time and Pressure Data

```
[Time_Stitched,index] = sort(Time_Stitched);
for ii = 1:length(index(1,:))
A(:,ii) = Pressure_Stitched(index(:,ii),ii);
end
% Replacing the sorted data over the unorganized values
% Only saving the values that are not all zero rows
```


www.manaraa.com

```
Pressure_Stitched = A(any(A,2),:);
Time_Stitched = Time_Stitched(any(Time_Stitched,2),:);

end
```

Published with MATLAB® R2018a

O.3 Dropout Resample

Removing Dropouts 228

```
function [ty,y] = Dropout_Resample(t,A,fs)

% Required format:
% t - 1st input: is the time vector associated with A
% A - 2nd input: is the vector to have dropouts removed and resampled
% fs - 3rd input: is desired sampling frequency for vector to be resampled at
% ty - 1st output: is the resampled time vector
% y - 2nd output: is the resampled, dropouts removed vector
%
%Purpose of Code:
% Removes drop outs and resamples the data to a specified sampling
% frequency
```

Removing Dropouts

```
B = hampel(A,1000);
B = hampel(B,1000);
% p = 5, upsampling parameter, q = 10, downsampling parameter




y = resample(B,t,fs,5,10);
ty = 1/fs:1/fs:length(y)*1/fs;

end
```

Published with MATLAB® R2018a

O.4 Telemetry Organizer

Finding Marker 229

Data Matrix.....232

Partial Data Sets at Beginning and End 232

```
function [Time,Frequency] = Telemetry_Organizer(Time_raw,Freq_raw,Ch_num)
```


www.manaraa.com

```
% Required Format:
% Time_raw - 1st input: time vector associated with the freq_raw vector
% Freq_raw - 2nd input: raw frequency vector
% Time_Freq - 1st output: Time matrix associated with the frequency matrix
% Frequency - 2nd output: Frequency matrix- rows contain frequency, columns
%                         are each channel (7 or 15)
% Purpose of Code:
% Takes a multiplexed data set and spilts the data according to the marker
% size and location. The data is placed in a 3D matrix for each channel
%
% Last Update: Mark Woodland 03/22/2019
%
% Updates: 03/22/19- Ch 15 on turbine is no longer working which means
% marker start cannot be identified. Using marker ends with channel length
% provided by IRT to determine number of samples per channel
```

Finding Marker

```
thresh = 10000;                                                    % [Hz]
threshold level for marker
fs = 1/(Time_raw(2)-Time_raw(1));                                  % [Hz]
sampling frequency

Marker_start = find(Freq_raw(1:end-1)>thresh...
                    & Freq_raw(2:end)<thresh);                     % Start of
marker location
Marker_end =   find(Freq_raw(1:end-1)<thresh...
                    & Freq_raw(2:end)>thresh);                     % End of
marker location

% Removing all partial starting markers that can be at end of data set
Marker_start(Time_raw(Marker_start)>Time_raw(end)-1) = [];
% Removing all parital ending markers that can be at beginning of data set
Marker_end(Time_raw(Marker_end)<Time_raw(1)+1) = [];

% Verifying is Marker Start and Ends are Markers and not dropouts
% Marker starting
Marker_remove = zeros(1,length(Marker_start));
for ii = 1:length(Marker_start)
    % Checking values after the start of marker
    if(mean(Freq_raw(Marker_start(ii):Marker_start(ii)+fs*.01))<thresh)     % Looking for
1% of the sampling frequency as the number of points to verify marker
        Marker_remove(ii) = 1;                                     % Logic to
keep marker values
    end
end
Marker_start(Marker_remove<1)=[];                                  % Removing
dropout values from

% Looking for dropouts inside of marker and removing as marker starts
count = 0;
```


www.manaraa.com

```
if Ch_num == 7
    Limit = floor(Time_raw(end)/8)+1;
else
    Limit = floor(Time_raw(end)/16)+1;
end

% Always check the first marker for dropouts inside the marker
count = count+1;
Marker_remove = [ones(1,count) Time_raw(Marker_start(count+1:end))-...
    Time_raw(Marker_start(count))];                                    % 1 placed as a
place holder to ensure first value is kept
Marker_start(Marker_remove<0.98) = [];

% Continues looking at other markers for dropouts if necessary
if Ch_num == 15
else
    while length(Marker_start)>Limit
        count = count+1;
        Marker_remove = [ones(1,count) Time_raw(Marker_start(count+1:end))-...
            Time_raw(Marker_start(count))];                                % 1
placed as a place holder to ensure first value is kept
        Marker_start(Marker_remove<0.98) = [];
    end
end

% Marker ending
Marker_remove = zeros(1,length(Marker_end));
for ii = 1:length(Marker_end)
    % Checking values prior to end of marker
    if(mean(Freq_raw(Marker_end(ii)-fs*.01:Marker_end(ii)))<thresh)         % Looking for
1% of the sampling frequency as the number of points to verify marker
        Marker_remove(ii) = 1;                                             % Logic to
keep marker values
    end
end
Marker_end(Marker_remove<1)=[];                                            % Removing
dropout values


count = 0;
% Always check the first marker for dropouts inside the marker
count = count+1;
Marker_remove = [ones(1,count-1) Time_raw(Marker_end(count:end))-...
    Time_raw(Marker_start(count))];                                        % 1 placed as
a place holder to ensure first value is kept
Marker_end(Marker_remove<0.98) = [];


if Time_raw(Marker_end(1))+Ch_num+1 <= Time_raw(end)
    % Looking for dropouts inside of marker and removing as marker ends
    while length(Marker_end)>Limit
```


www.manaraa.com

```
        count = count+1;
        % Condition to end loop if there is a dropout really close to the end
        % of the marker and will not be removed otherwise
        if count > Limit
            Marker_end = Marker_end(1:Limit);
            break
        end
        % Removing bad end markers based off of correct start markers
        Marker_remove = [ones(1,count-1) Time_raw(Marker_end(count:end))-...
            Time_raw(Marker_start(count))];                                    % 1
placed as a place holder to ensure first value is kept
        Marker_end(Marker_remove<0.98) = [];
    end

    % Final check to remove end markers that are near the ends that are
    % dropouts
    index =[0 Time_raw(Marker_end(1:end-1))+Ch_num+0.8>Time_raw(Marker_end(2:end))];
    Marker_end(index>0) = [];

else
    % Final check to remove end markers that are near the ends that are
    % dropouts
    index =[0 Time_raw(Marker_end(1:end-1))+Ch_num+0.8>Time_raw(Marker_end(2:end))];
    Marker_end(index>0) = [];

end

% Determining locations for marker locations
Marker_time = Time_raw(sort([Marker_start; Marker_end]));                  % [sec] Time
of each marker location sorted in order from lowest to highest
Marker_length = Marker_time(2:end)-Marker_time(1:end-1);                   % [sec] Time
between each value True marker and time between markers

% Counting number of full channel sets
if Ch_num == 15
    Ch_time = 1.003;                                                       % [sec]
length of Turbine channels
    Marker_start = zeros(length(Marker_end),1);
    for ii = 1:length(Marker_end)
        if Marker_end < Ch_time
        else
        Marker_start(ii) = find(Time_raw >= (Time_raw(Marker_end(ii))-Ch_time),1);
        end
    end
else
    Ch_time = mean(Marker_length(Marker_length<2));                        % [sec]
Length of each channel (~1 sec)
end
Ch_length = mean(Marker_length(Marker_length>2));                          % [sec]
Length of each set of channels (~7 or 15 sec)
%Ch_num = round(Ch_length/Ch_time);                                        % Number of
```


www.manaraa.com

```
channels in each channel set
Ch_sets = length(Marker_end)-1;                                    % Number of
full channel sets

% Counting number of data points per channel
v = find(Marker_end>Marker_start(1),1);                             % Finding
first marker pair
Ch_point = round(mean(Marker_end(v:end)-Marker_start));             % Number of
data points in each channel
```

Data Matrix

Creating 3D matrix for data

```
Frequency = zeros(Ch_point-1000,Ch_num,Ch_sets+2);                  % Rows-
remove 500 data point for ends, Column- # of CH, Layers- Add two for possible partial
data sets at begining and end
Time = Frequency;                                                  % Time matrix
associated with the Frequency Matrix
if Ch_sets == 0                                                    % If there
are no full data sets just skip this portion of code and go to partial data sets code
else
    for ii = 1:Ch_sets
        A = Freq_raw(Marker_start(ii)+Ch_point:Marker_start(ii)...
            +Ch_point*(Ch_num+1)-1);                               % Pulling
full channel set from data
        B = Time_raw(Marker_start(ii)+Ch_point:Marker_start(ii)...
            +Ch_point*(Ch_num+1)-1);
        A_m = reshape(A,[],Ch_num);                                % Reshaping
data to splilt each channel
        B_m = reshape(B,[],Ch_num);
        A_m(1:500,:) = [];                                          % Removing
first 500 data points
        A_m(end-499:end,:) = [];                                    % Removing
last 500 data points
        B_m(1:500,:) = [];
        B_m(end-499:end,:) = [];
        Frequency(:,:,ii+1) = A_m;                                 % Assigning
values to 3D Results Matrix, Keep first layer open for possible partial data
        Time(:,:,ii+1) = B_m;
    end
end
```

Partial Data Sets at Beginning and End

Finding if partial set at beginning of data

www.manaraa.com

```
if Time_raw(Marker_start(1)) < Ch_num+Ch_time
    Ch_comp = floor(Time_raw(Marker_start(1))/Ch_time);                    % Number of
full 1 sec channels in uncompleted data set
    if Ch_comp == 0                                                        % Do nothing
if there are no complete channels of data in partial data set
        Frequency(:,:,1)=[];                                               % If there is
no partial data remove the first zero matrix layer
        Time(:,:,1)=[];
    else
        Data = Freq_raw((Marker_start(1)-Ch_comp*Ch_point):...
            (Marker_start(1)-1));                                          % Extracting
channels from partial set
        Data_B = Time_raw((Marker_start(1)-Ch_comp*Ch_point):...
            (Marker_start(1)-1));
        Data_m = reshape(Data,[],Ch_comp);                                 % Creating a
matrix of channels (n by # of CH)
        Data_mB = reshape(Data_B,[],Ch_comp);
        Data_m(1:500,:) = [];                                              % Removing
first 500 data points
        Data_m(end-499:end,:) = [];                                        % Removing
last 500 data points
        Data_mB(1:500,:) = [];
        Data_mB(end-499:end,:) = [];
        Frequency(:,(Ch_num-Ch_comp+1):end,1) = Data_m;                    % Adding
partial data to beginning of matrix
        Time(:,(Ch_num-Ch_comp+1):end,1) = Data_mB;
    end
end

% Finding if partial set at end of data
if Time_raw(Marker_end(end)) < Time_raw(end)
    Ch_comp = floor((Time_raw(end)-Time_raw(Marker_end(end)))/Ch_time);     % Number of
full 1 sec channels in uncompleted data set
    if Ch_comp == 0                                                        % Do nothing
if there are no complete channels of data in partial data set
        Frequency(:,:,end)=[];                                             % If there is
no partial data remove the last zero matrix layer
    else
        Data = Freq_raw((Marker_end(end)+1):...
            (Marker_end(end)+Ch_comp*Ch_point));                           % Extracting
channels from partial set
        Data_B = Time_raw((Marker_end(end)+1):...
            (Marker_end(end)+Ch_comp*Ch_point));
        Data_m = reshape(Data,[],Ch_comp);                                 % Creating a
matrix of channels (n by # of CH)
        Data_mB = reshape(Data_B,[],Ch_comp);
        Data_m(1:500,:) = [];                                              % Removing
first 500 data points
        Data_m(end-499:end,:) = [];                                        % Removing
last 500 data points
        Data_mB(1:500,:) = [];
```


www.manaraa.com

```
        Data_mB(end-499:end,:) = [];
        Frequency(:,1:Ch_comp,end) = Data_m;                                % Adding
partial data to beginning of matrix
        Time(:,1:Ch_comp,end) = Data_mB;
    end
end

end
```

Published with MATLAB® R2018a

O.5 Telemetry Calibration

Calibration 234

```
function [Pressure] = Telemetry_Calibration(Frequency,cal_set)

% Required Format:
% Frequency- 1st input: is the demultiplexed 3D matrix that is built from
%                       the Telemetry Organizer code
% cal_set- 2nd input: determines if the data set is 1-Impeller, 2-Stator,
%                     or 3-Turbine cal factors
% Pressure- output: calibrated 3D matrix of pressures
%
% Purpose of Code:
% Calibrates the telemetry frequency to a pressure (PSIa)
```

Calibration

loads the calibration values for the appropriate data set

```
if cal_set == 1
    load('Impeller_Calibration.mat')
    cal = Impeller_Calibration;
    Ch_num = 7;
elseif cal_set == 2
    load('Stator_Calibration.mat')
    cal = Stator_Calibration;
    Ch_num = 7;
else
    load('Turbine_Calibration.mat')
    cal = Turbine_Calibration;
    Ch_num = 15;
end

% Loops through each channel and applies the calibration
Pressure = zeros(size(Frequency));
for jj = 1:length(Frequency(1,1,:))
    for ii = 1:Ch_num
        Pressure(:,ii,jj) = Frequency(:,ii,jj)*cal(ii,1)+cal(ii,2);
```


www.manaraa.com

```
    end
end

% Replacing all negative calibrated values with zero
Pressure(Pressure<0) = 0;

end
```

Published with MATLAB® R2018a

O.6 Tach to RPM

```
function [ts,RPM,ts_raw,RPM_Raw] = Tach_to_RPM(Tach,thresh,Pulse_Rev,dt)

% Treshhold values:
% DC One Tach: -0.6
% AC One Tach: -0.6
% TSS Tach:0.03
% OSS Tach:0.03
% DC Dyno Tach: N/A
% AC Dyno Tach: 0

%Pulse per revolution
% DC One Tach: 1
% AC One Tach: 1
% TSS Tach: 36
% OSS Tach: 24
% DC Dyno Tach: DC Offset Value 1mV/RPM
% AC Dyno Tach: 60

% User Changes Varibales
% Tach = OSS_Tach;
% thresh = 0.03;
% Pulse_Rev = 24;

%%%%%%%%%%%%%%%%%%% CODE BEGINNING %%%%%%%%%%%%%%%%%%%%%%%%%
% Code is built to convert a tachometer signal into a RPM

t = ((1:length(Tach))*dt)';             %Total time of data set
ta1 = Tach(1:(length(Tach))-1);         %Trailing value
ta2 = Tach(2:(length(Tach)));           %Leading value
v = find(ta1>=thresh & ta2<thresh);     %Locating each period

z(1:2)= [v(1) v(2)];
for i = 3:length(v)
    if z(i-1) == 0
        if (v(i)-v(i-2)) >= (.75*(v(2)-v(1)))
            z(i) = v(i);
        else
            z(i) = 0;
```


www.manaraa.com

```
        end
    else
        if (v(i)-v(i-1)) >= (.75*(v(2)-v(1)))
            z(i) = v(i);
        else
            z(i) = 0;
        end
    end
end
z(z<1) = [];

vs = Tach(z);                           %Tach values where peaks occur
ts = t(z);                              %Time when peak occurs

% RPM Calculation
RPM = zeros(1,length(ts)-1);
for i = 1:(length(ts)-1);
    RPM(i) = (60/(ts(i+1)-ts(i)))/Pulse_Rev;
end

% Raw RPM Calculation
vs_raw = Tach(v);                           %Tach values where peaks occur
ts_raw = t(v);                              %Time when peak occurs

RPM_Raw = zeros(1,length(ts_raw)-1);
for i = 1:(length(ts_raw)-1);
    RPM_Raw(i) = (60/(ts_raw(i+1)-ts_raw(i)))/Pulse_Rev;
end

% disp([ 'Average Speed- ', num2str(mean(RPM)), ' RPM'])

% Plotting Tach Signal with pulled values to calculate RPM
% subplot(2,1,1)
% plot(t,Tach,ts,vs,'o')
% xlabel('Time[sec]')
% ylabel('RPM')
%
% % Plotting RPM Signal
% subplot(2,1,2)
% plot(ts(2:end),RPM)
% xlabel('Time[sec]')
% ylabel('RPM')
end
```

Published with MATLAB® R2018a

O.7 Clutch Capacity

Data files 237

www.manaraa.com

```
% Purpose of Code:
% Takes averaged pressure data and creates a clutch capacity curve
```

Data files

```
close all
clear
clc

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%
% Opening excel file with averaged pressures for each channel
%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% Selecting file with data to be processed
answer = questdlg('Select Averaged Pressure Results',...
    'Data File Selection',...
    'Browse','Cancel','Cancel');
% Handle Response
switch answer
    case 'Browse'
        selection = 1;
    case 'Cancel'
        selection = 0;
end
if selection == 1
    [file,path] = uigetfile('*.*');
else
    return
end

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%
% Opening all corresponding dyno data
%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% Selecting file with data to be processed
answer = questdlg('Select Test Lab Data',...
    'Data File Selection',...
    'Browse','Cancel','Cancel');
% Handle Response
switch answer
    case 'Browse'
        selection = 1;
    case 'Cancel'
        selection = 0;
end
if selection == 1
```


www.manaraa.com

```
    [file2,path2] = uigetfile('*.*','Select One or More Files',...
        'MultiSelect','on');
else
    return
end

% Selecting Impeller, Turbine, or Stator for channel naming
list = {'Impeller' 'Stator' 'Turbine'};
Names = (listdlg('PromptString','Select test location:', 'SelectionMode',...
        'single','ListString',list));
```

Calculations

```
Pressure = importdata(fullfile(path,file));
count = 0;
Results = zeros(length(file2),length(Pressure.data(1,:))+5);

for ii = 1:length(file2)
    LMS_Data_to_Matlab(path2,file2{ii})

    %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
    %
    % Pressure Conversions (Pa to PSI)
    %
    %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

    Conv = 6894.757;
    C35R_Pressure = C35R_Pressure/Conv;
    C456_Pressure = C456_Pressure/Conv;
    CB1234_Pressure = CB1234_Pressure/Conv;
    CB26_Pressure = CB26_Pressure/Conv;
    CBLR_Pressure = CBLR_Pressure/Conv;
    LINE_Pressure = LINE_Pressure/Conv;
    SOL_FEED_Pressure = SOL_FEED_Pressure/Conv;
    TCC_APPLY_Pressure = TCC_APPLY_Pressure/Conv;
    TCC_REL_Pressure = TCC_REL_Pressure/Conv;
    Trans_IN_Pressure = Trans_IN_Pressure/Conv;
    Trans_OUT_Pressure = Trans_OUT_Pressure/Conv;

    %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
    %
    % Speed Multipled by Factor of 10 to get correct speed
    %
    %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

    AC_Tach = AC_Tach*10;
    DC_Tach = DC_Tach*10;
    TSS_RPM = TSS_RPM*10;
    Output_Speed = Output_Speed*10;
    Slip = Slip*10;
```


www.manaraa.com

```
    %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
    %
    % Averaged Values of interest
    %
    %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
    LINE_Pressure = mean(LINE_Pressure);
    TCC_APPLY_Pressure = mean(TCC_APPLY_Pressure);
    TCC_REL_Pressure = mean(TCC_REL_Pressure);
    DC_Tach = mean(DC_Tach);
    Output_Speed = mean(Output_Speed);
    Slip = mean(Slip);
    DC_Torque = mean(DC_Torque);
    AC_Torque = mean(AC_Torque);

    %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
    %
    % Delta pressure between each channel and TCC Apply and Rel pressure
    %
    %%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

    if TCC_APPLY_Pressure > TCC_REL_Pressure
        dP = Pressure.data(ii,:) - TCC_APPLY_Pressure;
        Charge_Pressure = TCC_APPLY_Pressure;
    else
        dP =  Pressure.data(ii,:) - TCC_REL_Pressure;
        Charge_Pressure = TCC_REL_Pressure;
    end

    Results(ii,:) = [DC_Tach DC_Torque Output_Speed AC_Torque Charge_Pressure dP];
    disp(['Processed Run ', num2str(ii), ' of ', num2str(length(file2))])
end

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%
% Clutch Capacity Calculations
%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% Radial distance for sensors on clutch plate
% Ch 5 through 11 in order
Radial_Location = [127 62.5 25.9 96.7 62.5 96.7 25.9]'/1000; % [mm] to [m]

F_loc = zeros(length(Results(:,1)),1);
Force = F_loc;
P_profile = zeros(205,length(F_loc));
F_profile = zeros(204,length(F_loc));

for ii = 1:length(Results(:,1))
    [F_loc(ii),Force(ii),x,P_profile(:,ii),F_profile(:,ii)] =...
        Resultant_Force(Radial_Location,Results(ii,10:16),0);
end
```


www.manaraa.com

```
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%
% Friction Coefficient Calculations
%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

r_o = 0.1235;       % [m] outer effective radius of TCC, outer radius of friction
material
r_i = 0.0215;       % [m] inner radius of TCC
r = 0.0215:0.0005:0.1235; % m



c = 3/(2*pi*(r_o^3 - r_i^3));

mu = (Results(:,2)./((mean(P_profile)' + Results(:,5))*6894.757))*c;

c = ((P_profile(2:end,:) + Results(end,5))*6894.757).*repmat((r(2:end).^3-r(1:end-
1).^3)',1,11);

mu_profile = (3*Results(end,2))./(2*pi*sum(c));

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%
% Clutch Capacity Plots
%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

figure
box on
hold on
plot(Results(:,5),Results(:,2),'o')
p = polyfit(Results(:,5),Results(:,2),1);
y = polyval(p,Results(:,5));
plot(Results(:,5),y)
ylim([0 140])
xlabel('TCC Apply Pressure [PSI]')
ylabel('Torque [Nm]')
title('Torque Converter Clutch Capacity')

yyaxis right
plot(Results(:,5),mu_profile,'d')
ylabel('Friction Coefficient [--]')

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%
% Force Location Plots
%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
```


www.manaraa.com

```
figure
box on
hold on
scatter(Results(:,5),F_loc,Force*10)
p = polyfit(Results(:,5),F_loc,1);
y = polyval(p,Results(:,5));
plot(Results(:,5),y)
plot([Results(1,5)-10 Results(end,5)+10],[0.108 0.108],':k')
xlim([15 55])
ylim([0.0215 0.1235])
xlabel('TCC Apply Pressure [PSI]')
ylabel('Resultant Force Location [m]')
title('Torque Converter Clutch Force')

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%
% Pressure Plots
%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

% Plots for either turbine 15 channels or 7 channels
if Names == 3
    figure
    box on
    plot(Results(:,5),Results(:,6:9),'--k')
    plot(Results(:,5),Results(:,16:end),'--k')
    hold on
    plot(Results(:,5),Results(:,10:16),'k')
    ylim([-40 40])
    xlabel('TCC Apply Pressure [PSI]')
    ylabel('Effective Pressure [PSI]')
    title('Turbine')
elseif Names == 2
    figure
    box on
    plot(Results(:,5),Results(:,6:end),'--k')
    ylim([-40 40])
    xlabel('TCC Apply Pressure [PSI]')
    ylabel('Effective Pressure [PSI]')
    title('Stator')
else
    figure
    box on
    plot(Results(:,5),Results(:,6:end-2),'--k')
    hold on
    plot(Results(:,5),Results(:,end-1:end),'k')
    ylim([-40 40])
    xlabel('TCC Apply Pressure [PSI]')
    ylabel('Effective Pressure [PSI]')
    title('Impeller')
end
```


www.manaraa.com

Published with MATLAB® R2018a

O.8 Resultant Force

```
function [F_loc,Force,x1,P_profile,F_profile] = Resultant_Force(Radial_Location,Data,on)
% Required Format:
% Radial_Location - 1st input: radial distance on the clutch plate for each
% sensor
% Data - 2nd input: Open, Slip, or Locked Data
% on - 3rd input: on means the TCC is in the open condition
% F_loc - 1st output: Radial location where the resultant force is acting
% Force - 2nd output: resultant force from the pressure in kN
%
% Purpose of Code:
% Finds the resultant force from experimental pressure data on clutch plate

% Back
% Largest raduis of friction material on clutch plate is 123.5 mm
% Smallest radius of clutch plate is 21.5 mm
x1 = 0.0215:0.0005:0.1235; % m
p = polyfit(Radial_Location(1:4),Data(1,1:4)',2);
y1 = polyval(p,x1);

% Front
if on == 1
    x2 = 0.0215:0.0005:0.1235; % m
else
    % Max radius to friction material is 108 mm
    x2 = 0.0215:0.0005:0.108; % m
end
p = polyfit(Radial_Location(5:end),Data(1,5:end)',2);
y2 = polyval(p,x2);

% Pressure profile acting on the clutch plate
P_profile = y1(1:length(y2))-y2;
P_profile = [P_profile y1(length(y2)+1:end)];

A = 2*pi*x1(2:end).^2-2*pi*x1(1:end-1).^2; % m^2
F_profile = P_profile(2:end).*6894.757.*A; % N
Force = cumsum(F_profile);
F_loc = find(Force >= max(Force)/2,1);
F_loc = x1(F_loc);
if isempty(F_loc)
    F_loc = x1(1);
end
Force = max(Force)/1000;                        % kN
end
```

Published with MATLAB® R2018a

www.manaraa.com

O.9 Shape Graphing

```
function RGB = Shape_Graphing(I,x,mag,mag_max)
% Required Format:
% I - 1st input: imread('image name')
% x- 2nd input: width of rectangles (default 25 for TC)
% mag - 3rd input: pressure mags of ch 5-11 for turbine
% mag_max - 4th input: maxium value for all pressures in maq matrix
% RGB - output: Info for imshow(RGB)
%
% Purpose of Code:
% Create a frame of the pressures across the TC clutch plate

%I = imread('TC Clutch.png');

%x = 25;

% Bottom Right Channel
if mag(1,3) < 0
    RGB = insertShape(I,'FilledRectangle',[270 725-x abs(mag(1,3))/mag_max*100
x],'Color','cyan','Opacity',1);
else
    RGB = insertShape(I,'FilledRectangle',[270 725-x mag(1,3)/mag_max*100
x],'Color','red','Opacity',1);
end

if mag(2,3) < 0
    RGB = insertShape(RGB,'FilledRectangle',[270 725 abs(mag(2,3))/mag_max*100
x],'Color','blue','Opacity',1);
else
    RGB = insertShape(RGB,'FilledRectangle',[270 725 mag(2,3)/mag_max*100
x],'Color','green','Opacity',1);
end

% Middle Right Channel
if mag(1,2) < 0
    RGB = insertShape(RGB,'FilledRectangle',[220 485-x abs(mag(1,2))/mag_max*100
x],'Color','cyan','Opacity',1);
else
    RGB = insertShape(RGB,'FilledRectangle',[220 485-x mag(1,2)/mag_max*100
x],'Color','red','Opacity',1);
end

if mag(2,2) < 0
    RGB = insertShape(RGB,'FilledRectangle',[220 485 abs(mag(2,2))/mag_max*100
x],'Color','blue','Opacity',1);
else
    RGB = insertShape(RGB,'FilledRectangle',[220 485 mag(2,2)/mag_max*100
x],'Color','green','Opacity',1);
end
```


www.manaraa.com

```
% Top Middle Right Channel
if mag(1,4) < 0
    RGB = insertShape(RGB,'FilledRectangle',[180 270-x abs(mag(1,4))/mag_max*100
x],'Color','cyan','Opacity',1);
else
    RGB = insertShape(RGB,'FilledRectangle',[180 270-x mag(1,4)/mag_max*100
x],'Color','red','Opacity',1);
end

if mag(2,4) < 0
    RGB = insertShape(RGB,'FilledRectangle',[180 270 abs(mag(2,4))/mag_max*100
x],'Color','blue','Opacity',1);
else
    RGB = insertShape(RGB,'FilledRectangle',[180 270 mag(2,4)/mag_max*100
x],'Color','green','Opacity',1);
end

% Top Right Channel
if mag(1,1) < 0
    RGB = insertShape(RGB,'FilledRectangle',[170 90-x abs(mag(1,1))/mag_max*100
x],'Color','cyan','Opacity',1);
else
    RGB = insertShape(RGB,'FilledRectangle',[170 90-x mag(1,1)/mag_max*100
x],'Color','red','Opacity',1);
end

if mag(2,1) < 0
    RGB = insertShape(RGB,'FilledRectangle',[170 90 abs(mag(2,1))/mag_max*100
x],'Color','blue','Opacity',1);
else
    RGB = insertShape(RGB,'FilledRectangle',[170 90 mag(2,1)/mag_max*100
x],'Color','green','Opacity',1);
end

% Top Left Channel
if mag(1,6) < 0
    RGB = insertShape(RGB,'FilledRectangle',[160-abs(mag(1,6))/mag_max*100 270-x
abs(mag(1,6))/mag_max*100 x],'Color','cyan','Opacity',1);
else
    RGB = insertShape(RGB,'FilledRectangle',[160-mag(1,6)/mag_max*100 270-x
mag(1,6)/mag_max*100 x],'Color','red','Opacity',1);
end

if mag(2,6) < 0
    RGB = insertShape(RGB,'FilledRectangle',[160-abs(mag(2,6))/mag_max*100 270
abs(mag(2,6))/mag_max*100 x],'Color','blue','Opacity',1);
else
    RGB = insertShape(RGB,'FilledRectangle',[160-mag(2,6)/mag_max*100 270
mag(2,6)/mag_max*100 x],'Color','green','Opacity',1);
end
```


www.manaraa.com

```
% Middle Left Channel
if mag(1,5) < 0
    RGB = insertShape(RGB,'FilledRectangle',[180-abs(mag(1,5))/mag_max*100 490-x
abs(mag(1,5))/mag_max*100 x],'Color','cyan','Opacity',1);
else
    RGB = insertShape(RGB,'FilledRectangle',[180-mag(1,5)/mag_max*100 490-x
mag(1,5)/mag_max*100 x],'Color','red','Opacity',1);
end

if mag(2,5) < 0
    RGB = insertShape(RGB,'FilledRectangle',[180-abs(mag(2,5))/mag_max*100 490
abs(mag(2,5))/mag_max*100 x],'Color','blue','Opacity',1);
else
    RGB = insertShape(RGB,'FilledRectangle',[180-mag(2,5)/mag_max*100 490
mag(2,5)/mag_max*100 x],'Color','green','Opacity',1);
end

% Bottom Left Channel
if mag(1,7) < 0
    RGB = insertShape(RGB,'FilledRectangle',[250-abs(mag(1,7))/mag_max*100 720-x
abs(mag(1,7))/mag_max*100 x],'Color','cyan','Opacity',1);
else
    RGB = insertShape(RGB,'FilledRectangle',[250-mag(1,7)/mag_max*100 720-x
mag(1,7)/mag_max*100 x],'Color','red','Opacity',1);
end

if mag(2,7) < 0
    RGB = insertShape(RGB,'FilledRectangle',[250-abs(mag(2,7))/mag_max*100 720
abs(mag(2,7))/mag_max*100 x],'Color','blue','Opacity',1);
else
    RGB = insertShape(RGB,'FilledRectangle',[250-mag(2,7)/mag_max*100 720
mag(2,7)/mag_max*100 x],'Color','green','Opacity',1);
end
end
```

Published with MATLAB® R2018a

O.10 Text Graphing

```
function RGB = Text_Graphing(I,Data,Cond)
% Required Format:
% I - 1st input: imread('image name')
% Data - Open, Slip, or Locked Data
% Cond - Condition the TC is in; Open, Slip, Locked
%
% Purpose of Code:
% Add text to a frame with input, output, and charge pressure information
```


www.manaraa.com

```
RGB = insertText(I,[590 30],['TCC '
Cond],'FontSize',36,'BoxOpacity',1,'BoxColor','white');
RGB = insertText(RGB,[530 100],'Charge
Pressure','FontSize',36,'BoxOpacity',1,'BoxColor','white');
RGB = insertText(RGB,[530 175],['30 Nm: ' num2str(Data(1,17),'%0.1f') ' [PSIa]'],...
    'FontSize',30,'BoxOpacity',1,'BoxColor','white');
RGB = insertText(RGB,[530 240],['75 Nm: ' num2str(Data(2,17),'%0.1f') ' [PSIa]'],...
    'FontSize',30,'BoxOpacity',1,'BoxColor','white');
RGB = insertText(RGB,[550 310],'Input Speed',...
    'FontSize',36,'BoxOpacity',1,'BoxColor','white');
RGB = insertText(RGB,[550 380],[num2str(Data(1,18),'%0.0f'),'/'
num2str(Data(2,18),'%0.0f'), ' [RPM]'],...
    'FontSize',30,'BoxOpacity',1,'BoxColor','white');
RGB = insertText(RGB,[550 460],'Output Speed',...
    'FontSize',36,'BoxOpacity',1,'BoxColor','white');
RGB = insertText(RGB,[590 530],[num2str(Data(1,1),'%0.0f') ' [RPM]'],...
    'FontSize',30,'BoxOpacity',1,'BoxColor','white');
RGB = insertText(RGB,[600 600],'40 PSI =',...
    'FontSize',30,'BoxOpacity',1,'BoxColor','white');
RGB = insertShape(RGB,'FilledRectangle',[620 650 100 25],'Color','black','Opacity',1);

end
```

Published with MATLAB® R2018a

www.manaraa.com

www.manaraa.com