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TRANSIENT MANEUVERS AND PRESSURE ANALYSIS ON AN AUTOMOTIVE
TORQUE CONVERTER

By

Abigail A. Hempy

A THESIS

Submitted in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

In Mechanical Engineering

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

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Preface

This research is a continuation of a Ford-sponsored project from a previous student, Mark Woodland. The previous work involved three main objectives. First was to develop a test cell to run a torque converter instrumented with 29 pressure transducers along with its pairing front wheel drive six-speed transmission [1]. Second was to create a procedure for collecting data and measuring transient events in addition to publishing this procedure through SAE in order to further the development of efficient powertrains as well as being able to present large sets of data in a manageable fashion [1]. Lastly, the test procedures created needed to mimic conditions seen in-vehicle; this involved gathering baseline performance data, gear shifting, and multiple torque converter clutch engagement scenarios [1].

The current work presented sought to build upon the previous work by one main objective: altering the test cell to better mimic in-vehicle scenarios by replacing the large-inertia DC dynamometer with a smaller BorgWarner electric machine. Thus, with new control and performance capability, the current research completed new test conditions requested by the customer. The objective was to identify any vibration and harshness or controllability issues with these scenarios through examining internal fluid behavior. The test conditions included a negative torque sweep, coast down, and negative torque input with a slip condition.

Acknowledgements

Without being able to visit Michigan Tech, attend graduation, or watch my defense in person, I hope this thank you at least makes up for some of what we have all been through in 2020. Thank you to my family. I have written so many articles and essays explaining "my mom is an artist, and my dad is a computer engineer" and while it may capture some of my personality and work ethic, it does not capture their roles in my life. I could not ask for better parents and I am so proud to be their daughter. My brothers have been my solid foundation and motivation through trying times during graduate school and I thank Willy and Samantha for listening and encouraging me over the phone. My family's support through my schooling has been essential to my success and I thank God for their patience and love.

I would like to thank Ford Motor Company for sponsoring this project, without their financial support, this research would not be possible. Engineers John Brevick, Steve Frait, and Ram Sudarsan Devedran provided unending technical knowledge and I appreciate their insight greatly.

Thank you to my advisors, Dr. Jason Blough and Dr. Darrell Robinette. They reassured me and were eager to be actively involved throughout my project and answer questions. They provided guidance for my future career and reminded me of the light at the end of the tunnel.

I would like to provide my most sincere gratitude for Mark Woodland. His previous research, unending support over the phone, wealth of knowledge, and extremely organized and detailed documentation made the project continuation a seamless transition. At times I thought I was lost; Mark was always there to help. I hope he is proud of the continued work, as I have put my best effort to match the dedication that he demonstrated throughout his graduate career at Tech.

Thank you to Luke Jurmu. We shared the test cell but also a lot of time working on issues and troubleshooting. He helped me many times and was available for phone support.

I would like to give a special thanks to Tucker Alsup. Though he was not directly involved with this project, he assisted me in many accessory installations for electrical wiring and other periphery in the test cell. Thank you to all the engineers at APS Labs for your patience and insight.

Abstract

This work involves an investigation of internal fluid behavior of an automotive torque converter in a front-wheel drive automatic 6-speed transmission. The fluid behavior is identified through 29 pressure transducers instrumented throughout the torus, acquired through IR Telemetrics multiplexed channels, and analyzed with custom MATLAB code. The main vehicle operating conditions studied in this research are back drive scenarios or low motoring torques. Findings showed speed and torque limits for open converter coast down conditions as well as pressure field behavior with negative input torque.

1 Introduction

Torque converters are used to assist in power transmission in a vehicle from the engine to the transmission to the wheels. Their design can be manipulated to change fuel efficiency and drive quality, primarily sacrificing one for the benefit of the other. Improving both qualities to conserve fuel and enhance driver feel are of interest to many automotive companies around the world.

1.1 Objectives

The objective of this research was to identify fluid behavior causing instances of vibration, harshness, or lack of controllability during negative torque transient conditions. Through utilizing telemetry-based pressure measurements, the internal flow data was gathered to provide data toward computational fluid dynamics (CFD) modeling of the torque converter. Through physical testing and simulation, a greater understanding can be gathered about the interactions between all three units: engine, transmission, and torque converter. The tests conducted for this research were completed on a test stand with an electric motor connected in series with the torque converter/transmission and ending with an AC dynamometer. The tests consisted of performance runs, negative torque sweeps, coast downs, and tests with negative torque input with a slip condition.

1.1.1 Torque Converter Basics

A torque converter transfers power from an engine output shaft to transmission input using fluid interactions. The three main parts of a torque converter as the impeller, stator, and turbine. The combination of these three components is called the torus. A torque converter can act as a torque multiplication device when utilizing fluid as the medium of transmission or as a direct coupling when the torque converter is mechanically locked by

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way of a lock-up clutch. These two modes of power transmission are demonstrated in Figure 1.
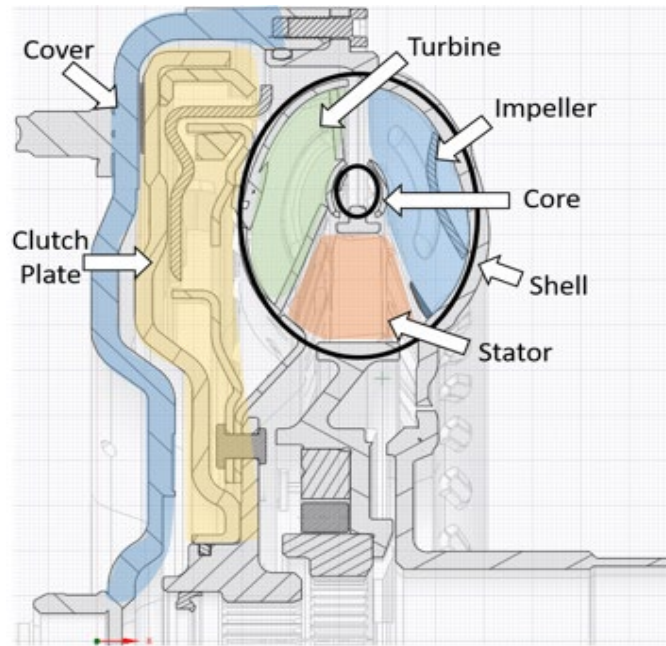
Figure 1: Cross-sectional diagram of torque converter parts [1]

The fluid interaction is accomplished by the impeller pumping fluid into the turbine; the turbine then absorbs the energy and deflects it in the opposite direction toward the stator. The stator creates the torque multiplication by directing flow back to the impeller.

Using the lock-up clutch generates nearly 100% efficiency in power transmitted from the source to the transmission. This is done by pressurizing the fluid and thus the clutch plate friction material is pressed on the outer cover of the torque converter as shown in Figure 2 .

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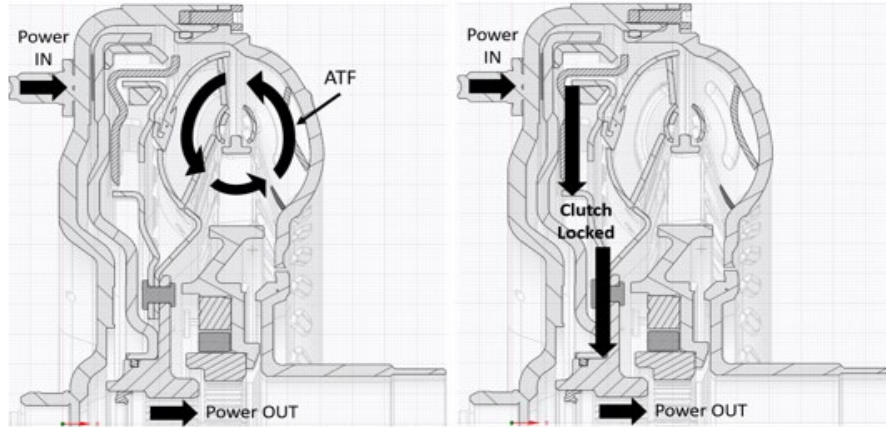
Figure 2: Torque converter power transmission diagram [1]

However, utilizing the clutch in all operating conditions will result in negative noise, vibration and harshness (NVH). It is also important to apply the clutch at the correct time in order to avoid glazing the clutch. The friction material on the surface of the clutch plate, often made out of paper-thin material, has the potential to be damaged if the surfaces are applied too forcefully or in situations of high-heat. There is an ideal time to start clutch application as shown in Figure 3.
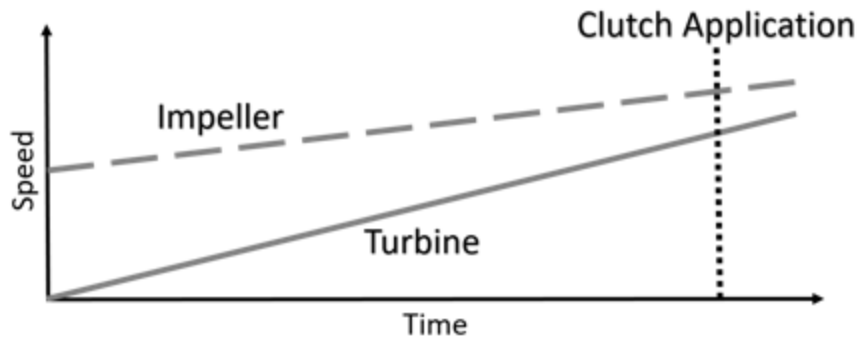
Figure 3: Clutch application demonstration [1]

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Therefore, to provide driver comfort and prevent damage to the components, the fluid inside the torque converter moves from the impeller (input side) to the turbine (output side) by way of the stator (middle). The stator can operate in two modes: stationary and free-wheeling. When the stator is stationary, torque is multiplied through the fluid. When the stator is rotating, it spins in one-direction by way of a one-way clutch to transfer fluid to the turbine.

The governing equations for run conditions and torque converter performance are explained below. These values will be used throughout the work to quantify data. Speed ratio is defined by Equation 1-1.

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

where SR represents speed ratio which is constituted by N_o, the turbine speed, and N_i, the impeller speed. A speed ratio close to 1 implies a small torque multiplication, and when the speed ratio is low (close to 0), torque multiplication is greater. Torque ratio is defined by Equation 1-2.

$$TR = \frac{T_o}{T_i} \qquad \textit{1-2}$$

where TR represents torque ratio which consists of T_o, the turbine torque, and T_i, the impeller torque.

A measure of torque converter performance is defined by K-factor. K-factor is represented by KF, which is constituted by N_i and T_i as shown in Equation 1-3.

$$KF = \frac{N_i}{\sqrt{T_i}} \qquad \textit{1-3}$$

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1.1.2 Transmission Basics

A transmission is intended to transmit power from the engine output shaft to the differential and to the wheels of a vehicle. This can be accomplished in a variety of ways. For example, BMW 5-speed manual transmissions made by ZF use a dual mass flywheel and spring clutch assembly to allow the user to manually apply the clutch, while reducing vibration, when shifting gears [2]. In this study, a 6-speed, FWD automatic transmission with a locked differential is used. A cross-section of such a transmission can be seen in Figure 4. The power comes in through the turbine shaft of the torque converter, through a series of planetary gears and clutch packs - with different clutches becoming engaged and disengaged depending upon the gear, to a chain leading to the differential and out to the axles. The clutches are engaged and disengaged by hydraulic pressure controlled by electronic solenoids controlled from the electronic control unit (ECU). Depending upon the amount of current sent from each solenoid will determine which gears are engaged.

1.Power IN
2. Planetary Gear Transfer
3. Chain Transfer
4. Final Drive
5. Power OUT
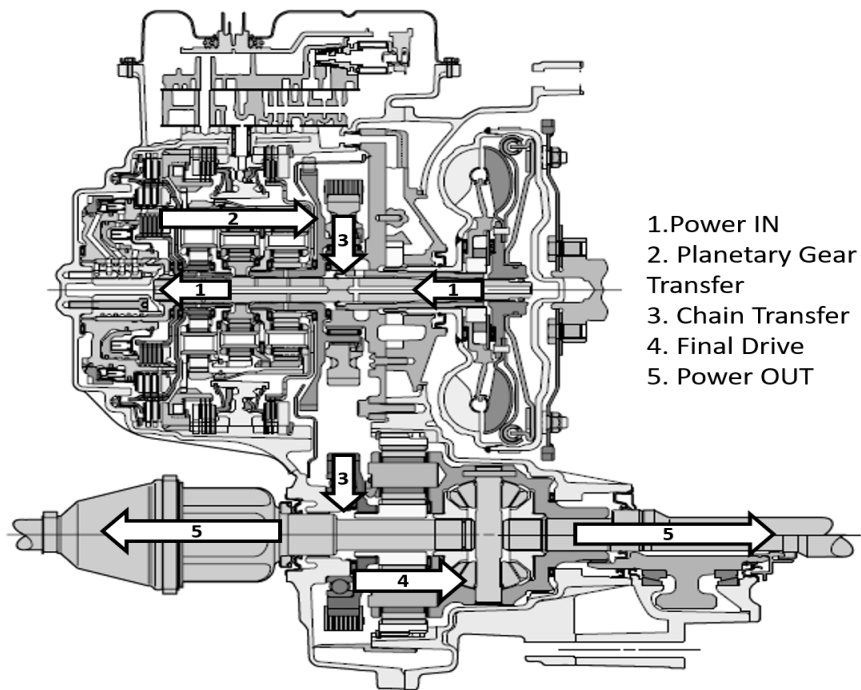
Figure 4: Transmission power flow diagram [1]

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2 Literature Review

Reviewing the literature of the field allowed this research to expand upon and dive deeper into areas that have not been previously explored. In terms of physical testing, there has been a number of studies on internal pressures and flow visualization of the general internal cavities in the impeller, stator, and turbine, but nothing extensive on clutch interaction. There have been few studies completed with specialty instrumentation to examine clutch fluid pressure effects during transmission conditions identical to in-vehicle operation. The studies that have been completed have either significantly modified the torque converter operation to examine the fluid or changed the characteristics of the fluid itself. Regarding simulation, there have been multiple studies on the design and development of different blade patterns of the torus, clutch friction material, fluid flow studies, and torque converter damping. However, no dynamic models of a clutch operation inside the torque converter have been developed. This research fills both vacancies by using specialty instrumentation to examine pressures on and near the torque converter clutch and using this testing, creates a functional dynamic model of a torque converter clutch interaction.

2.1 Torque Converter Experimentation

Torque converters and their internal flows have been studied in a multitude of ways. The torque converter internal pressures and clutch interactions during transient events have been studied under positive input torque scenarios [1]. A torsional shaker test was created to find isolation and damping capabilities of a torque converter clutch [3]. Torque converter turbine noise and cavitation noise was investigated over a range of speed ratios using acoustic measurement techniques [4]. The torque converter clutch interface has been studied using radiotelemetry to examine friction material effects from temperature variation [5]. Torque converter clutch slip control has been measured, with and without all-wheel drive, using an electronically controlled clutch and several controllers [6]. Ratcheting one-way clutches were also studied to examine the difference between roller one-way clutches and its effects on stresses in the converter [7]. Laser velocimetry was

used to observe flow fields inside a torque converter by creating a Plexiglas surface with different oil and metallic glass particles [8]. Tests were completed using liquid resin to paint onto material surfaces inside torque converter and a red spotted pigment to create a relationship between efficiency and flow pattern [9]. Static pressure measurements were completed in a torque converter stator with 72 pressure taps along different sections of the blade to calculate stator torque [10].

2.2 Transmission Experimentation

Multiple disk clutches were studied for Toyota's new front-wheel drive eight-speed transmission to determine the best performance characteristics of both friction material and torus design [11]. Developments were made for an 8-speed transmission to optimize oil pump control, installation sizing, and adaptation to its respective engine saving 6% efficiency in comparison to the previous 6-speed [12]. Shift quality was improved for a wet-type dual clutch transmission by using a control strategy that accounts for oil pressure and engine speed [13].

2.3 Simulation

Research has been completed on correlating CFD to pressure measurements taken from cavities inside a torque converter [14]. This research was expanded upon further to be able to predict pressure trends during tests, specifically with flow recirculation in low speed ratio conditions [15]. Numerical investigations included a study on flow-induced excitations in a torque converter using CD-Adapco to test a modified stator design [16]. Simulation was also used to reduce noise and vibration in a torque converter clutch by a lumped parameter model to represent damping through a series of mass-damper systems [17]. Investigations into jet-wake and lows in a torque converter were completed in STARCCM to examine possible sources of non-uniformity to reduce losses [18]. Dynamic torque characteristics of a torque converter were also studied using a one-

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dimensional parameter model to see the effects of speed, torque, and design on vibration frequency [19].

3 Experimental Set-Up

As previously stated, the research presented here is a continuation of an ongoing study to understand internal flow fields of the torque converter during clutch applications. The initial goal of the study was to create a test cell capable of examining multiple different transmission set-ups. As can be seen from Figure 5, this was accomplished with a versatile set-up. 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 [1].

This test cell set-up, shown in Figure 5 was used to practice working with the transmission and dynamometer controller to understand the accessible maneuvers of this layout. Performance testing was completed to create a comparison for future set-ups. After examining data from this study, the test conditions of interest for future testing required more capability than the previous set-up. The goals of the new test cell set-up were to first, create a better set-up for mimicking vehicle operation with a lower inertia driving input and second, to understand the controllability or vibration of the torque converter during negative torque scenarios. The following sections describe the new test
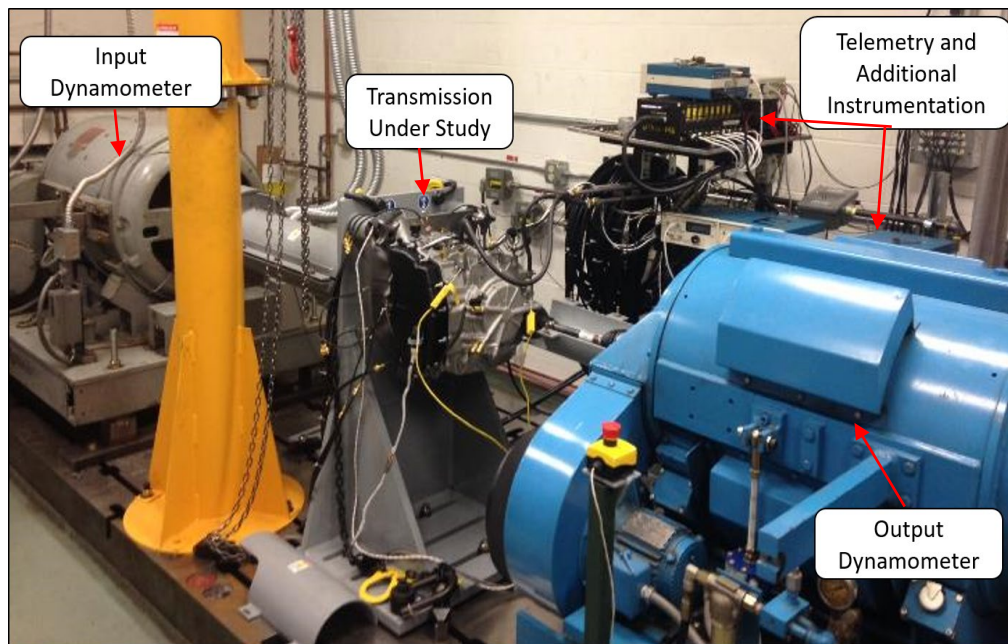
Figure 5: Previous experimental set-up [1]

cell set-up, data acquisition, absorbing dynamometer controller, electric motor controller, transmission instrumentation and controller, and lastly, the torque converter instrumentation.

3.1 Test Cell Set-Up

The test cell arrangement used in this study is diagramed in Figure 6.
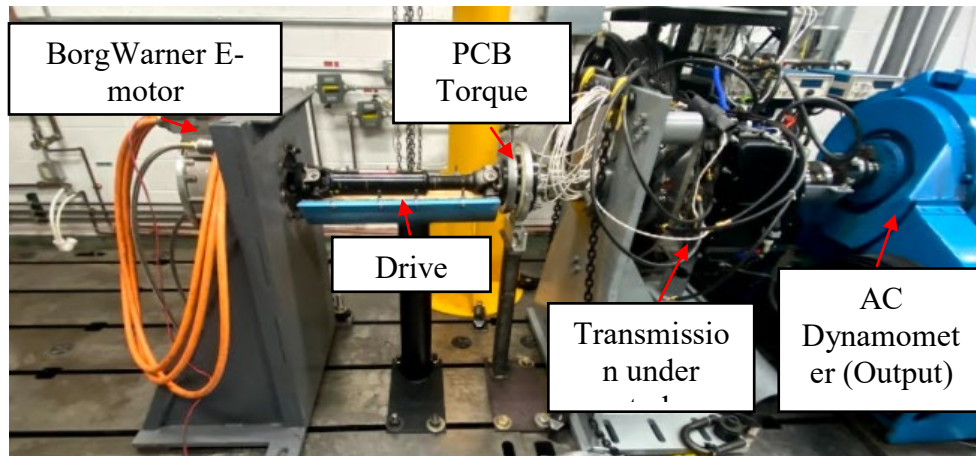
Figure 6: New test cell set-up

The input motor is a BorgWarner HVH250-090 Electric Motor capable of 320 Nm of input torque at 700 V DC Bus Voltage with a peak power rating of 340 kW [20] . The output dynamometer is a General Electric 540 kW AC dynamometer. The transmission used in this study is a 6-speed 6F35 FWD transmission, used in commercial vehicles similar to a Ford Explorer or Escape. Input torque is recorded with a separate torque meter and speed with a laser tachometer on the rotating shaft. Output torque and speeds are recorded using the AC Dynamometer instrumentation and another laser tachometer. The differential on the transmission is welded to prevent any torque vectoring from interfering with results, in other words, the final drive is a fixed ratio.

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3.1.1 Fixtures and New Hardware

3.1.1.1 Shafting

Adapters were created to attach the torque meter hardware to the input bearings. A tone wheel was added to collect speed input RPM data. Using a dial indicator, each adapter was bolted and torqued in sequence and measured as shown in Figure 7. This was done one component at a time to adjust runout for each connection point. The goal runout for the final assembly was 0.005", but the system function without vibration issues up to 0.007". After final torque, the total runout is less than 0.003".
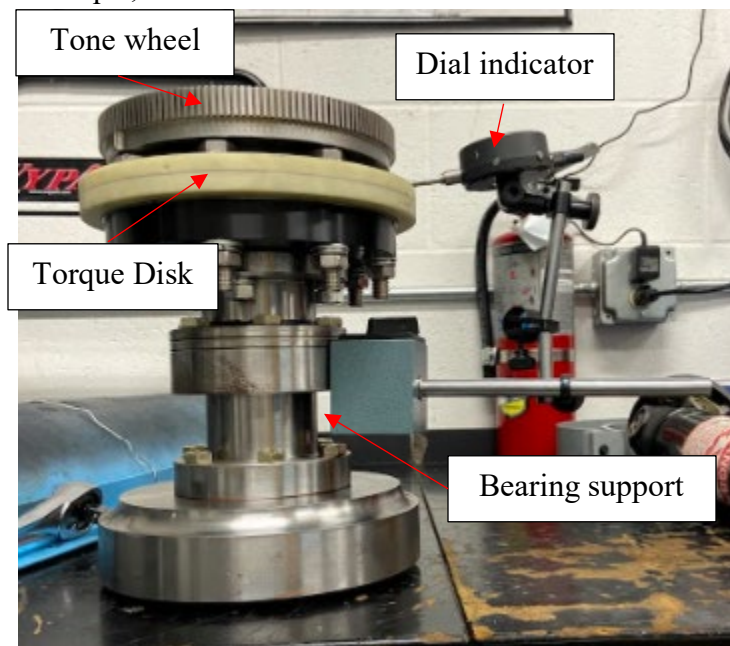
Figure 7: Torque meter shafting attachment runout measurement

3.1.1.2 Test Stand

A fixture was created to hold the electric motor on the bedplate during testing. Modifications were made from the previous test stand, shown in Figure 8, to bolt the stand directly to the bedplate rather than raising it off the floor using other mounts.
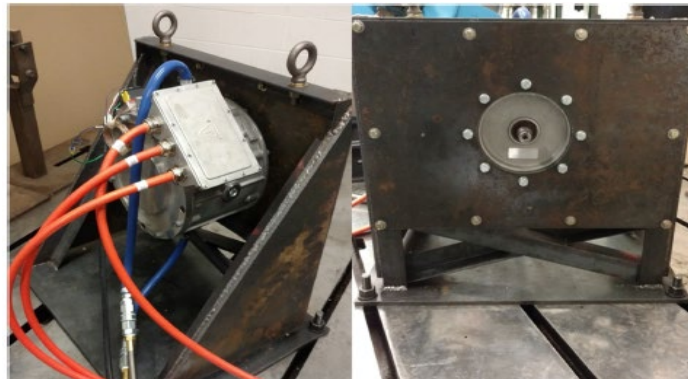
Figure 8: Electric motor stand for other side of test cell [3]

The new design, shown in Figure 9 weighed 450lbs but reduced complexity: no cross-bracing or angle-iron supports. Finite element analysis was used prior to finalizing the design to confirm that the stand would remain rigid during all testing scenarios.
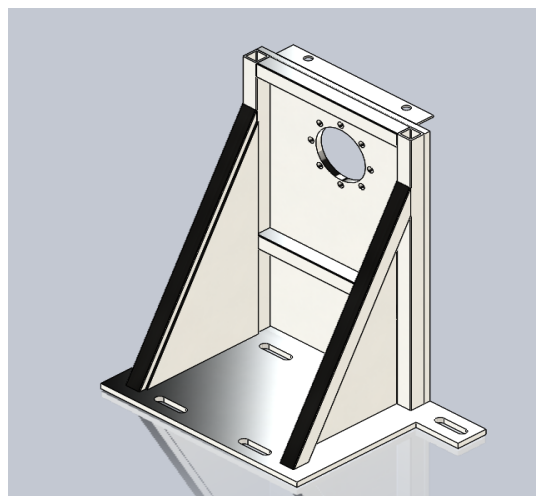
Figure 9: New motor stand design

Frequencies of interest were between 0 and 200 Hz because the primary operating

condition of the electric motor is between 500 and 3000 RPM which corresponds to 18.3-50 Hz. However, 2nd and 3rd order excitations were also of interest because of transient testing and any accidental axial misalignment during installation or deformation [3]. These frequencies would occur between 54.9 – 150 Hz.

Using the face of the bottom plate as a fixed constraint, a 50 kg mass (mass of the electric motor) was distributed among the 8 motor mounting bolts and a torsional load of 1000 Nm was applied or approximately three times the motor's peak torque capability. The frequencies of each bending mode of the fixture are listed in Table 1. This testing was completed to ensure that no bending mode occurred at a frequency of operation. For example, the maximum speed of the input to the transmission is 2500 RPM or 41.66 Hz and the first bending mode is beyond 41.66 Hz and its first and second order.

Table 1: Modes and frequencies for fixture analysis

Mode	Frequency
1	148.21 Hz
2	263.25 Hz
4	342.03 Hz
5	382.81 Hz

As shown in Figure 10, the first and second modes behaved in frequencies above the area of concern. The design was finalized, and drawings were distributed to be manufactured.

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3.1.2 Dynamometer Controller

The previous set-up with a DC driving dynamometer and a AC absorbing dynamometer
was controlled using a DYN-LOC IV and an AC2000 IGBT Digital Adjustable Speed
Driver controller [1]. These were interfaced with a custom LabVIEW Virtual Instruments
program to be able to run scripts automatically, run both dynamometers manually, and to
examine the test cell status [1]. Data could also be recorded in this software, but only
dynamometer and temperature measurements. A LabVIEW-based controller was used
with the BorgWarner electric machine as an input and the same AC2000 IGBT Digital
Adjustable Speed Driver for the AC dynamometer as an output.
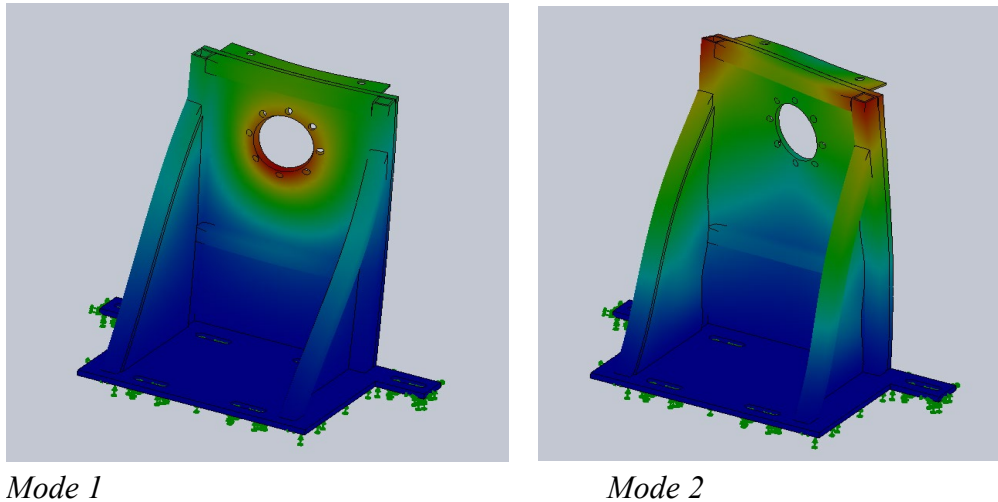
Mode 1   *Mode 2*
Figure 10: Main modes of concern and failure points

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3.2 Transmission Instrumentation

The transmission is instrumented with a set of pressure transducers as shown in the Table 2. The primary channels of interest are the line pressure, clutch pack pressures, and TCC apply and release because of the transient clutch maneuvers studied.

Table 2: Transmission Channels Only

Channel Number	Channel Name	Description
9	Trans_IN_Pressure	Transmission input pressure
10	Trans_OUT_Pressure	Transmission output pressure
11	LINE_Pressure	ATF feed line pressure
13	CB26_Pressure	Clutch pack pressure
31	C35R_Pressure	Clutch pack pressure
14	SOL_FEED_Pressure	Solenoid feed line pressure
15	CB1234_Pressure	Clutch pack pressure
16	CBLR_Pressure	Clutch pack pressure
17	TCC_APPLY_Pressure	Torque Converter Clutch apply pressure
18	TCC_REL_Pressure	Torque Converter Clutch release pressure
32	C456_Pressure	Clutch pack pressure

The instrumentation is installed as shown in Figure 11.
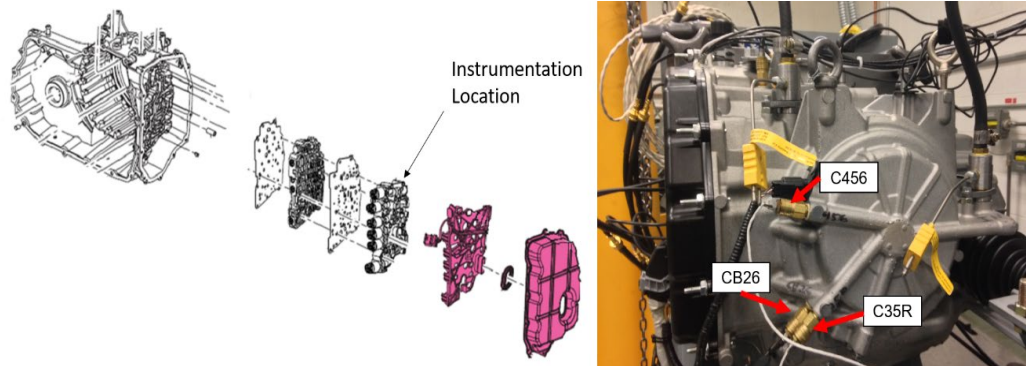
Figure 11: Transmission sensors [1]

The transmission was primarily run in 5th and 6th gear for practice tests because this ensured less load on the instrumentation (not as high of torque multiplication). For the recorded data, most tests were run in 2nd and 3rd gear since it was requested that the gear state for situations such as a stop-and-go light match the in-vehicle state. The gear ratios are listed in Table 3.

Table 3: Transmission gearing

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

3.3 Torque Converter Instrumentation

The torque converter was instrumented with 29 pressure transducers that transmit signals via radio waves. There are 7 on the impeller, 7 on the stator, and 15 on the turbine and clutch [1]. There are more on the clutch since the behavior of this region was of most interest to the study. The reason for the large amount was to gather the best possible signal from every region of the torque converter. The sensors are dispersed throughout different blades. The two types of sensors used are Kulite XCEL-072 and Kulite LE-160 to handle the temperature and range of the conditions inside (ATF temperatures limited to 230°C) [1]. The sensors were instrumented by IR Telemetrics (IRT) as well as the radio communication system.

There are three transmitters internal to the torque converter. One for the impeller, one for the stator, and one for the turbine. Each transmitter was tuned to a specific frequency to

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communicate the data acquired. The data was acquired through antennae placed throughout the torus. There are three different bundles of antennae for each section of the torus. The first bundle contains four antennae for the turbine, three for the stator, and three for the impeller. There are three receivers for each transmitter. Each receiver was tuned to the same frequency as its corresponding transmitter. The separation of frequencies was done so as not to interface with the signals coming from a different section of the torque converter. Table 4 shows the three different transmitters, their corresponding sections, antennae color, and frequencies.

Table 4: Transmitter Information [21]

Transmitter	Number of Channels	Antennae Bundle Color	Corresponding Frequency	Instrumentation Location on Torque Converter
A	7	Green	2490 kHz	Impeller
B	7	Blue	2395 kHz	Stator
C	15	Red	2454 kHz	Turbine & Clutch

Transmitter A, B, and C instrumentation locations are shown in Figure 12, Figure 13, and Figure 14.
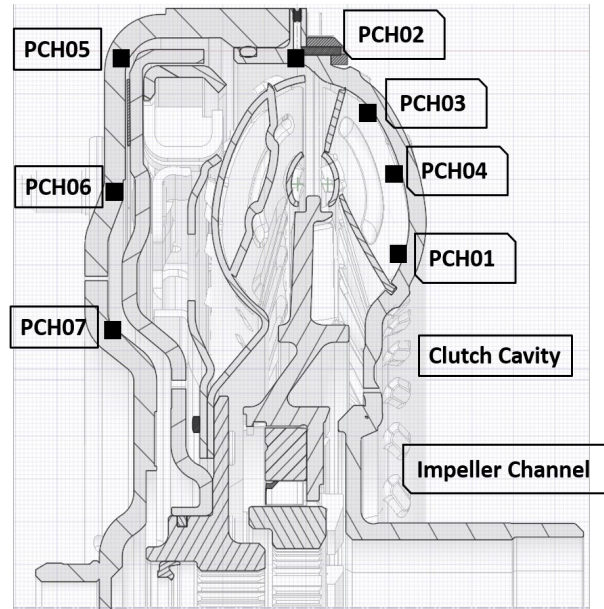
Figure 12: Transmitter A pressure transducer locations [15]

Figure 12: Transmitter A pressure transducer locations [15] shows three channels inside the clutch cavity on the front cover (PCH05, PCH06, PCH07), three between the impeller blades (PCH01, PCH03, PCH04), and one in between the impeller and turbine (PCH02).

Figure 13: Transmitter B pressure transducer locations [15] shows channels near the core
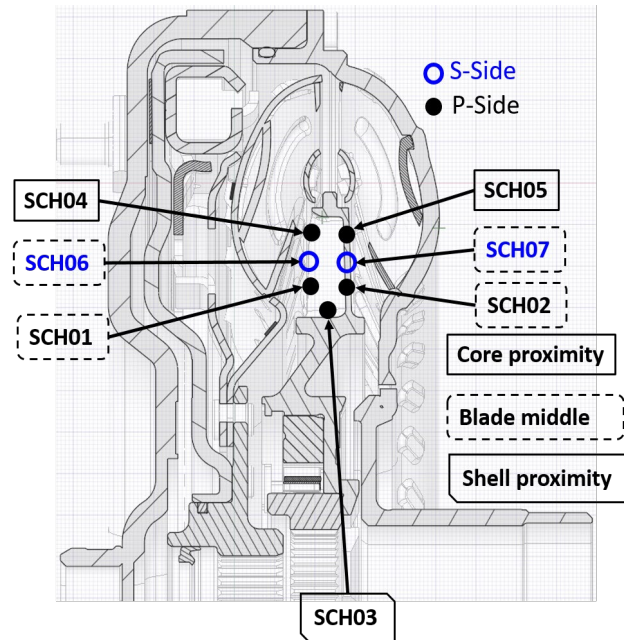
Figure 13: Transmitter B pressure transducer locations

(SCH04, SCH05), the middle (SCH06, SCH07), and shell (SCH01, SCH02, SCH03) on the stator blades. The suction and pressure sides of each measurement location is shown in blue and black respectively.

Figure 14: Transmitter C pressure transducer locations [15] shows the locations of the 15 transducers for the turbine and clutch. 6 are on the turbine blades and 9 on the clutch cavities [1].
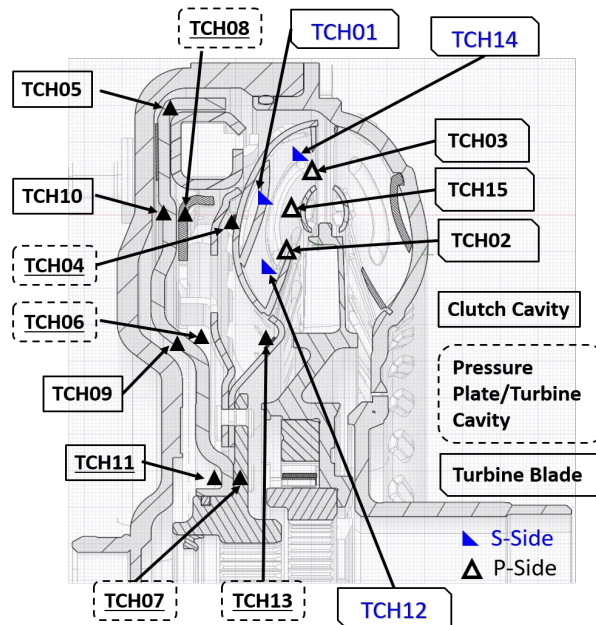
Figure 14: Transmitter C pressure transducer locations

Each transmitter was powered via induction coils to allow each portion of the torus to spin without wire interference [1]. Mounting locations for each transmitter and the induction coils are shown in Figures 15-21.
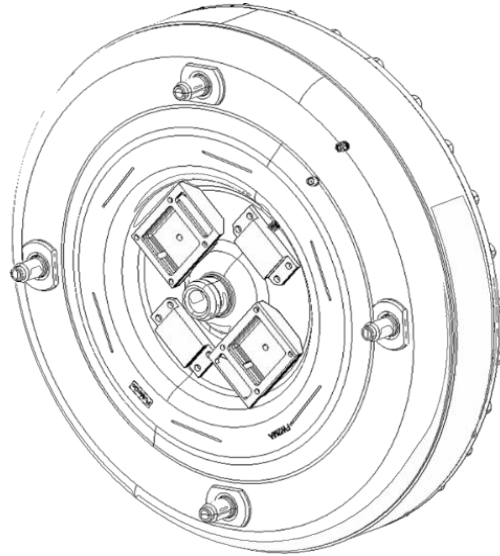
Figure 15: Transmitter A hardware for
power supply and transmitter [14]

Figure 15 shows the hardware for measuring the impeller channels from Transmitter A. They are located on the outside of the cover.
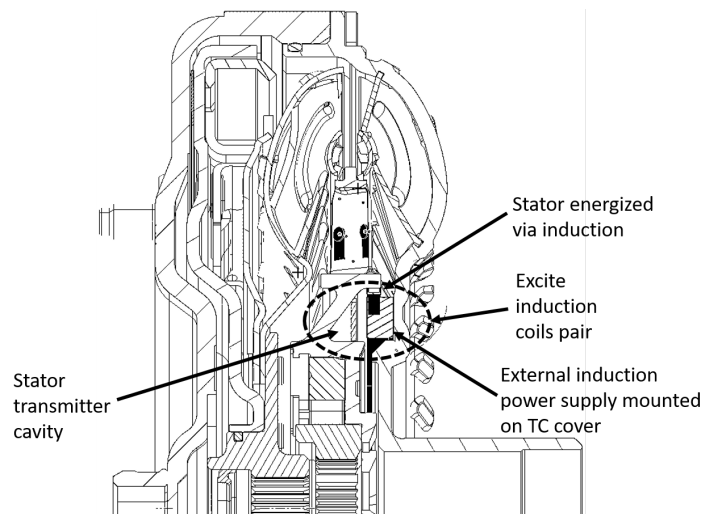
Figure 16: Transmitter B induction coils and transmitter location [14]

Figure 16 shows hardware locations for Transmitter B. Slots were cut into the impeller shell as shown in Figure 17 in order for the data to transmit outside of the converter [1].

External induction power supply mounted on TC cover

Signal slot
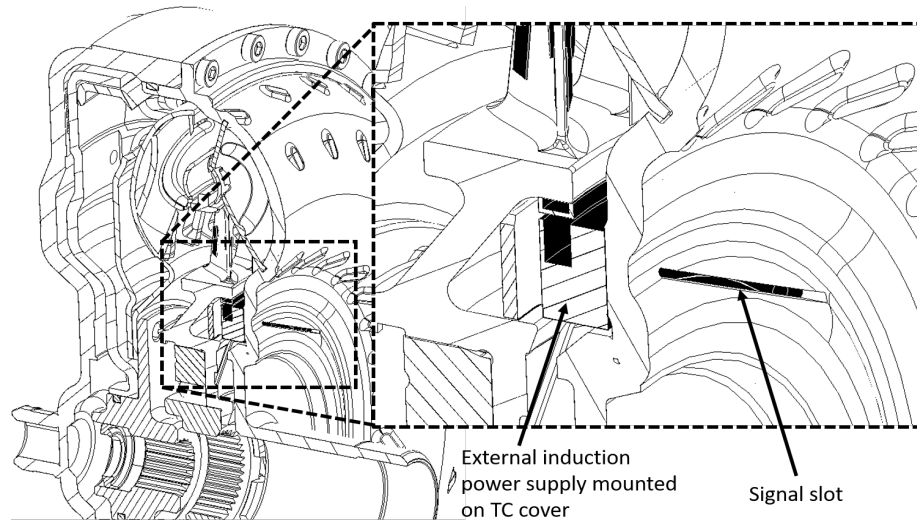
Figure 17: Transmitter B slot to transmit signal out of torque converter [14]

Figure 18 shows the induction coils for powering Transmitter C. The instrumentation was powered by the induction coil on the plate, but the turbine channels required pins to transmit power and signals [1]. The pins were designed to float for the clutch plate to move without crushing the hardware as shown in Figure 19 and Figure 20.

Transmitter packs

Pressure plate energized via induction

Excite induction coils pair

External induction power supply mounted on TC cover
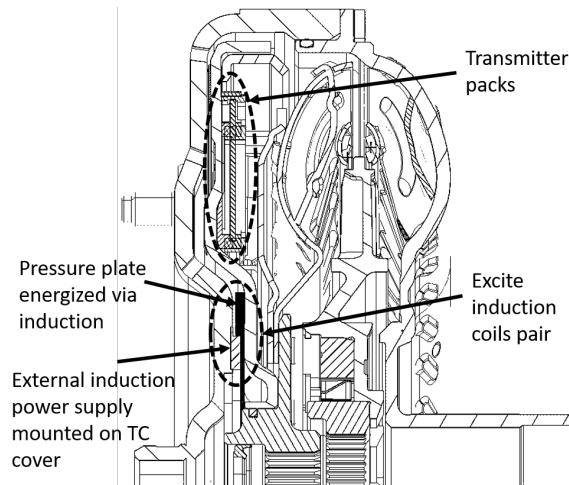
Figure 18: Transmitter C induction coil diagram [14]

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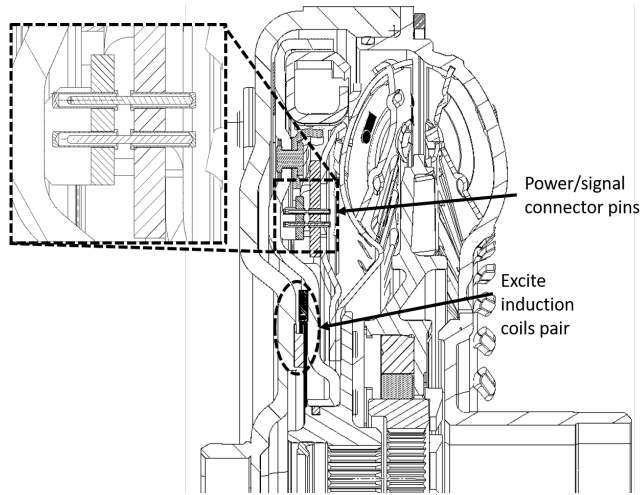
Figure 19: Power/signal connector pins for Transmitter C
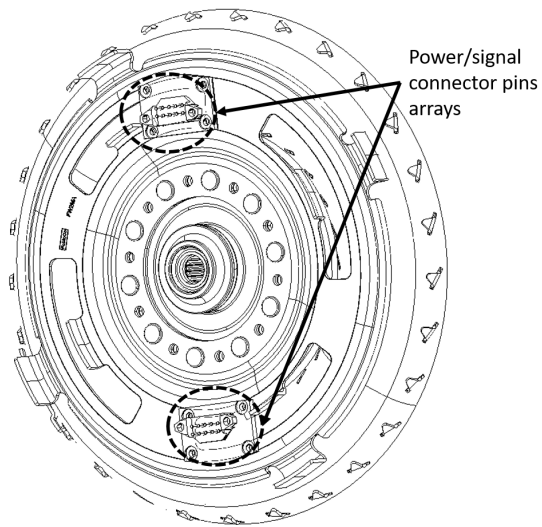
Figure 20: Transmitter B&C power and

signal connections [14]

Slots also needed to be cut in the pressure plate for the signals to transmit outside of the torque converter as shown in Figure 21.
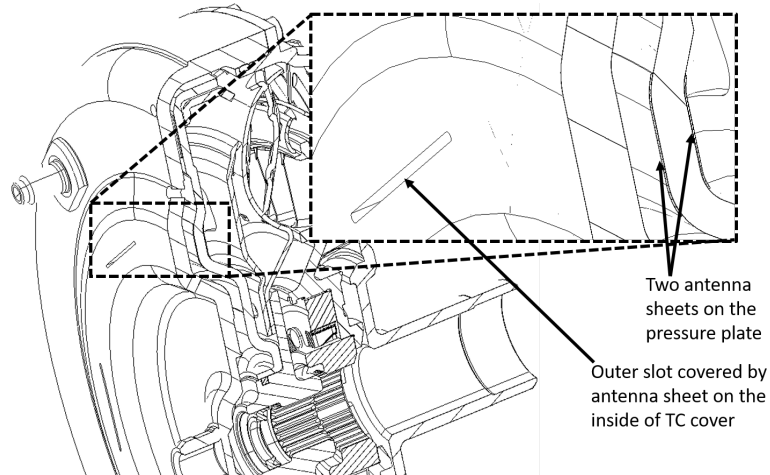
Figure 21: Transmitter C slot for signal [14]

4 Methods

4.1 Hardware Set-Up Procedures

A process must be followed to ensure the safe operation of the test cell. Prior to starting any test, a check list for this process can be found in Appendix G. Procedures for swapping transmissions can also be found in Appendix H.

4.1.1 Test Cell Set-Up

Before turning on any power for the drive cabinet or inverter cart, the test cell should be set up. The test fixture needs to be connected to the AC dynamometer. Install the half shaft adapter and half shaft with a ¾" standard socket using an impact driver as shown in Figure 22. This should be done in a crisscross pattern.
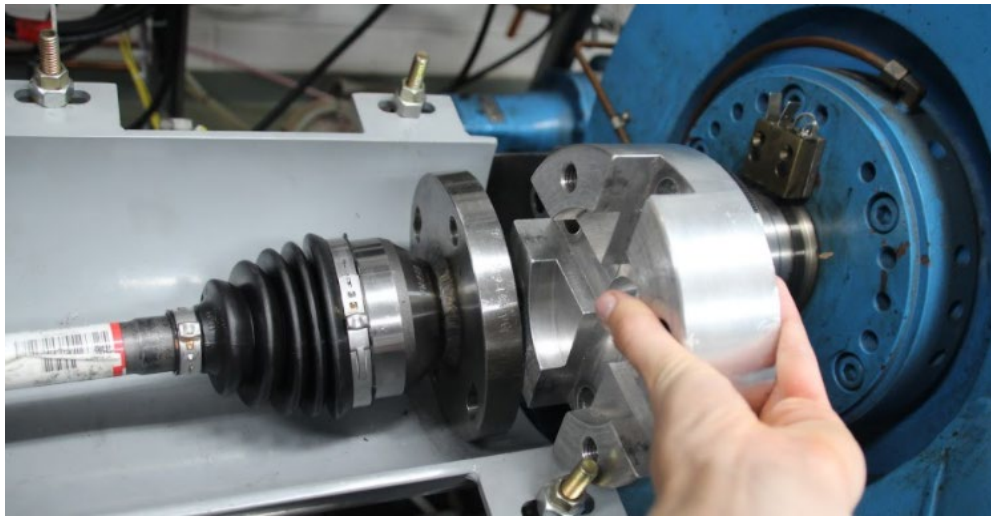
Figure 22: Transmission output shaft and adapter

Install the shaft guard using $\frac{9}{16}$ " standard hardware as shown in Figure 23.

Figure 23: Transmission output shaft guard

The AC dynamometer direction needs to be set to FORWARD as shown in Figure 24. (The direction needs to be set to REVERSE when the GM set-up on the front side of the cell is running).

Figure 24: AC Dynamometer direction set to FORWARD

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Turn on the NI Controller box to enable data collection and dynamometer control as shown in Figure 25.

Figure 25: NI Controller box

Turn on the solenoid controller power supply and solenoid controller as shown in Figure 26.

Figure 26: Solenoid controller and power supply.

Turn on power supply for transmission sensors and signal conditioning box for the AC speed. See Figure 27 and Figure 28.

Figure 27: Signal conditioner for AC One Tach

Figure 28: Power supply for transmission

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Ensure that both the electric motor and AC dynamometer rotate freely by hand as shown in Figure 29 and Figure 30.

Figure 29: Checking free rotation of input motor shaft
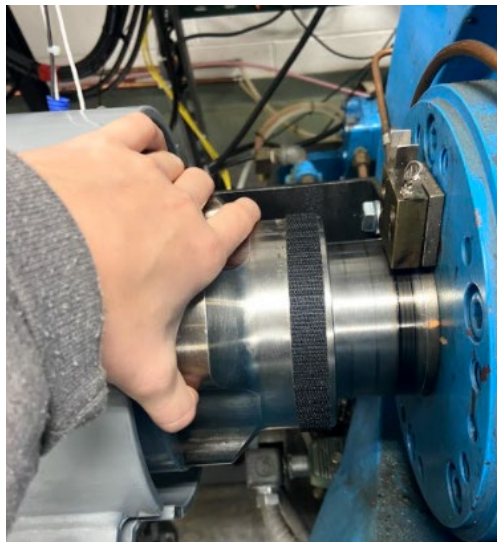
Figure 30: Checking free rotation of AC dynamometer shaft

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4.1.2 Inverter Cart Set-Up

The BorgWarner HVH250 motor must be powered using an inverter to convert the DC power from the dynamometer cabinet to AC. Before turning on the drive cabinet or contactors this procedure should be followed. The proper hook-up procedure begins with bolting the ground strap for the inverter to the bed plate as shown in Figure 31.

Figure 31: 9/16" grounding bolt for inverter to bedplate

The ground for the main electrical connector to the e-motor must also be connected to the ground bolt as shown in Figure 32.
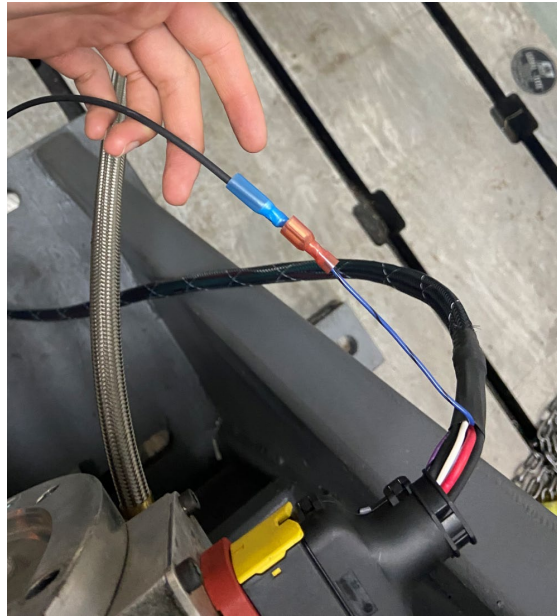
Figure 32: Ground connection for e-motor
electrical connector must be bolted to the

Then the cooling lines for the e-motor must be connected to the cart cooling system. This circulates and cools antifreeze from the cart to the electric motor to maintain a safe temperature during operation. Note that the input cooling line and the return line cannot be hooked up incorrectly because there is a female connection on the e-motor side for the inlet line and a male connection (also on the e-motor side) for the outlet line (Figure 33).

Figure 33: Cooling line connection for electric
motor to inverter cart cooling system

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Install the electrical connector to the e-motor to be able to provide torque commands and receive information on the motor's position as seen in Figure 34.
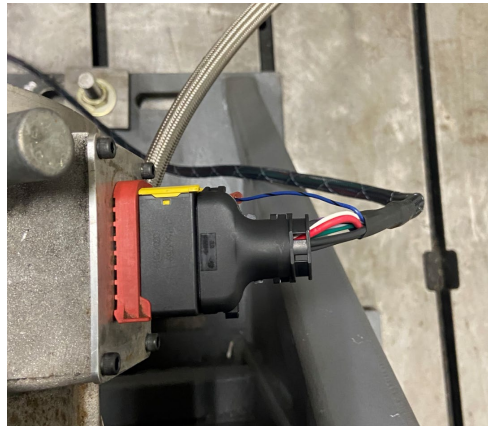
Figure 34: Electrical connector for e-motor position,
torque, and other controller information

The main high current plugs connect to the inverter cart. In Figure 35, on the left is the high current DC power from the dynamometer cabinet above the test cell and on the right is the high current AC power exiting the inverter connecting to the e-motor.

Figure 35: High current connections to the inverter cart. On the left,
DC power from the dynamometer cabinet, and on the right, high current
AC power feeding the e-motor.

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Reconnect the e-stop plug as shown in Figure 36.
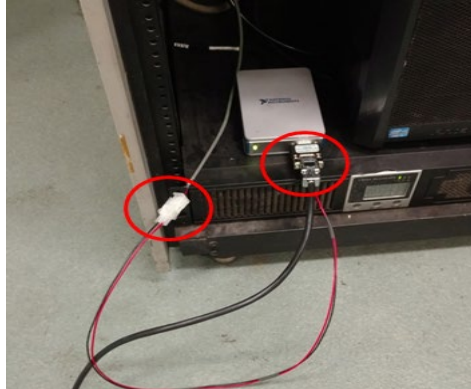
*Figure 36: NI system connections for
recording data and calibration*

Connect the NI system module 9862 for recording data, calibration, and motor control as
shown in Figure 37.
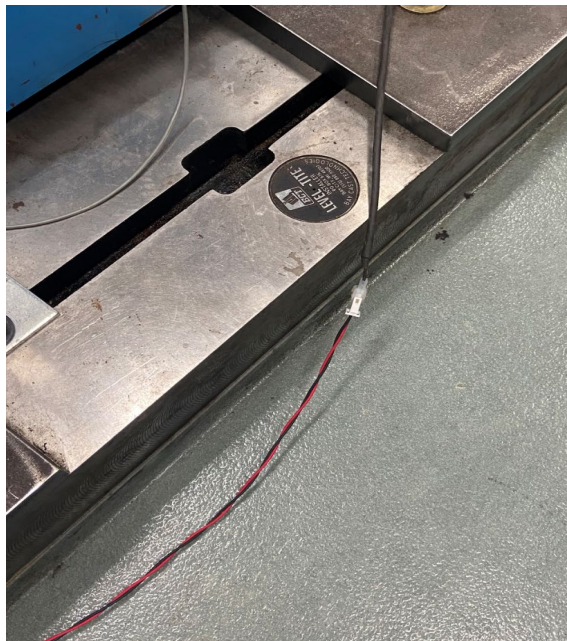
*Figure 37: E-stop connection running from
inverter cart to test cell connector*

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Plug the cart power into the wall as shown in Figure 38.

Figure 38: Cart power plug

Connect DB9 9-Pin VGA cable to the USB outside the test cell to begin the calibration procedure. See Inverter Cart Calibration Procedure for instructions on calibrating the inverter cart using Phoenix Utility software. This must be completed each time the inverter cart is swapped between different motors.

4.1.3 Telemetry Set-Up

To gather pressure data internal to the torque converter, the telemetry system must be prepared. The receiver wire bundles must be connected to the antennae on the transmission to gather data. Recall from Table 4 that there are three receivers, one for each transmitter as shown in Figure 39, Figure 40, and Figure 41.

Figure 40: Three antennae connections for Transmitter A – green

Figure 39: Three antennae connections for Transmitter B – blue

Figure 41: Four antennae connections for Transmitter C – red

The antennae connections should join with their respective colored antennae on the transmission. In theory, it does not matter which specific antennae is connected to which wire because the receiver will pick up the strongest signal from each transmitter, but because of the different locations of each antennae internal to the transmission, some are in more advantageous positions for collecting data on a specific section of the torus. The antennae have been color coded based upon which antennae sent the strongest signal for the given section of interest (See Figure 42). For example, all the red labelled antennae
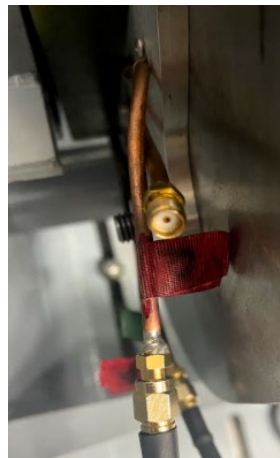
Figure 42: Transmitter C connection
on the transmission – red color code

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connections provide the strongest signal for transmitter C and thus are the best connections for collecting data from the turbine.

After connecting all the antennae to each receiver. The receivers in the test cell should be powered on as shown in Figure 43.

Figure 43: Telemetry receiver powered on.

Next, the power supply outside the test cell should be powered on. As shown in Figure 44, the settings for the switch on the back and the frequency are determined by the transmitter calibration sheets provided by IRT [21]. To reduce wear on the electrical components, it is best to "disable output" on the power supply when not gathering data.
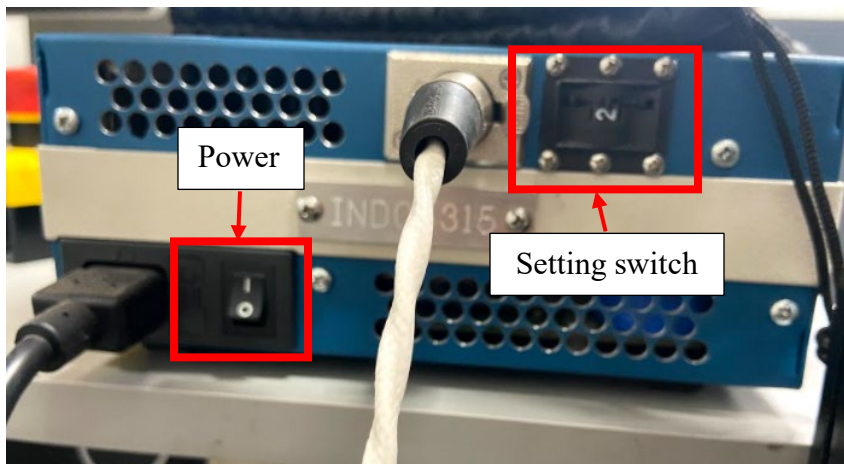
Figure 44: Power supply for telemetry instrumentation

4.2 Hardware Power-up Procedures

4.2.1 Contactors

After setting up the hardware for the test cell, the inverter cart and calibrating the cart, and the telemetry system, the contactors for the test cell must be turned on. Make sure that the power for the cart is OFF and the dynamometer cell power is OFF before powering ON the contactors. If the contactors are turned on when the dynamometer power is ON, it is highly likely that the contactors will weld shut. It is also important to first check that the vehicle dynamometer cell does not have its contactors engaged prior to turning on the TCC Contactors as shown in Figure 45. If the vehicle dynamometer cell has its contactors engaged while powering the TCC Contactors, they will also weld shut.
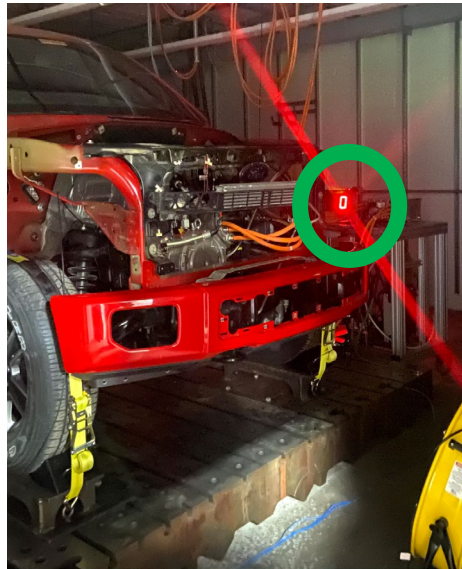
Figure 45: Contactor power indicator in vehicle dynamometer cell.
Contactors are off for this cell when the digital display reads zero.

To turn on the contactors, enter NI MAX software shown in Figure 46.

Figure 46: NI Max software

Select "TCC Contactors" and hit "Run" to turn on as shown in Figure 47 and Figure 48. An audible click can be heard from upstairs after this field is selected.
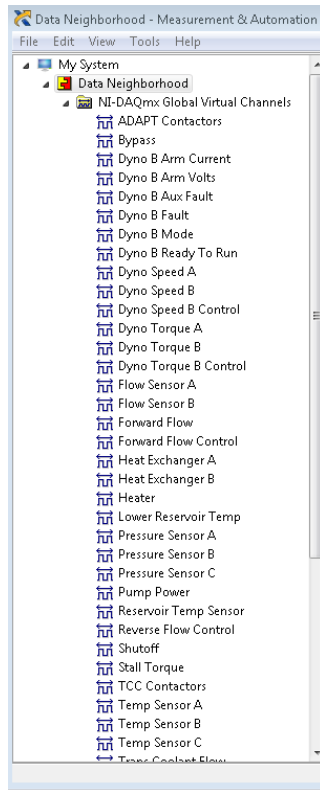
Figure 47: NI MAX channel selection field

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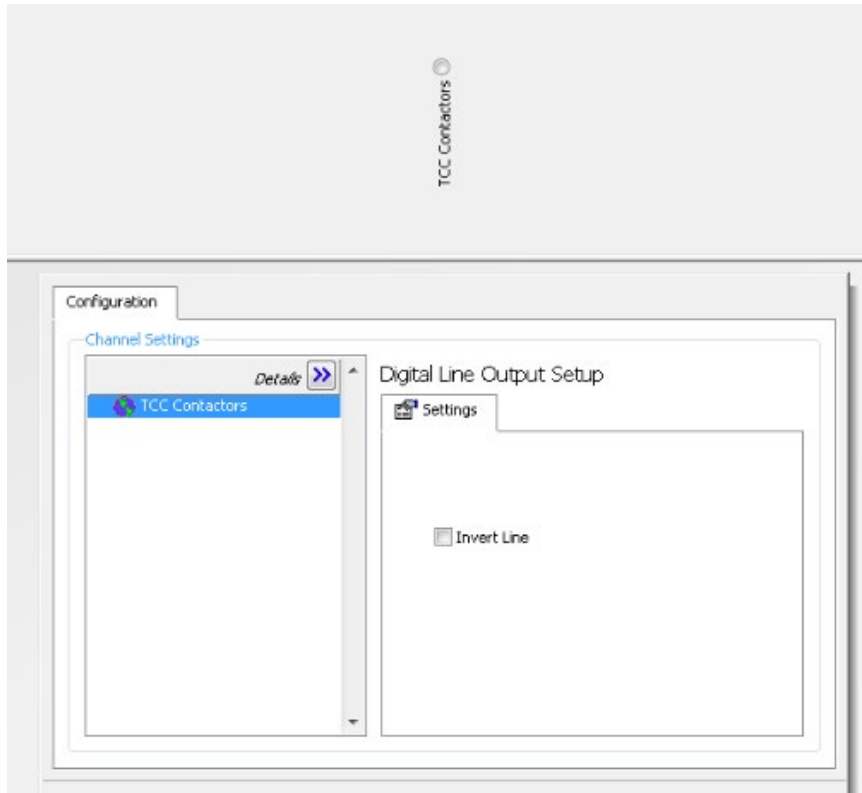
Figure 48: NI MAX TCC Contactors run selection.

4.2.2 Starting the Cart

Double check the coolant level on the inverter cart before starting, check for leaks, repair, and re-fill if necessary, as shown in Figure 49.

Figure 49: Inverter cart coolant bottle

Take care to remove the cover over the power supplies so that they receive as much airflow as possible and do not overheat during testing as shown in Figure 50.

Figure 50: Remove enclosure cover to

provide airflow to power supplies

Turn on the cart power and make sure the inverter power switch is also switched to ON as shown in Figure 51.
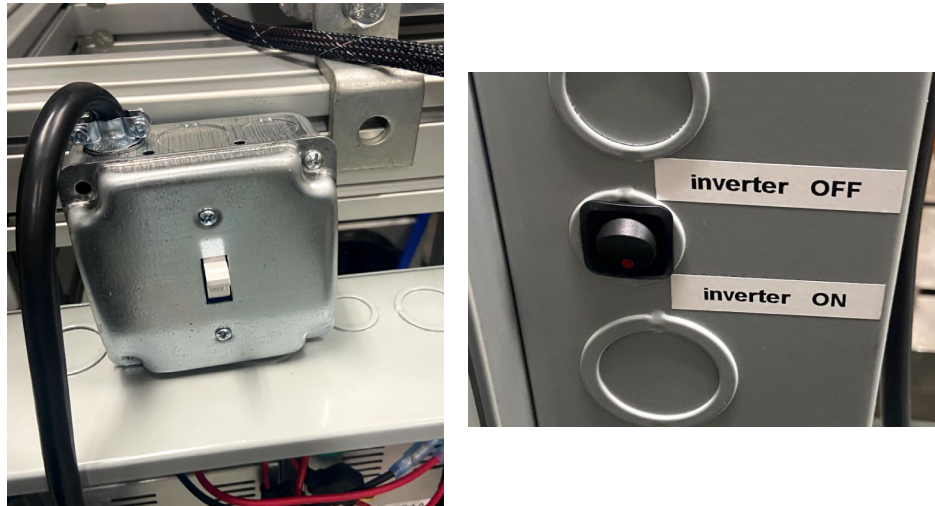
Figure 51: Cart power in ON position (left) and inverter power (right)

4.2.3 Starting the Test Cell

Turn on the AC drive cabinet upstairs above the test cell as shown in Figure 52.

Figure 52: AC drive power switch [3]

Double check that the AC Dynamometer has oil pressure for the bearings as shown in Figure 53.

Figure 53: Oil pressure gauge for AC dynamometer bearings

Turn on the Scadas III DAQ system and power supply to begin gathering data as shown in Figure 54. The power supply provides a DC offset to the turbine speed channel as shown in Figure 55.

Figure 54: Turn on the DAQ systems. Turn on the Master DAQ (top) before turning on the smaller DAQ (bottom)
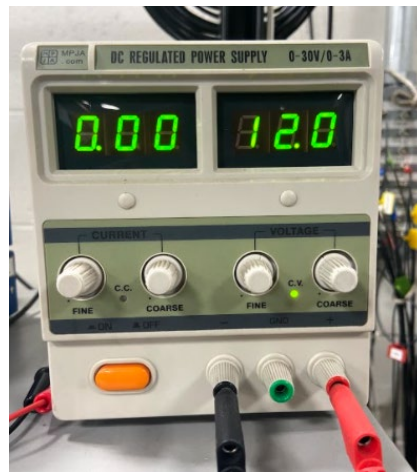
Figure 55: Power supply for turbine speed sensor DC offset

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4.3 Software Procedures

4.3.1 Dynamometer Control

With the inverter cart powered ON, the LabView Torque Converter controller software can be opened as shown in Figure 56. First remote into the "gmtorque" computer inside the test cell. (Password is "nirvana"). Without the inverter cart powered, the LabView software will not run. Confirm that this software is opened with LabView 2018 or newer as shown in Figure 57.
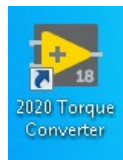
Figure 56: LabView
Torque Converter
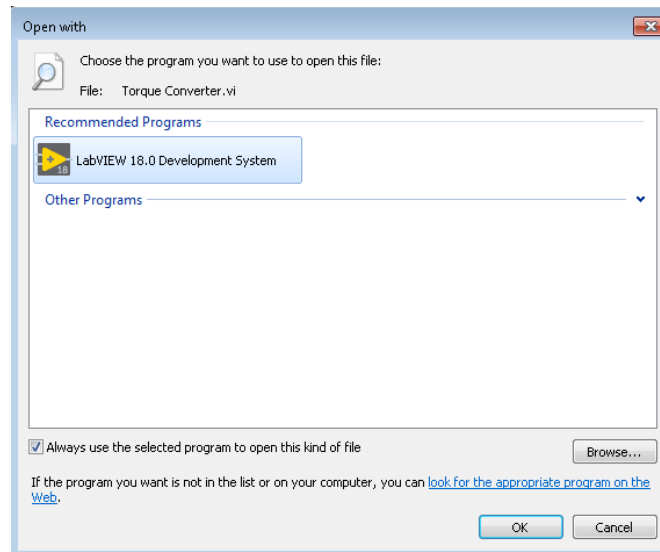
Figure 57: Opening with LabView 2018

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The information for this step is retrieved from previous research instructions. "The inverter voltage can be viewed by clicking the "Startup" button on the VI as shown in Figure 58. When the inverter is powered up, the display should show the inverter voltage
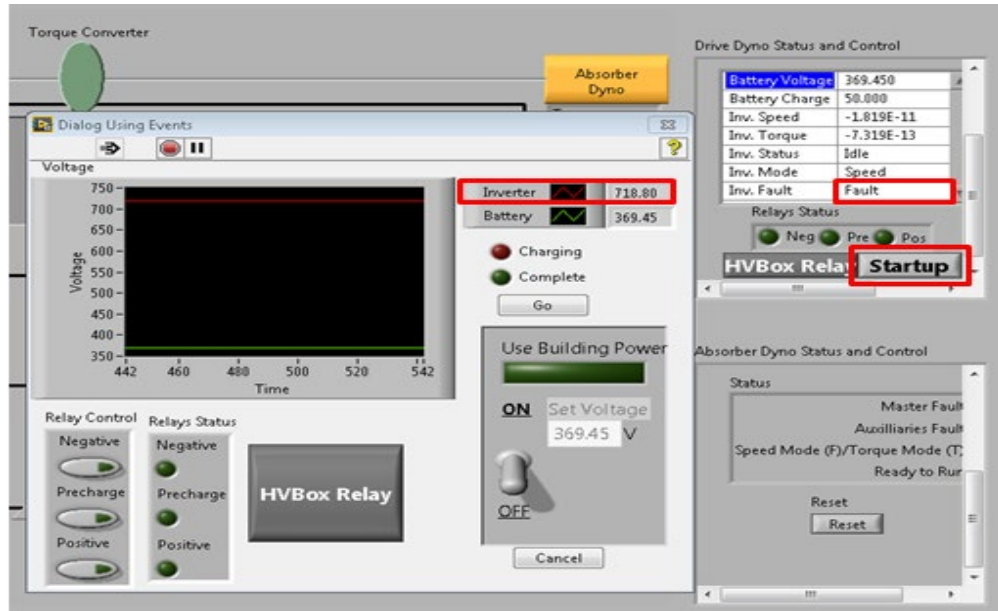
Figure 58: Inverter supply voltage viewer. Hit "cancel" when finished [3]

around 718 - 719 V. The battery voltage is not a concern when operating on the cabinet power supply. In roughly a minute or so after the high voltage power switches are thrown, the "Inv. Fault" field should change from "Fault" to "No Fault". If the inverter stays in the fault condition well after this event, there is issue in system that must be corrected before operation." [3].

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To begin test cell operation, the "manual" tab must be selected in LabView as shown in Figure 59. Make sure to select "OFF" for the mode of operation since this transmission does not require the hydraulic circuit in the room. See Figure 59 for detail.

To begin a test script, the "experiment" tab must be selected in LabView. A test script file needs to be loaded with safety limits and proper commands for each step.
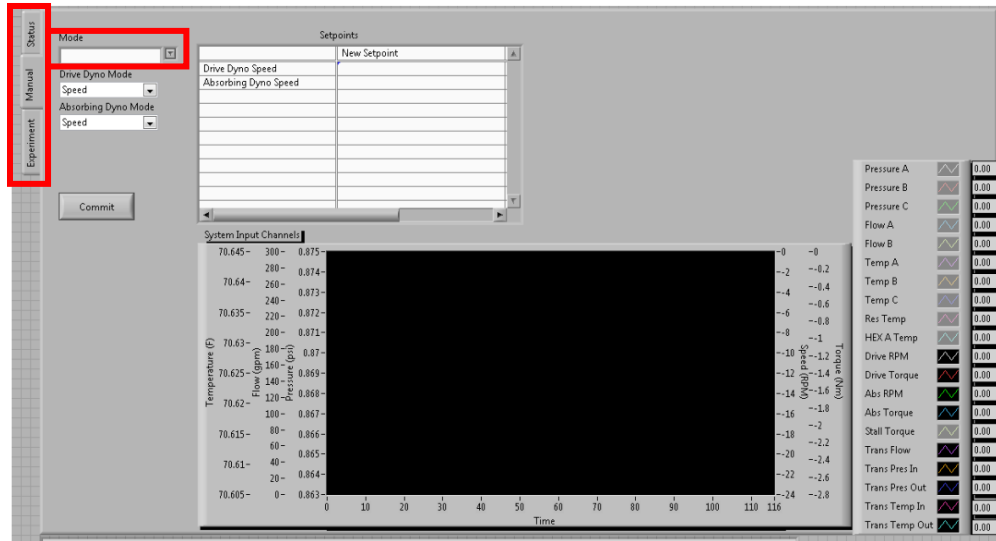
Figure 59: LabView Software start-up. Select "OFF" for the mode condition. Then set speed or torque points.

4.3.2 Solenoid Controller Software

This research utilized a Next Gen solenoid driver developed by Ford to control the gear states and clutch pressures through a LabView software GUI also developed by Ford and MTU from the previous research [1]. Current commands can be sent from the LabView software ranging from 0-1000mA to each individual solenoid as can be seen in Figure 60.

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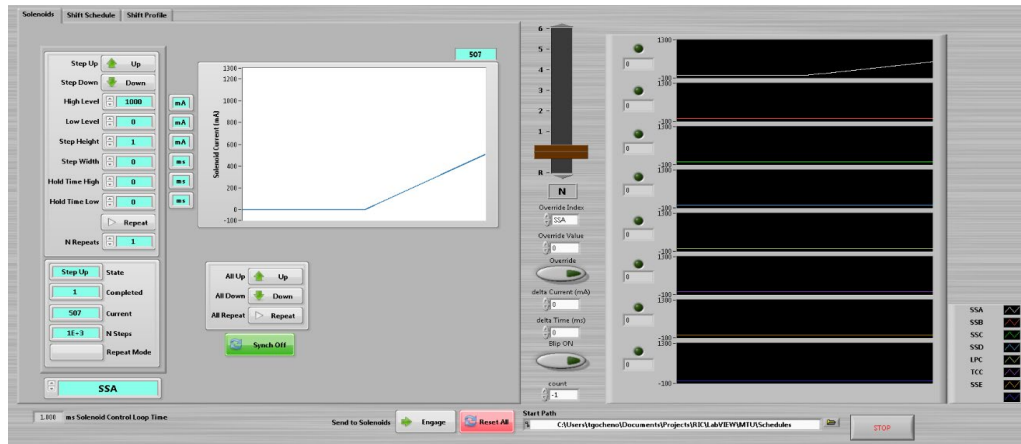
Figure 61: Solenoid Command Window [1]

The next window in the LabView software, "Shift Schedule" defines the active solenoids for a given gear state as shown in Figure 61. The default schedule, which is used for regular shift patterns enables the solenoids highlighted in green to be used for the corresponding gear. For example, for 5th gear, the only solenoids used are the LPC and TCC solenoids (Line Pressure and Torque Converter Clutch).

Figure 60: Shift schedule window [1]

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The final window is used for the "Shift Profile". This is used during testing to upload certain profiles to use during testing. This allows a trigger to be sent to the DAQ to start recording data as well as to the test steps in the Dynamometer Controller software to run speeds and torques requested for the test; furthermore, it activates whatever profile is currently uploaded to turn on solenoids at certain ramp rates. See Figure 62 below.
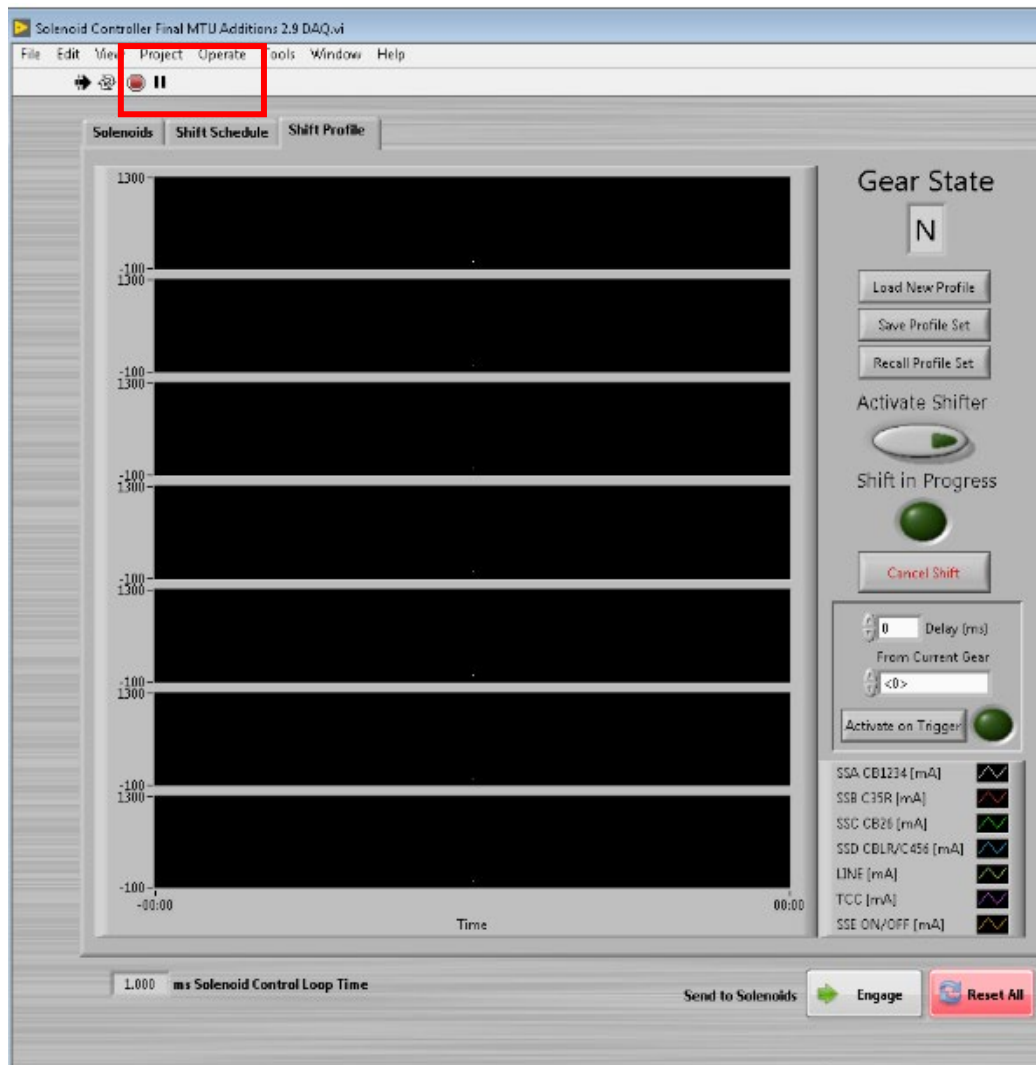
Figure 62: Navigating to Shift Schedule tab to recall a default schedule

Make sure the transmission is in gear by loading the correct files to the solenoid controller. This computer is remoted into the "Hydraulic Desktop" to send current values to the solenoids inside the transmission. A schedule and a shift profile must be uploaded prior to starting any tests. The schedule can be loaded by selecting "Recall" on the "Shift Schedule" tab as shown in Figure 63.
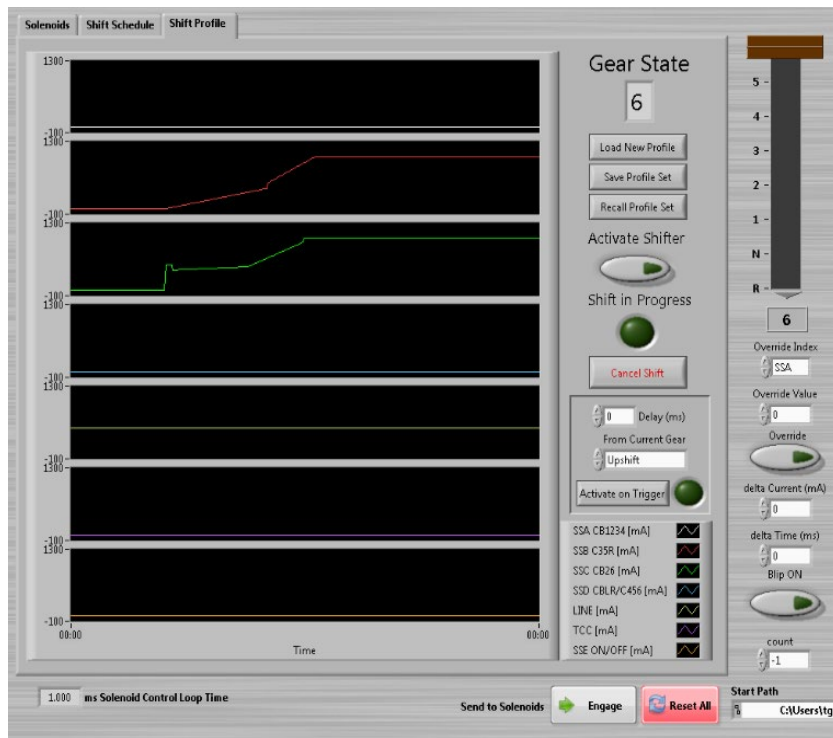
Figure 63: Shift profile window [1]

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The schedule shows what solenoids can be activated for a given gear. The shift profile determines what amount of current to send each solenoid. The default schedule that must be loaded is "6F35" under the "Next Gen Controller" folder on the desktop in the folder "Schedules" as shown in Figure 64 and Figure 65.
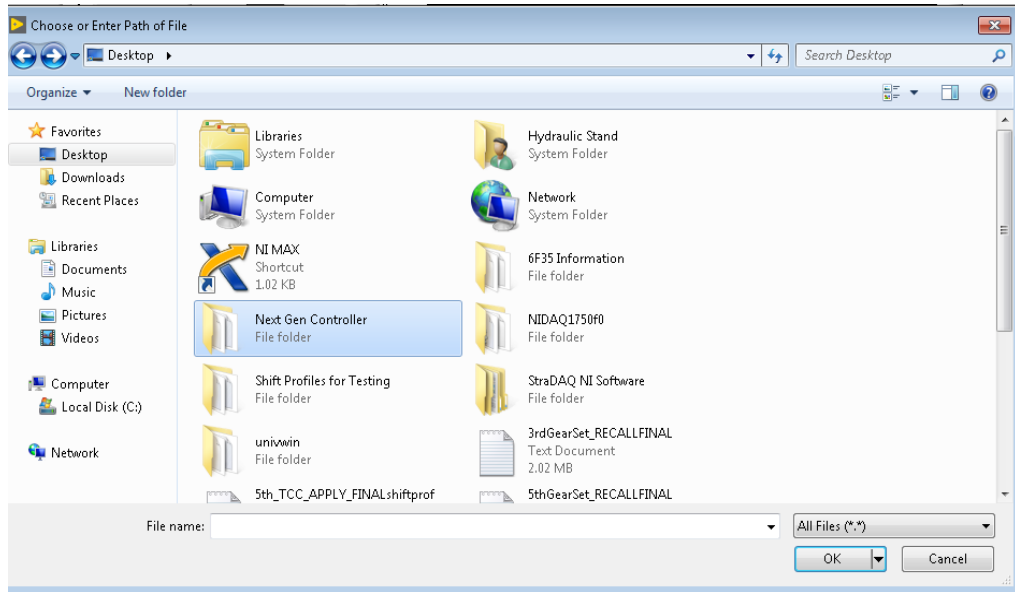
Figure 64: Top folder for all shift profiles and schedules for the LabView solenoid controller
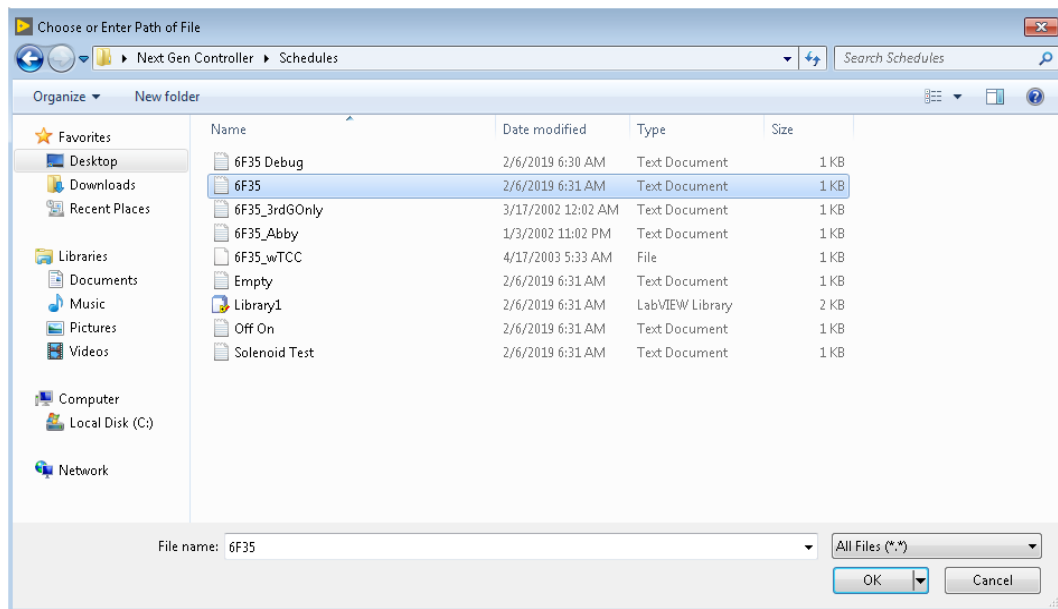
Figure 65: Default schedule for 6F35 transmission: 6F35

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The default shift profile that must be loaded is "Full Gear Set Default" under the "Next Gen Controller" folder on the desktop in Figure 66.
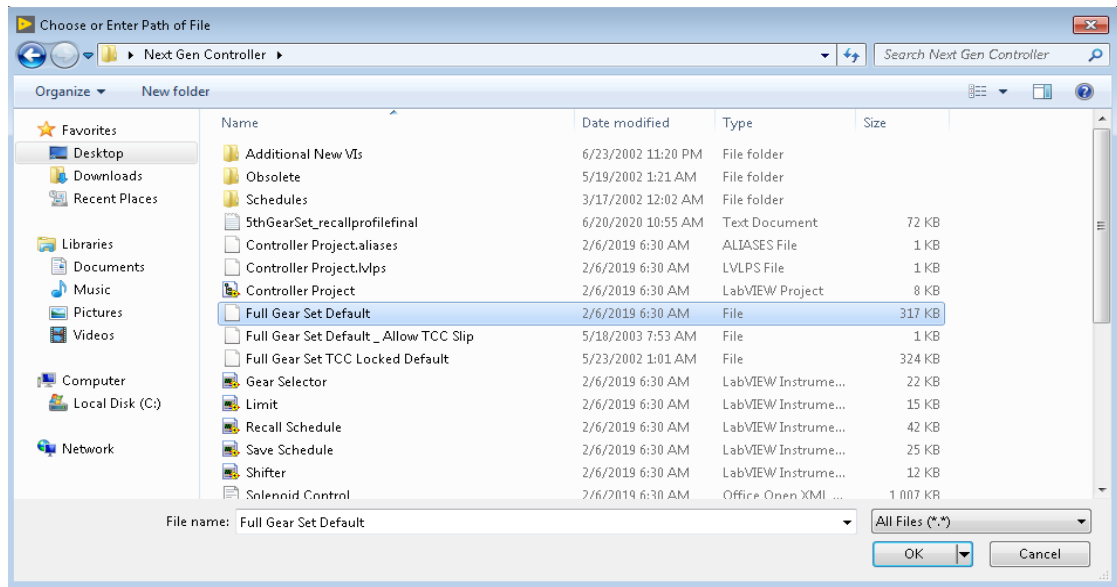
Figure 66: Default shift profile for 6F35 transmission: Full Gear Set Default

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To send commands to the solenoids "Engage" must be selected on the bottom of the menu. To shift the transmission "Activate Shifter" must be selected as shown in Figure 67.
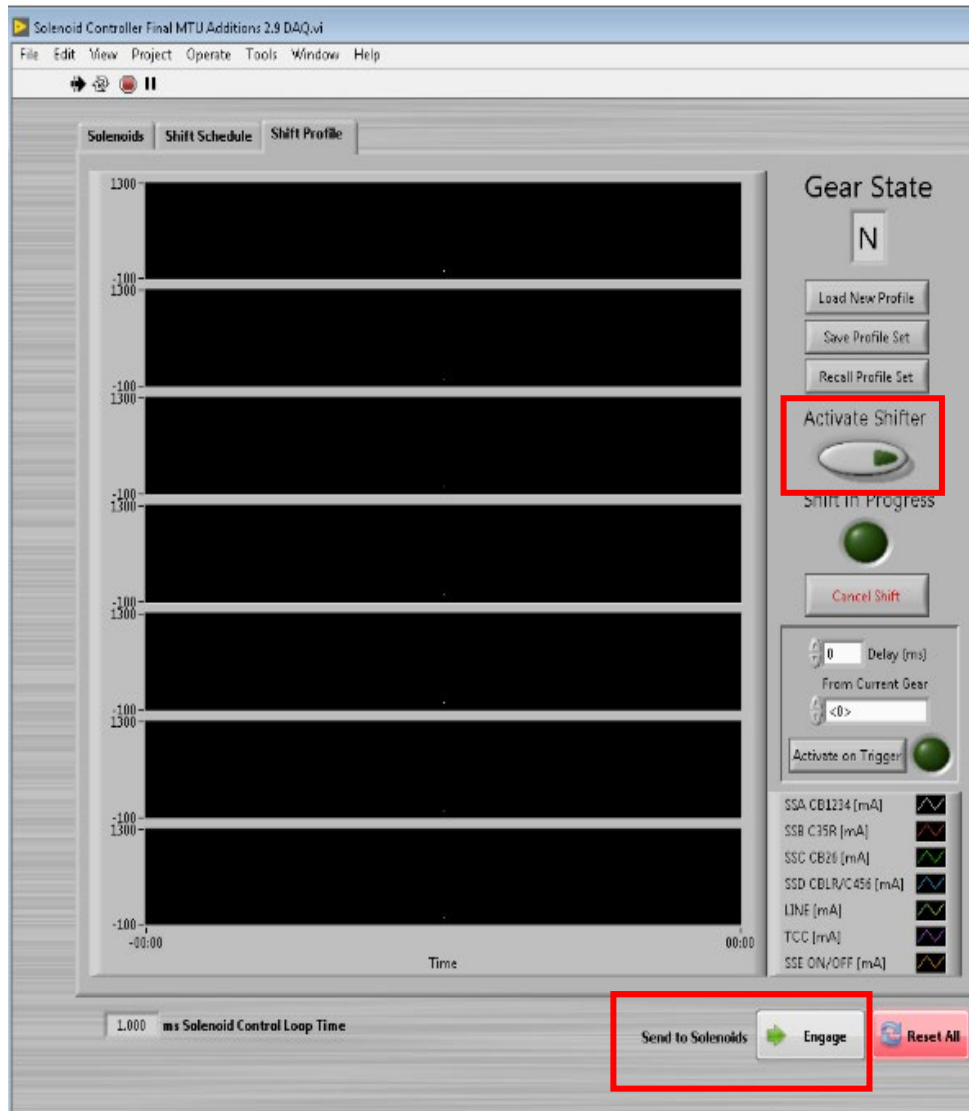
Figure 67: Selections to engage to be able to shift the transmission and send commands to solenoids

4.3.3 Telemetry Software

The telemetry software, Digital FV, created by Infrared Telemetrics (IRT), was utilized to gather data from the 29 pressure transducers instrumented in the torus as shown in Figure 68.
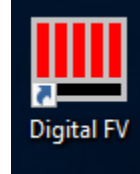
Figure 68: Digital FV software shortcut

The receivers are labelled A, B, and C and record data from the impeller, stator, and turbine, respectively. Any receiver may be used for any transmitter, as long as it has the correct configuration and is tuned to the correct frequency for the transmitter that is being recorded. For example, receiver A maybe used to record data from the stator as long as the stator configuration file is loaded and it is tuned to 2395 kHz as stated in the calibration sheet [21].

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Upon opening Digital FV, select "File" and "Open Configuration" to select the receiver configuration. Only use the "hot dynamics" files for testing. These files are calibrated with the instrumentation at operating temperature (170 – 200 °F) as shown in Figure 69.
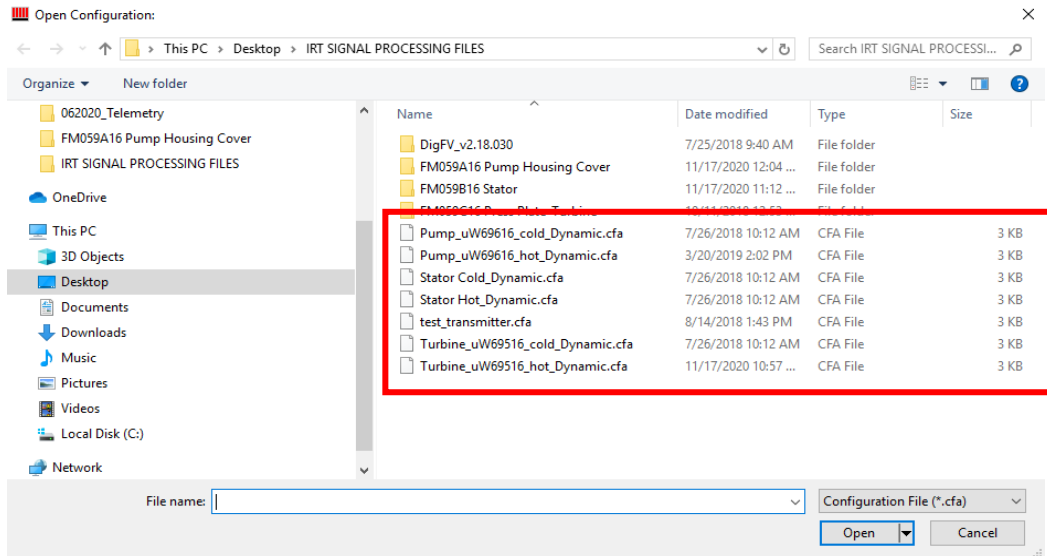
Figure 69: Telemetry configuration file location

The receiver letter and corresponding identification number are listed in Table 5.

Table 5: Receiver and corresponding ID number [21]

Receiver	Identification Number
A	RF02361A
B	RF05516A
C	RF04716A

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Then select "Connection" and select "Open Connection" to begin communication with the transmitter as shown in Figure 70.
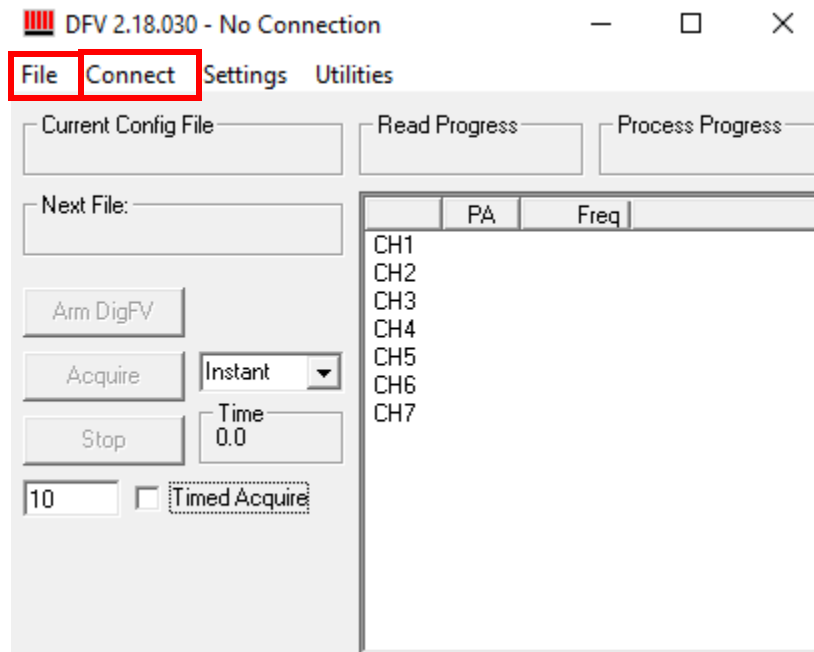
Figure 70: Digital FV connecting to receiver. 1) Click "File" and "Open configuration" to choose the transmitter configuration file. 2) Click "connect" and "open connection" to begin communication with the receiver

The interface should show that the configuration is loaded, and the receiver is connected. The receiver needs to be tuned to the correct frequency for whichever transmitter it is communicating with. To select options for incoming data and receiver settings, select "Utilities" as shown in Figure 71. To examine and change the frequency, select "Show Receiver Interface" as shown in Figure 72. To examine the incoming data, select "Show Chart Display" as shown in Figure 73.
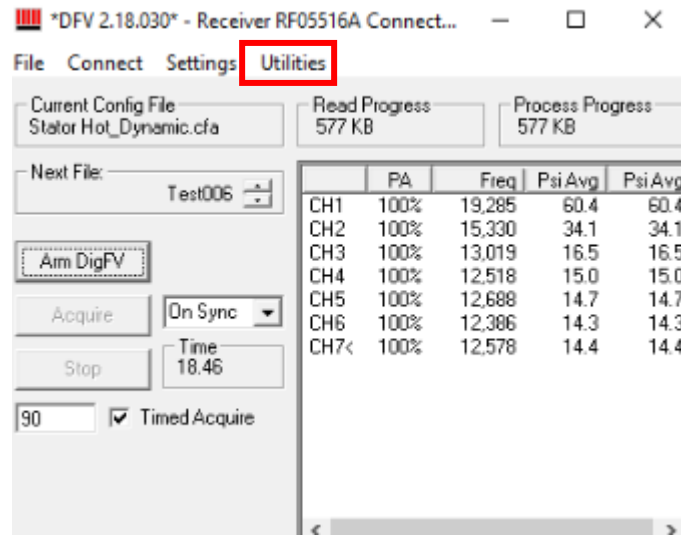
Figure 71: Interface connected and configured. Select "Utilities" and "Show Receiver Interface" and "Show Chart Display"
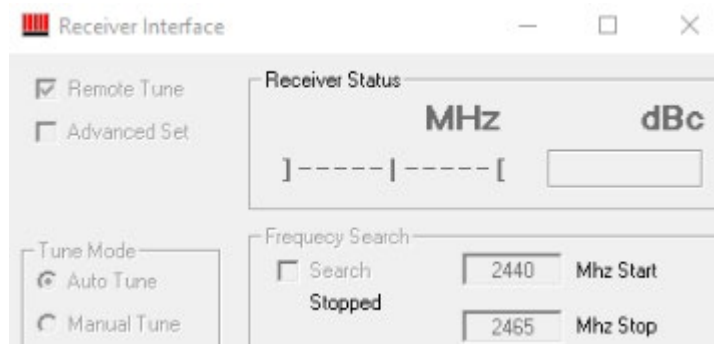
Figure 72: Digital FV receiver interface

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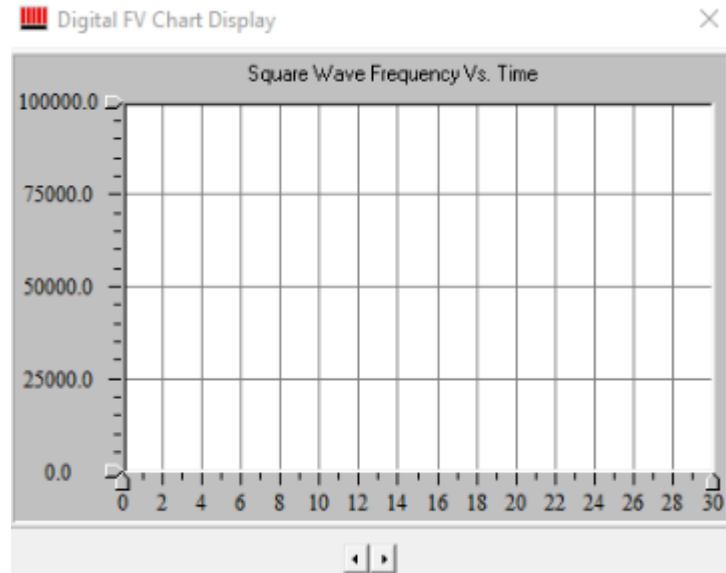
Figure 73: Digital FV Chart Display

There are two methods to latch onto the correct transmitter frequency. The first is "Auto Tune". Select "Remote Tune" and then "Auto Tune" and "Frequency Search". The receiver will automatically scan a range of frequencies to find the transmitter as shown in Figure 74.
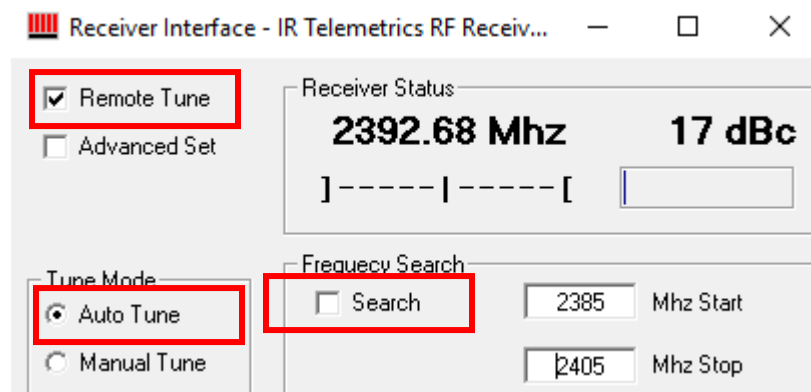
Figure 74: Remote tuning the receiver. Select "Remote Tune", "Auto Tune", and "Search" to find a frequency in each range

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However, this method can prove unreliable if the receiver latches onto the incorrect frequency for the configuration file loaded. The most dependable method is "Manual Tune". Select "Remote Tune", "Manual Tune" and then enter the frequency (within $\pm$ 5 Mhz) of the desired transmitter. This will keep the receiver connected and ensure that the correct configuration in paired with its transmitter. Make sure that the signal strength is higher than 10 dBc to obtain clean data.

Select a file to save the data to by selecting "Settings" and "File Options" to choose a location and name the tests as shown in Figure 75. Do not save the files directly to a hard drive, they must be saved locally to the computer for Digital FV to function properly.
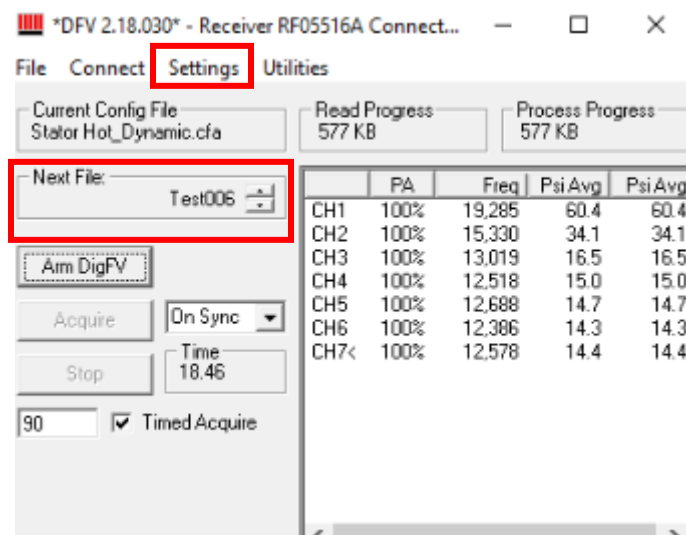
Figure 75: Select a file location by clicking "Settings"
and "File Options" to name and browse folders

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4.4 Calibration Procedures

4.4.1 Inverter Cart Calibration Procedure

Connect the DB9 cable to the cart and to the Vector Tool to the computer outside the test cell as shown in Figure 76.

Figure 76: DB9 Calibration connector

for Phoenix Utility Software

The Vector tool and cart connection are shown in Figure 77 and Figure 78.

Figure 77: Vector tool connection to USB to computer and to DB9 cable

Figure 78: Connecting DB9 cable to inverter cart

Open Phoenix Utility (Figure 79) software and hit the "play" button, select "user defined", and choose "read" to obtain the current position of the electric motor.

Figure 79: Phoenix Utility software

shortcut

Enter the new position (197.9 for the Ford test cell side) under "Position Offset" and hit "write", and then click "stop" as shown in Figure 80.
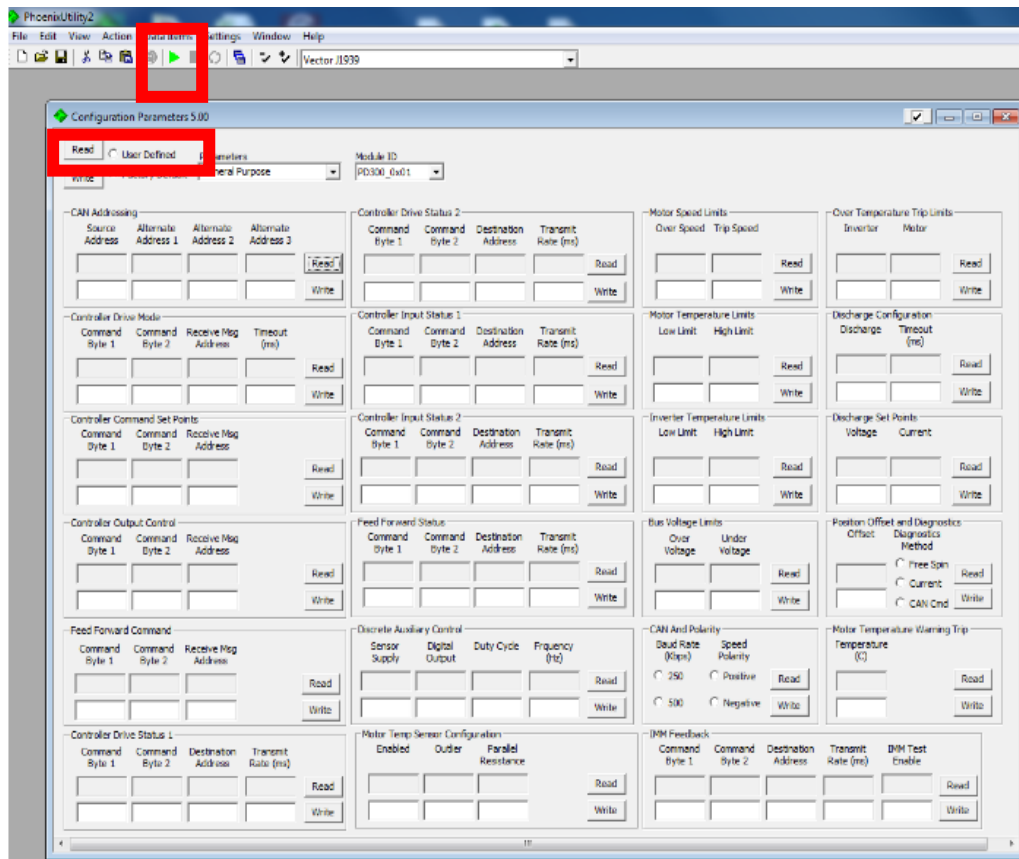
Figure 80: Phoenix Utility software calibration procedure. First select "play",

then "user-defined", and "read"

Power cycling the cart will allow the motor to settle its new position as shown in Figure 81 and Figure 82. Turn off the inverter power switch (black button) on the inverter cart for 10 seconds and turn it back on as shown in Figure 83. Enter the Phoenix Utility software again and hit "read" to confirm the new position is correct. Exit the software and enter the remote desktop.
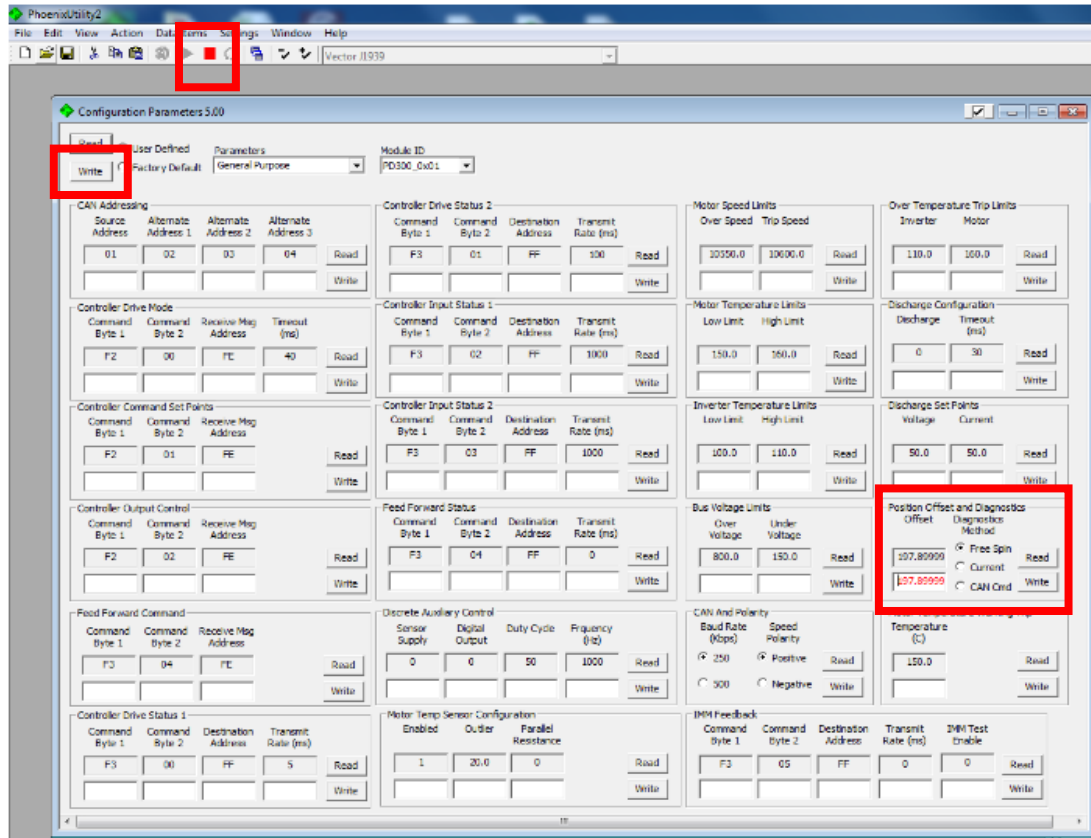
Figure 82: Entering new position offset in Phoenix Utility software. Hit "Write" and then "Stop"
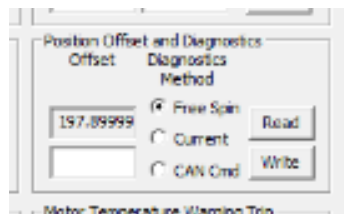
Figure 81: Entering new position offset for e-motor.

Figure 83: Power cycle the inverter to

establish new motor position

Make sure to remove the Vector tool from the computer before starting the electric motor because the system will not spin with the tool plugged in.

4.4.2 AC Dynamometer Calibration Procedure

Before starting any major testing, the AC dynamometer torque measurement should be checked for drift. This can be found when the dynamometer is powered on, but not

Figure 84: Calibration weight application

on AC Dyno

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spinning. If the torque measurement reads higher than 1-2 Nm while remaining
stationary, it should be re-calibrated as shown in Figure 84.

This can be done by opening the calibration for AC Torque in NI Max and setting it at a
1-1 scale: 1 Nm = 1 V. By adding calibration weights up and recording the voltage
reading, a new calibration curve can be determined and entered into NI Max.

4.5 Steady State Test Development

Steady state tests were completed with the previous test cell set-up as described in the
Experimental Set-Up. A performance test was run with the large inertia DC dynamometer
driving the torque converter and transmission and the AC dynamometer absorbing. This
test was done to become accustomed to the control methods, software, and transmission
and torque converter behavior. After installing the BorgWarner electric machine to
replace the DC dynamometer, steady state testing was required to ensure the function of
the hardware as well as the control software.

4.5.1 Spin Losses

There are three spin loss values that need to be determined and applied to gathered data in
order to report correct torque values. They are the input dynamometer loss, transmission
loss, and output dynamometer loss

4.5.1.1 Input Dynamometer Spin Loss Testing

This was determined when the transmission was removed from the system. A 10 second steady-state average of input torque was taken at each speed starting at 50 RPM, 100 RPM, up until 2250 RPM and then repeated in descending order to avoid hysteresis. This was completed with all bearings, u-joints, from the e-motor connection up until the flex plate of the transmission as shown in Figure 85, Figure 86 and Figure 87. This loss was subtracted from the input torque measurement to obtain a corrected impeller torque.
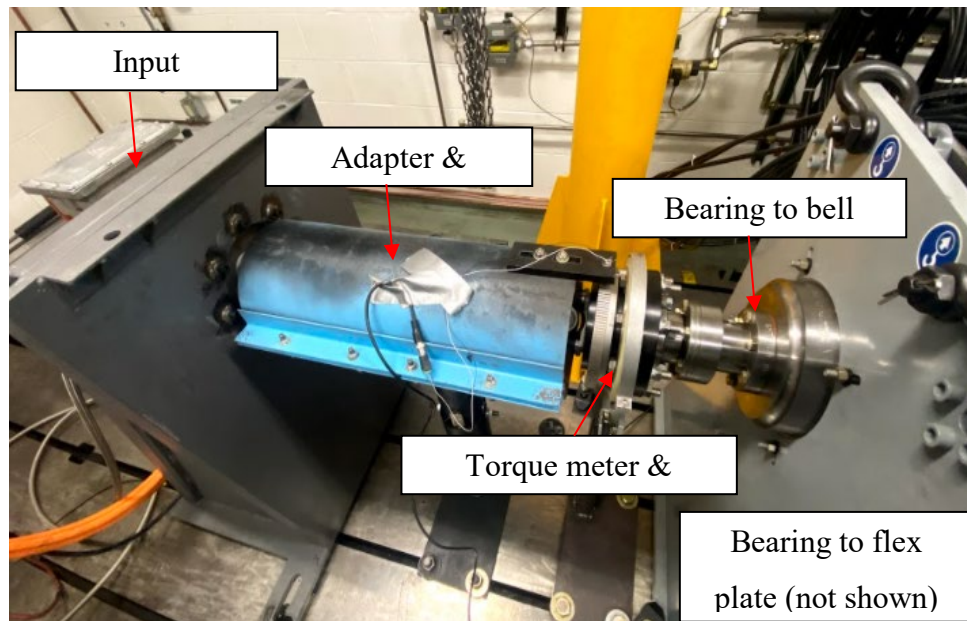
Figure 85: Shaft components of input dynamometer as part of the spin loss

Figure 86: Bearing to flex plate
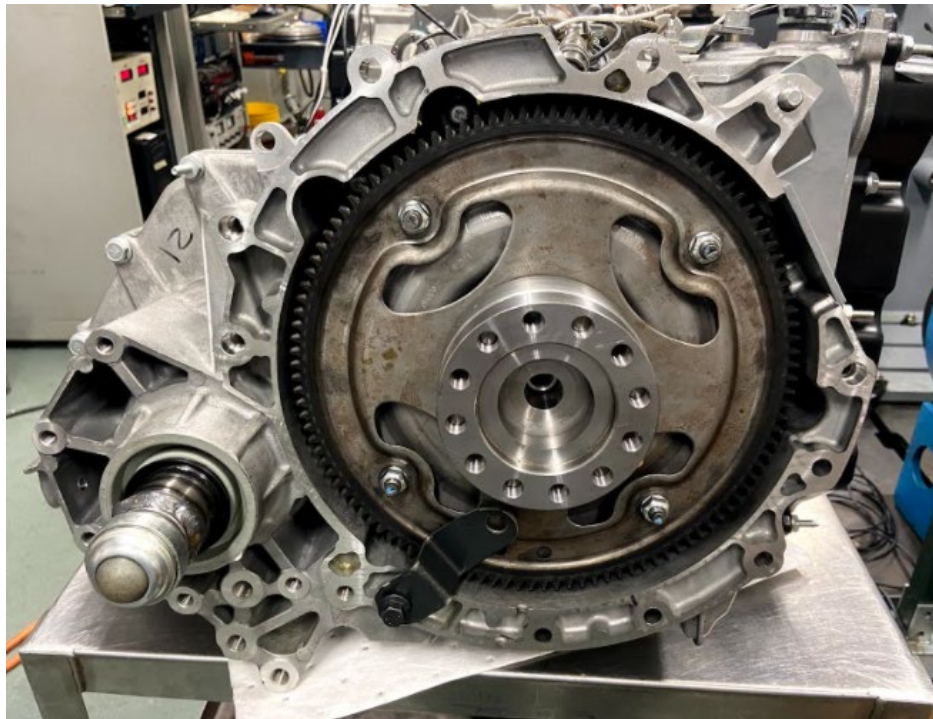
Figure 87: Transmission flex plate and adapter. Removed during
spin loss testing

4.5.1.2 Transmission Loss

Transmission loss is associated with the spin losses in the gearing from the torque converter output shaft – turbine shaft – to the final drive shaft. This torque value was added back into the final drive output torque to obtain a corrected transmission output torque.

4.5.1.3 AC Dynamometer Loss

AC Dynamometer loss is associated with the bearings in the AC dynamometer shafting. This test was complete in the same manner as the input dynamometer: running several speeds in ascending and descending order and recording the torque from the dynamometer with nothing attached. This was also added to the final drive output torque to obtain a corrected transmission output torque.

4.5.2 Warm-Up Procedure

Before running any tests, a warm-up procedure was completed to bring the ATF to operating temperature in a safe and controllable manner. The transmission was run at 75 Nm and the output speed was held at 150 RPM bringing the torque converter to a speed ratio of 0.3 [1]. This condition was held for 13 minutes, bringing the ATF from room temperature (60 °F) to operating temperature (170 – 200 °F) [1].

4.5.3 Performance Testing & Controlled Slip

The first test completed with the BorgWarner electric motor was a performance test. The purpose of the performance test was to compare the new BorgWarner set-up to the previous set-up to ensure repeatability. The BorgWarner electric motor was held at a constant 75 Nm input torque and the output speed was swept to achieve speed ratios ranging from 0.1 to 0.92. The transmission was held in 5th gear with line pressure ranging from 170 – 180 PSI. The output speeds in this test were identical to the output speeds commanded from the performance test for the previous set-up. The commanded input

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torque was higher than the required 75 Nm to compensate for input torque losses gathered from the input dynamometer spin loss test.

A full performance test was completed after a warm-up procedure in addition to a cold start condition. The cold start testing was completed with fluid temperature starting at 60 – 70 °F. Each speed ratio point was completed with the starting temperature in this range, by the end of the test, the temperature did not exceed 120 °F. There was a 45-minute cool-down period between test points. The purpose of this tests was to identify differences in performance characteristics between cold and hot ATF.

Controlled slip testing was required for steady state data to validate simulation. Tests were run at 50 Nm of input torque with speed ratios of 0.9, 0.92, 0.95, and 1.0.

All steady state testing was completed in 5th gear because it is a 1:1 gear ratio with a final drive ratio of 3.3556. This ratio provides the safest output speeds during test development.

4.6 Transient Test Development

Transient testing was completed in stages. After gaining knowledge and experience with steady state clutch control, transient clutch maneuvers were next. Clutch apply and release was accomplished in order to provide more validation for simulation. The tests of interest were regarding negative torque scenarios. These were completed out of interest for torque converter behavior when an engine is powered on and then powered off, when an engine is power on during coasting, and a slip event during an engine power off stage. Negative torques were generated to simulate a reverse in energy transfer to motor the engine. Data provided from Ford from real-world vehicle testing was used to determine test points.

4.6.1 Clutch Apply and Release

The clutch apply and release test was completed to provide conditions for CFD simulation and to validate results. This test was completed in 5th gear. The torque converter was held at a constant 63 Nm input and 295 RPM output prior to applying the clutch to obtain a speed ratio of 0.9. 63 Nm, including spin losses, resulted in a corrected input torque of 50 Nm. The clutch was applied to fully locked over a 2-second window, held for three seconds, and then released at the same rate (2 seconds) as shown in Figure 88.
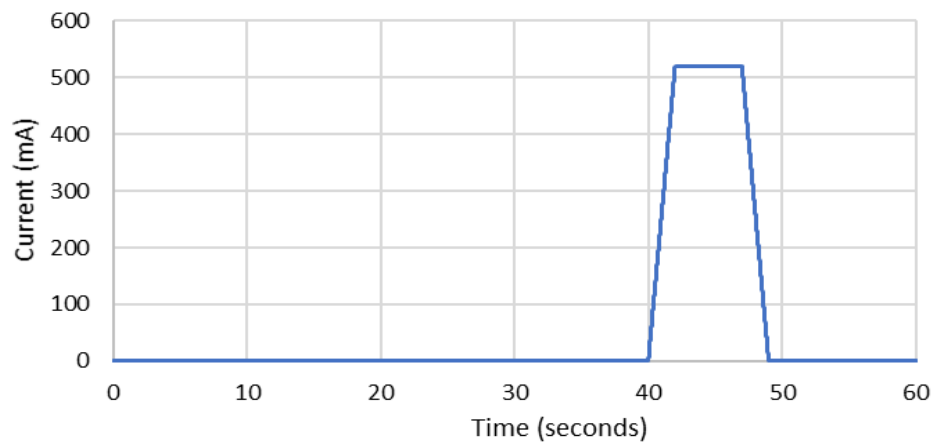
Figure 88: Clutch apply and release TCC solenoid current command

4.6.2 Negative Torque Sweep

The negative torque sweep test was completed to identify fluid behavior when switching from a positive input torque to a negative input torque. The in-vehicle equivalent to this scenario is when an engine is powered off during after cresting a hill and coasting down. For example, an engine is powered and transferring energy to the transmission while driving a car on a flat surface. When the car switches to coasting downhill, a driver removes their foot from the gas, and the engine is no longer transferring energy to the transmission and, in some control scenarios, it is turned off to conserve fuel. This control strategy is known as Deceleration Fuel Shut-Off (DFSO) [22]. During DFSO, the energy is transferred from the transmission to the engine and the engine acts as an absorber. The

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engine is still rotating and is being motored by the torque converter and transmission continuing to rotate as the wheels of the vehicle coast down a hill. The purpose of this test was to find the limit of negative input torque with an open converter clutch and identify any fluid behavior changes. The torque limit is identifiable by the point at which the torque converter loses hydraulic capacity: ATF is no longer flowing to the transmission because the input speed is too low to drive the pump. This test profile is shown in Figure 89.
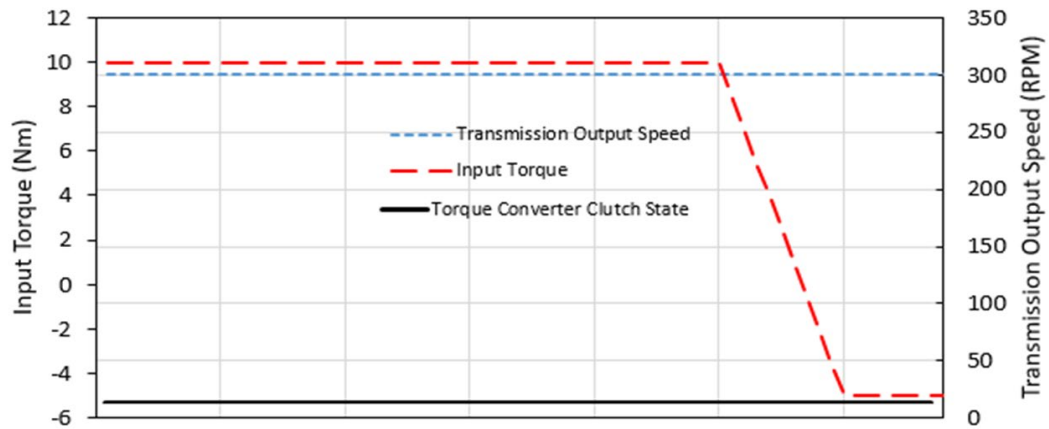
Figure 89: Negative torque sweep test profile

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4.6.3 Coast Down Test

The coast down test maintains a positive input torque (10 Nm) while sweeping down transmission output speed. The in-vehicle situation for this test is mimicking an engine power-on coast-down from 30 mph to 5 mph. For example, if a driver sees a stop sign some distance ahead and releases their foot from the gas and coasts on a flat surface. This test was completed in 3rd gear with transmission output speeds sweeping from 300 RPM to 100 RPM to follow the vehicle trace more closely. These speeds were calculated from road load data from 2019 EPA data and gear ratios. Assuming a nominal tire radius for a vehicle with a Ford 6F35 transmission, in 3rd gear, 300 RPM is approximately 27 mph, and 100 RPM is approximately 5 mph. Similar to the negative torque sweep, the torque converter will lose hydraulic capacity at a certain speed since the torque converter clutch is open and trying to multiply torque. The test profile is shown in Figure 90.The purpose was to identify the output speed limit with an open converter in addition to observing fluid behavior during this event.
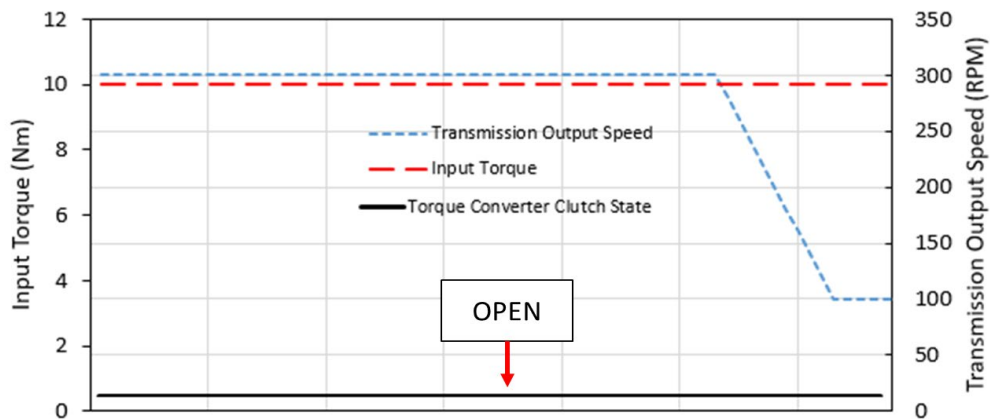
Figure 90: Coast down test profile

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4.6.4 Negative Input Torque with Slip

The negative input torque with slip test involves a transient condition. Input torque was held at -45 Nm, locked converter clutch, 350 RPM output. -45 Nm was determined to be an appropriate motoring torque for a standard 6-cylinder engine in a vehicle with a 6F35 transmission from road test data provided by Ford. A 100 RPM slip event occurs at 350 RPM transmission output speed. Slip is defined as the difference between input and output speed of the torque converter. This slip event happens over a 6-second period. The in-vehicle condition for this test could happen in numerous scenarios. One example might be an engine-power off coast preceding a shift event. Shifting the transmission requires some amount of slip prior to engaging the new gear. This represents a move from 100% mechanical efficiency with the clutch locked to an 80-90% efficient slip state. There were two purposes of this test. The first was to identify fluid interactions during a slip event with a negative input torque. The second was to identify any controllability issues during the event. A diagram of the event is shown in Figure 91.
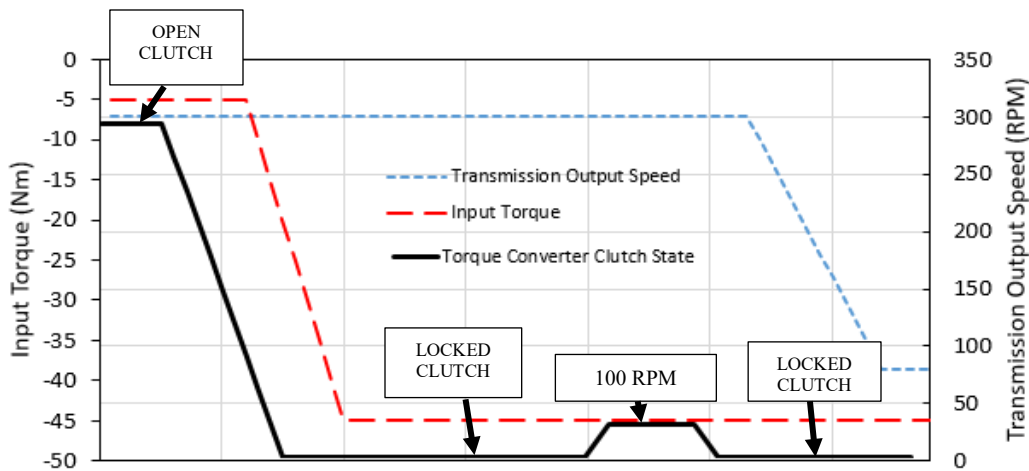
Figure 91: Demonstration of slip event for DFSO Test #3

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Current commands sent to the TCC solenoid applies pressure to complete clutch application. To make the test repeatable and consistent, a TCC solenoid current profile was created to be triggered off of the LabView test script as seen in Figure 92.
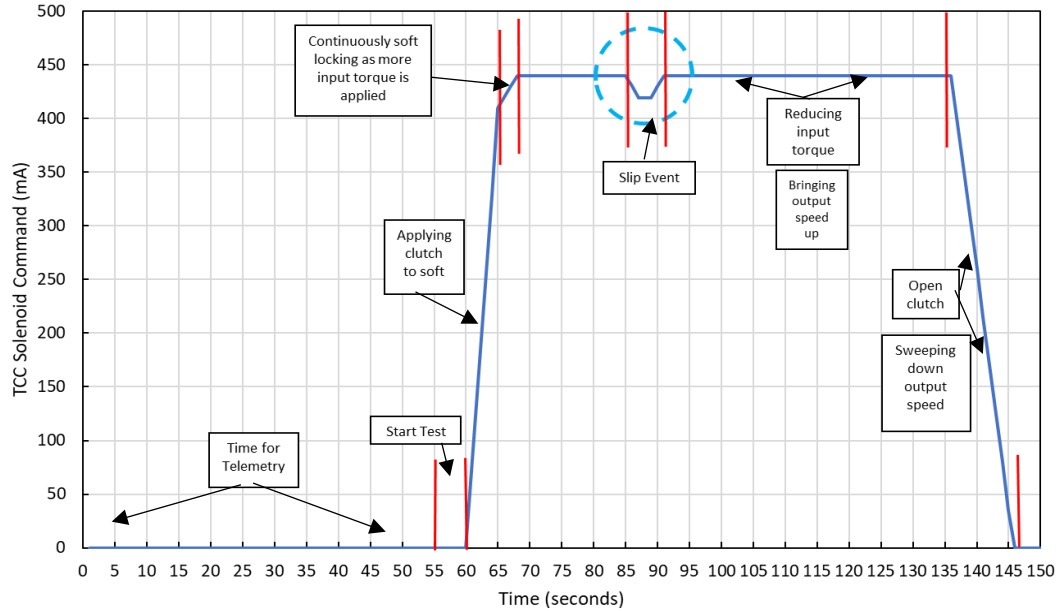
Figure 92: TCC solenoid command profile for DFSO Test #3

The first 55-60 seconds was time for the telemetry system to capture two markers and begin recording. Then the clutch was applied to a soft locked condition (hard locked is 1000 mA or full current). As more torque was applied to the input, the soft locked condition requires a small increase in current to maintain clutch apply pressure (10-15 PSI for this condition). Then, marked by the blue circle, the slip event was commanded by reducing TCC solenoid pressure. After re-locking the clutch, input torque was reduced and output speed was increased to begin a speed sweep to return to the initial conditions to repeat the test. The output speed was reduced and the clutch was re-opened to begin the next test.

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4.7 Data Acquisition

The test cell has three different acquisition systems: a custom LabView program, Signature Acquisition, and Digital FV as shown in Figure 93. The LabView program was recording data through an NI Controller. Signature Acquisition records data through a Scadas III DAQ with two tachometer cards. Digital FV records data through a separate DAQ for the telemetry system.
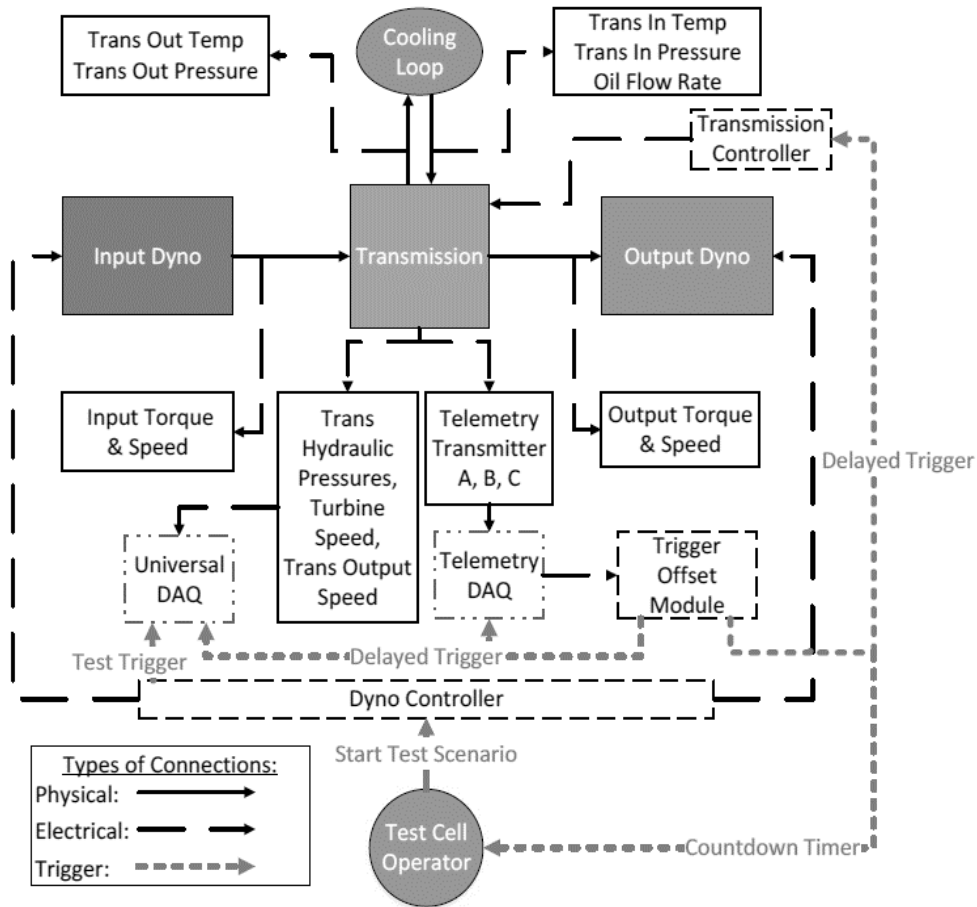
Figure 93: Test cell layout and acquisition diagram [1].

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4.7.1 LabView

The LabView program, Torque Converter 2020, was only used for ATF inlet and outlet temperatures because the Scadas III DAQ does not have a cold junction compensation and therefore the thermocouple measurements are recorded in the NI Controller pictured in Figure 25. The temperature of the ATF does not change quickly, so it was recorded at a frequency of 10 Hz. This data was saved to a text file and analyzed in MATLAB. All other visible channels in this software are recorded using Signature Acquisition.

4.7.2 Signature Acquisition

Primary measurements of the test cell include input and output speed, input and output torque, ATF temperature, and fluid pressure. Table 6 lists the channels recorded using LMS Signature Acquisition software from the Scadas III DAQ. The recording frequency was 6,400 Hz for speeds, torques, pressures, solenoid commands, and fluid flow. This was the default recording frequency in Signature Acquisition for the tachometer channels and the other channels are set to the same recording frequency to make data processing easier. 6,400 Hz was sufficient for any expected frequencies occurring in the torque, pressure, or flow channels. The DAQ also has an antialiasing filter built in in addition to low-pass Butterworth filters applied to each channel (10,000 Hz).

Table 6: LMS Signature Acquisition Channel Names and Descriptions

Channel Number	Channel Name	Description
Tacho1	TSS_RPM(TurbineSpeed)	Turbine Speed
Tacho2	OSS_RPM(TransOutput)	Transmission Output Speed
Tacho3	BW_RPM	Input Motor Speed (BorgWarner machine)
Tacho4	AC_One_Tach	Output Motor Speed (AC Dynamometer) – Laser Tachometer
3	BW_Torque	Input Motor Torque
4	AC_RPM	Output Motor Speed (AC Dynamometer) – NI Controller Readout
6	AC_Torque	Output Motor Torque (AC Dynamometer)

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9	Trans_IN_Pressure	Transmission inlet ATF pressure
10	Trans_OUT_Pressure	Transmission outlet ATF pressure
11	LINE_Pressure	ATF feed line pressure
13	CB26_Pressure	Clutch pack pressure
14	SOL_FEED_Pressure	Solenoid feed line pressure
15	CB1234_Pressure	Clutch pack pressure
16	CBLR_Pressure	Clutch pack pressure
17	TCC_APPLY_Pressure	Torque Converter Clutch apply pressure
18	TCC_REL_Pressure	Torque Converter Clutch release pressure
19	SD1_SSA	Solenoid A current
20	SD2_SSB	Solenoid B current
21	SD3_SSC	Solenoid C current
22	SD4_SSD	Solenoid D current
23	SD5_Line	Line Solenoid current
24	SD6_TCC	Torque Converter Clutch solenoid current
25	SD7_SSE	Solenoid E current
27	Flow_Meter	ATF flow meter GPM reading
28	Dyno_Trigger	Trigger for Dyno controller
29	Arduino_Trigger	Trigger for TOMBox
31	C35R_Pressure	Clutch pack pressure
32	C456_Pressure	Clutch pack pressure

4.7.3 Digital FV Telemetrics

4.7.3.1 Recording Telemetry Data

Digital FV has several options to record data. The two options used in this research are
"On Sync" and "Instant". The "On Sync" option was automatically triggered and was
used for transient testing. The dynamic maneuver needs to be captured at the same time
for every test to accurately analyze the data and thus the data file needs to be triggered
consistently. The "On Sync" option can be selected from the drop-down menu shown in
Figure 94. Then the telemetry system was armed by selecting "Arm DigFV". The
"Acquire" can be selected and the system will be paused while waiting for a trigger. Once
a trigger was sent, the data will start recording for the duration of the 'Timed Acquire"
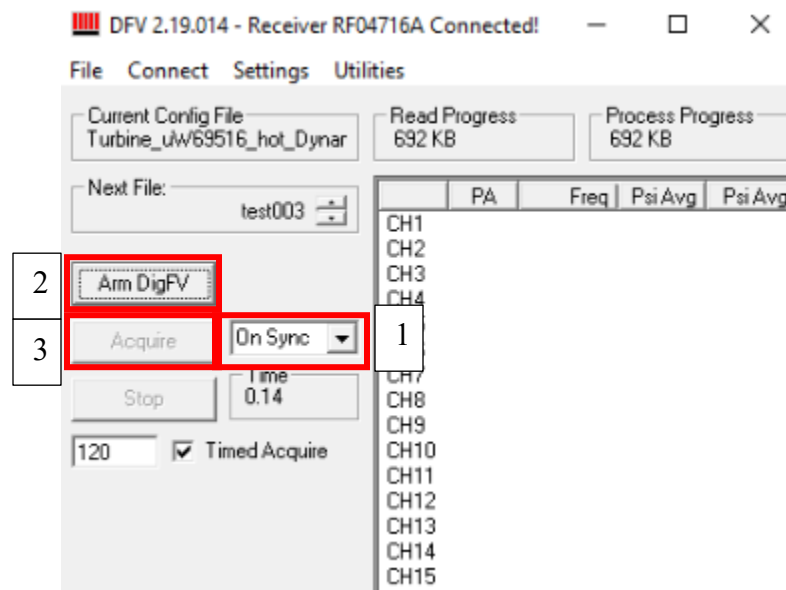
*Figure 94: Digital FV recording options. Select "On Sync" or
"Instant" from the drop down and "Arm DigFV" and "Acquire"*

. The "Instant" option was manually triggered and was used for steady-state testing. Since
there are no dynamic maneuvers happening, it was unnecessary to trigger the data file to
begin recording at a specific time. The "Instant" option can be selected from the drop-
down menu. After the system was armed, the data will begin recording immediately after
"Acquire" was selected.

4.7.3.2 TOMBox Triggering

The Digital FV acquisition software was triggered by the Trigger Offset Module Box (TOMBox) [1]. This device was comprised of an Arduino Mega 2560 that receives a marker channel from one of the three telemetry receiver boxes within the test cell from the "Frequency Out" port (See Figure 95). It sends a 5V signal back out to the receivers to begin recording data as shown in Figure 96.

Figure 95: Receiver box "Frequency Out" port to send marker signal to TOMBox
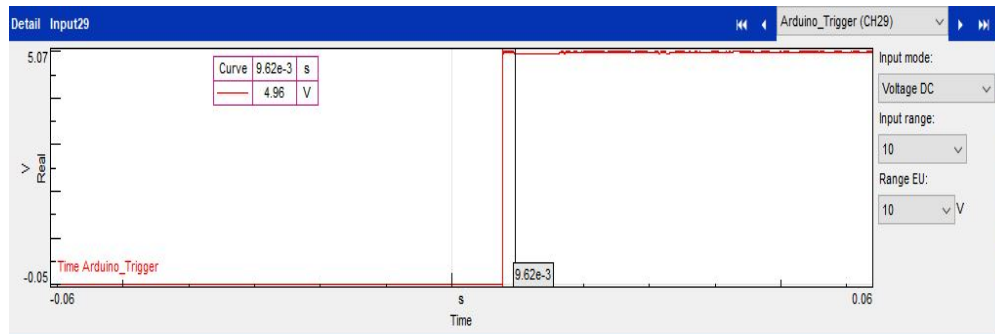
Figure 96: Arduino trigger signal recorded on Signature Acquisition

The TOMBox was required in order to send the 5V signal at the correct time [23]. The data for each transmitter was multiplexed and each individual channel receives approximately 1 second of data for every rotation of its respective portion of the torus. In order to record a full set of one channel, the data recorded must begin at the same time as that channel. For example, in order to record channel 2 of the stator, the 5V signal must be sent exactly 2.026 seconds after the Arduino receives a marker signal from the transmitter. This process must be repeated for every channel for each transmitter to capture a full data set for each pressure transducer. The time per channel is listed in Table 7. It takes two markers before the telemetry system begins recording. This can take up to 60 seconds before the system begins recording data after the acquisition process.

Table 7: Transmitter Time per Channel [23]

Transmitter	Time per Channel
A - Impeller	1
B – Stator	1.013
C – Turbine/Clutch	1.006

A depiction of the multiplexed data for a seven-channel transmitter is shown in Figure 97. IR Telemetrics custom software allows the data to be collected in this manner.
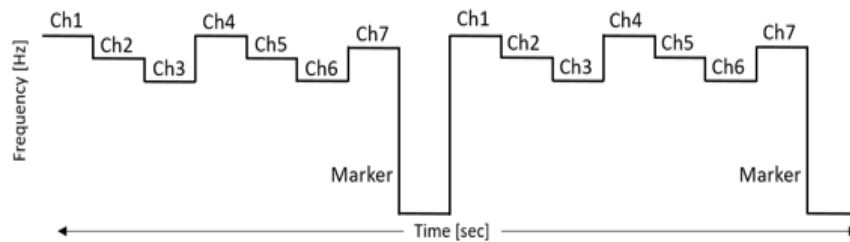
Figure 97: IR Telemetrics multiplexed data example [23]

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4.8 Data Processing

The ATF temperature output from LabView and the channels from Signature Acquisition are analyzed in MATLAB. The pressures are analyzed with a drop out function which removes any data higher than one standard deviation from the average. This removes any erroneous spiking from noise in the signals. The speeds and torques are analyzed with digital low pass filters. The speed filter has a cut-off frequency of 25 Hz and a stop band attenuation of 90 dB. The torque filter has a cut-off frequency of 20 Hz and a stop band of 70 dB. Only the input motor torque was filtered in MATLAB because it has the highest noise due to the EMI of the inverter and electric motor.

The Digital FV telemetry data was analyzed using custom MATLAB scripting found from [1]. A summary of this information can be found in Appendix E.

5 Results

5.1 Performance Testing

In Figure 98, the solid black lines represent the ideal K factor and torque ratio defined by Ford. The tolerance limits are shown in dashed lines. The data gathered from this study, shown in red and blue, is differentiated by squares being the K-factor data and circles being the TR data. Red represents data with the ATF temperature falling between 170 °F - 200° F. These tests were done after the warm-up procedure was completed. This data lies within the tolerance limits (except for 0.95 SR). The data in blue represents a performance run taken from cold start. This data was completed on the previous DC Dynamometer set-up.

ATF temperature was 70° F at the beginning of each run and did not come above 120 °F
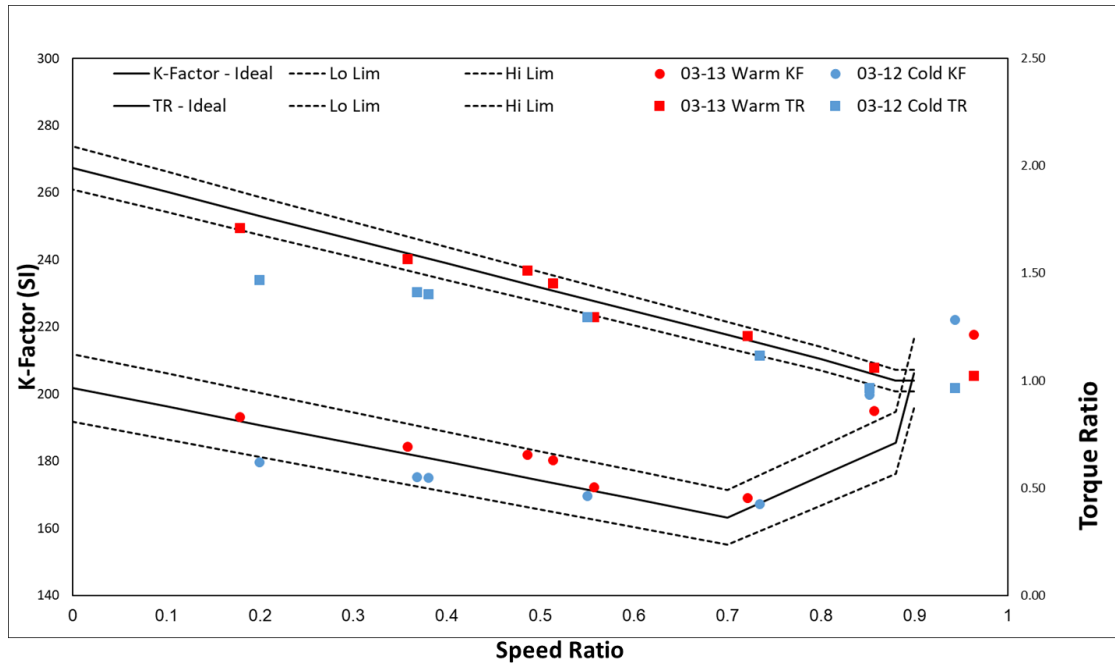
Figure 98: Performance test data from temperature comparison on DC Dynamometer set-up

for any test point. As can be seen from the graph, it shifts the curves for both K-factor and TR down by approximately 2.7%. All the data gathered in this study was done as a 5-

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second average at each point and with 180 PSI of line pressure - or similar to what would be seen in-vehicle. The temperature of the ATF changed from the starting point of 70 °F at the beginning of the test. The 5-second average performance point was gathered when the torques and speeds of the input and output were constant. Losses through the transmission and dynamometer were applied and the corrected data is shown.

A full performance test was run with the new BorgWarner machine to compare repeatability and consistency to the original DC dynamometer set-up as shown in Figure 99.
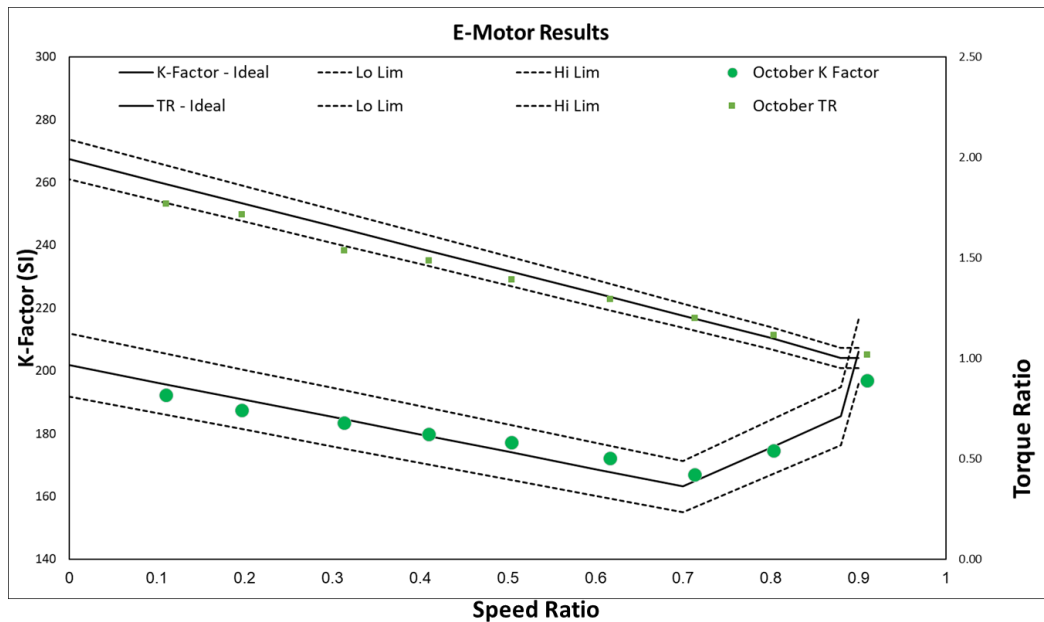
Figure 99: Performance testing with BorgWarner electric machine

Table 8 demonstrates the difference between the previous set-up and the BorgWarner machine set-up. This was compared by using an average of two warm performance test runs with the DC dynamometer set-up with the performance results of the E-motor shown above in Figure 99 at approximately the same speed ratio points. All these tests used the same warm-up procedure. The largest difference was 11% above 0.9 SR. This area was not of concern because of the difference in speed ratios reached between tests. During the DC dynamometer testing, the speed ratios above 0.9 were more challenging to hold constant due to variability between tests. The ratio reached was 0.964 and the highest

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ratio reached for the E-motor hardware was 0.91. Performance will vary significantly between these two points as shown by the trends defined by Ford in Figure 99. All other speed ratio points have a difference less than 3%, this difference can be attributed to repeatability. Several performance runs were completed on the DC dynamometer hardware in which differences of similar magnitude were seen between back-to-back runs on the same day. The difference could be due to ATF temperature, humidity, measurement drift in torques and speeds, etc. Given that a similar difference of 3% was found with comparing the E-motor hardware to the DC dynamometer, as well as between DC dynamometer performance runs, it can be concluded that the new hardware is reliable.

Table 8: E-Motor Performance Data vs. DC Dynamometer Performance Data

Speed Ratio	K Factor Difference	Torque Ratio Difference
0.94	11%	1%
0.83	3%	1%
0.72	1%	1%
0.59	0%	0%
0.51	2%	2%
0.45	1%	2%
0.34	0%	2%
0.19	3%	0%
0.14	0%	3%

5.2 Transient Testing

5.2.1 Clutch Apply and Release

The transient clutch apply and release event supplied boundary conditions for CFD simulation. The clutch was applied over a 2-second period, held locked for 3 seconds, and released over a 2-second period. This clutch apply and release gave a basis for data expectations in future tests. The channels gathered are shown in Figure 100. Only turbine/clutch telemetry data was gathered for this test and as shown in Figure 101, a drop in the cavity pressure as the clutch was applied was expected.
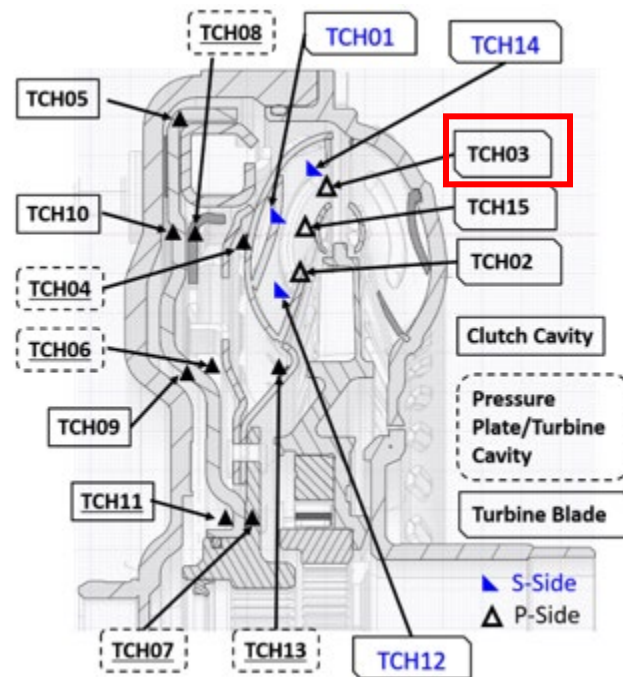
Figure 100: Channel three captures a trend of pressure drop as the clutch is applied [15]

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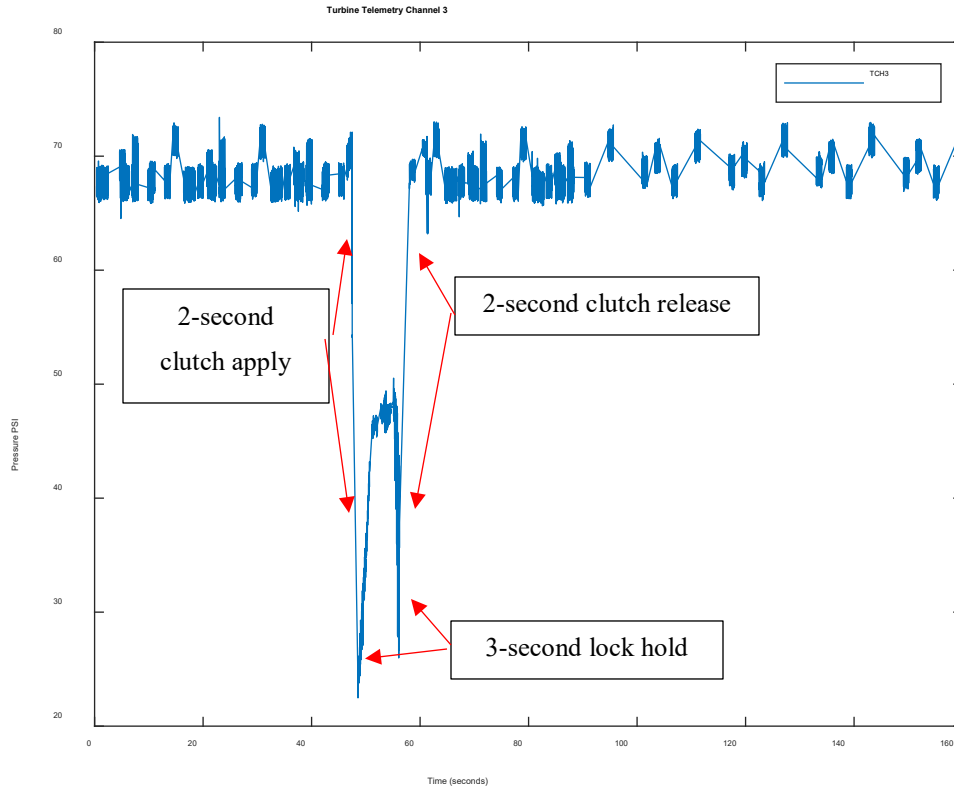
Figure 101: Channel 3 clutch apply reaction

A zero-slip condition was met, and the clutch was fully applied for 2.5 seconds as shown in Figure 102.
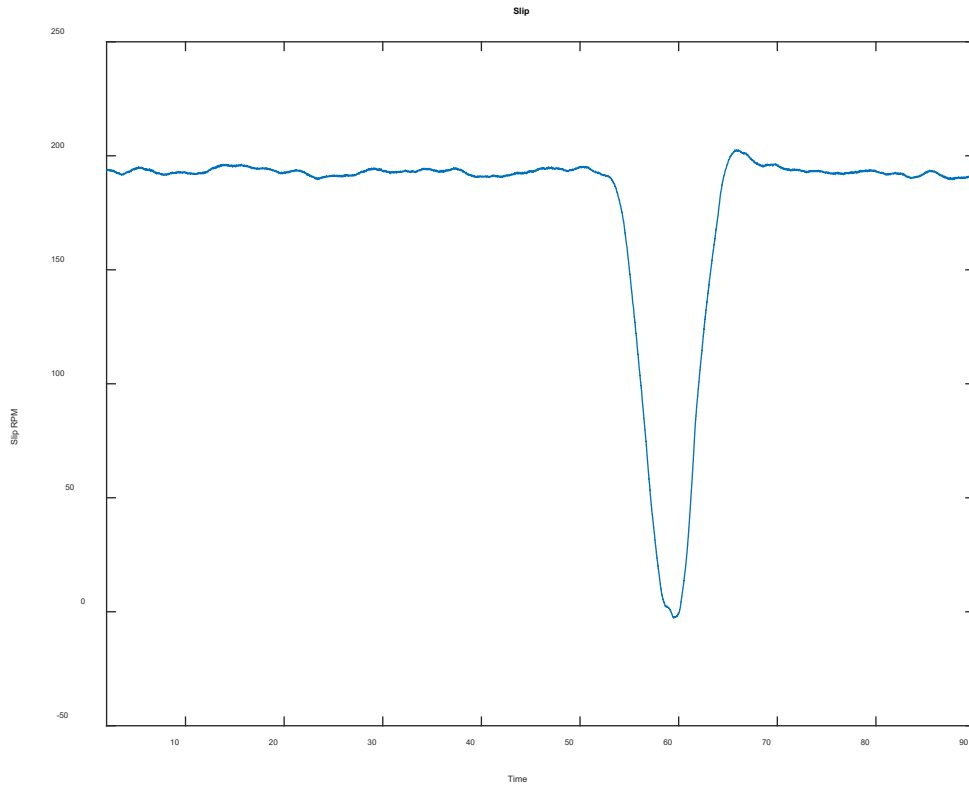
Figure 102: Slip channel during clutch apply and release

5.2.2 Negative Torque Sweep

The negative torque sweep examines a situation where the input is switched from positive to negative. As shown in Figure 103, the input torque was commanded from 15 Nm to -5 Nm and then the input speed reacted to this change. This transition caused the impeller speed to drop since it is no longer acting as the source of energy. Since the torque converter was in an unlocked state, the stator still attempted to multiply torque via fluid as the input speed slowed down. Since the input speed was slowing down, the stator eventually was unable to multiply torque and stalled the converter. With an open converter, the negative input limit for torque capacity was -5 Nm. This was found by trial-and-error before starting the test. Beyond -5 Nm, the torque converter stalled, and the input motor began to rotate in the other direction.
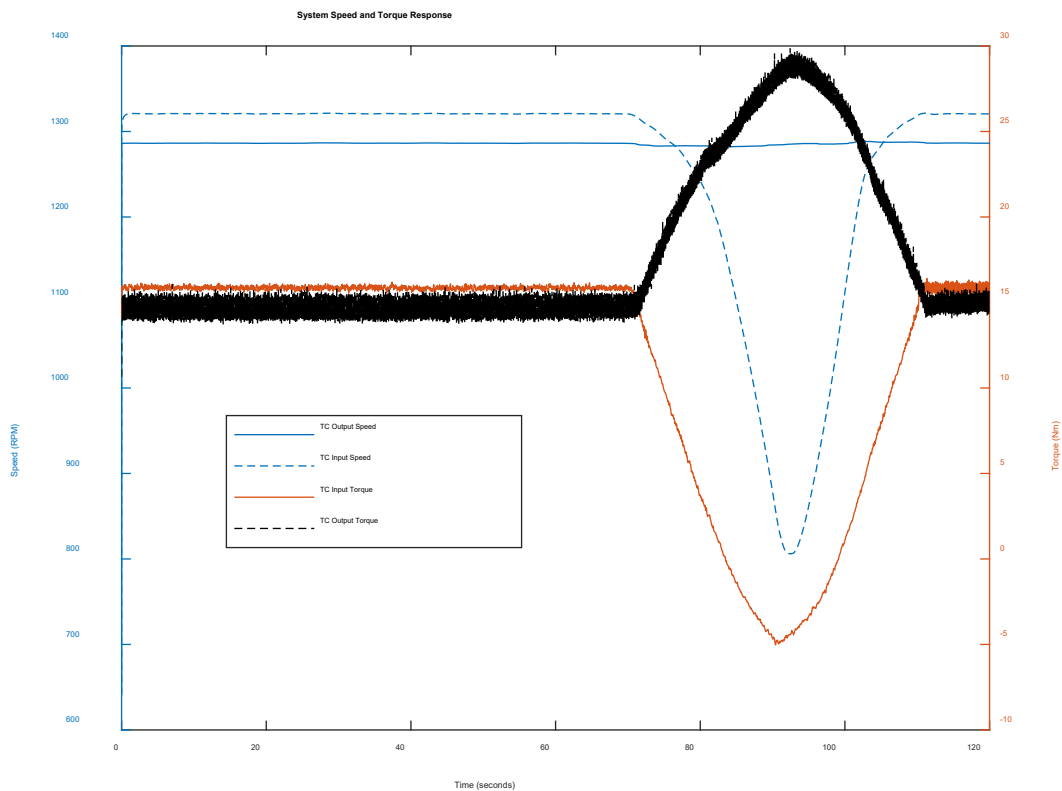
Figure 103: Torque converter torque and speed response for negative torque sweep test

The impeller pressure channels reacted as expected. As the input speed decreased, the fluid in the impeller lost centripetal momentum, and there was a decrease in pressure as shown in Figure 104. This is demonstrated with the outermost channel, PCH02 showing the lowest overall pressure as shown in Figure 105. The trend was similar in the stator and turbine channels as shown in Appendix A.
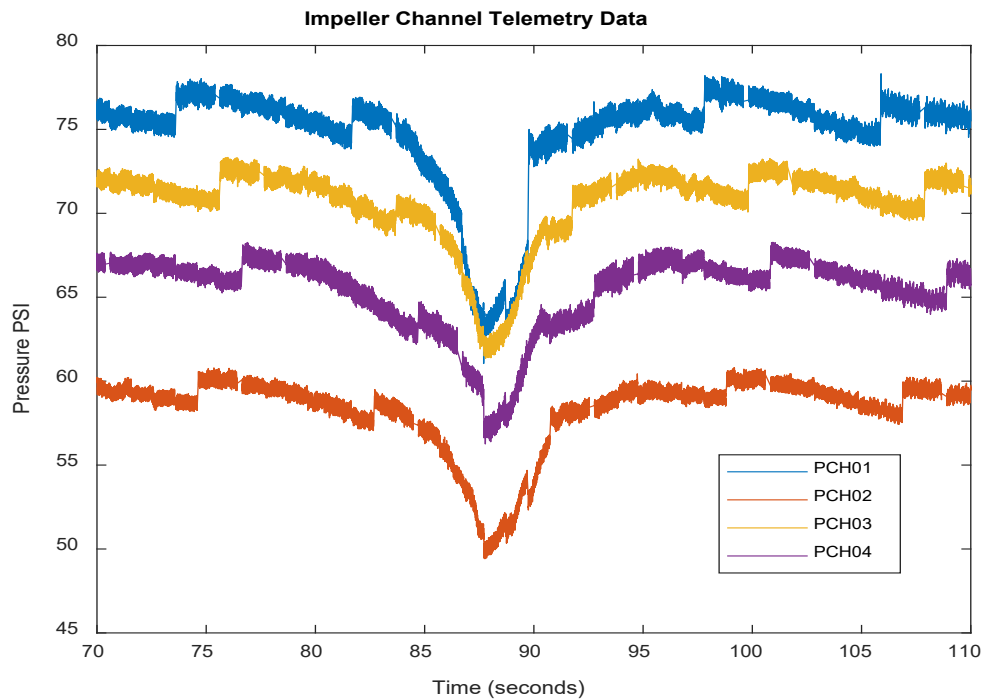
Figure 104: Impeller telemetry channel response
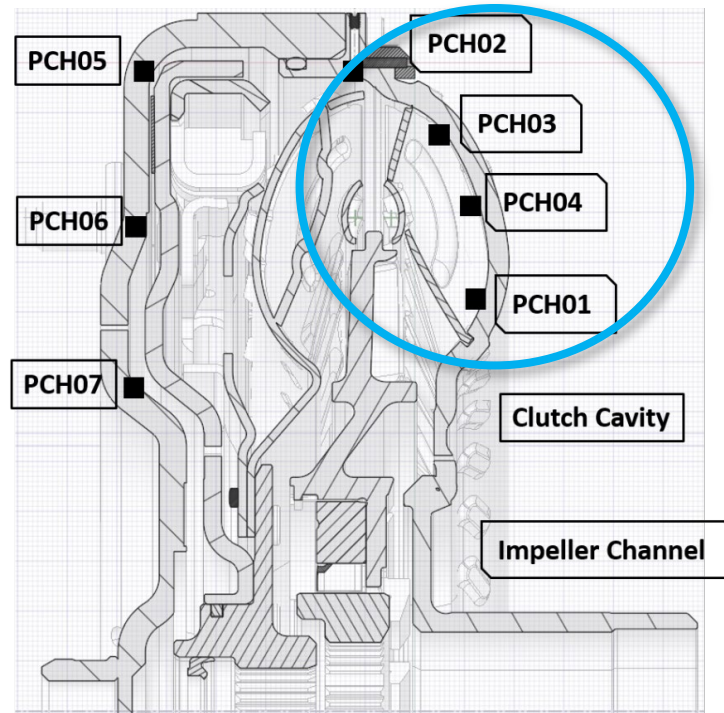
Figure 105: Impeller channels plotted in Figure 105.

The responses of the channels in the impeller, stator, and turbine follow the physics of the predicted behavior of the torque converter for this maneuver. The limit for the input torque to avoid stalling the converter was -5 Nm.

5.2.3 Coast down

This test accomplishes a similar trend as negative torque sweep but in a different method. The torque converter clutch will eventually lose capacity if it remains open while maintaining a positive input torque and reducing output speed. Centripetal pressure was reduced as input or output speed decreased and therefore fluid pressure inside the torque converter was reduced. The limit output speed, without stalling the converter, was determined to be 100 RPM in 3rd gear with 10 Nm input torque. This was found by trial-and-error method before running the test. Below 100 RPM, the torque converter lost capacity and the input motor began to spin the other direction. The torque converter will stall for the same reason as the previous scenario if the output speed drops too low. The

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turbine will lose speed and be unable to assist the stator in multiplying torque by redirecting flow back to the impeller. Reducing output speed caused the turbine to reduce speed before the impeller and this was confirmed upon examination of the data as shown in Figure 106. This is also exemplified in the telemetry pressure data shown in Figure 107 and Figure 108 the impeller channels drop pressure approximately 3 seconds after the turbine channels. No vibration or harshness issues were discovered during this test, the behavior in the data matched the expected changes, and the limit for output speed with an open converter was found to be 100 RPM in 3rd gear for a 10 Nm input torque.
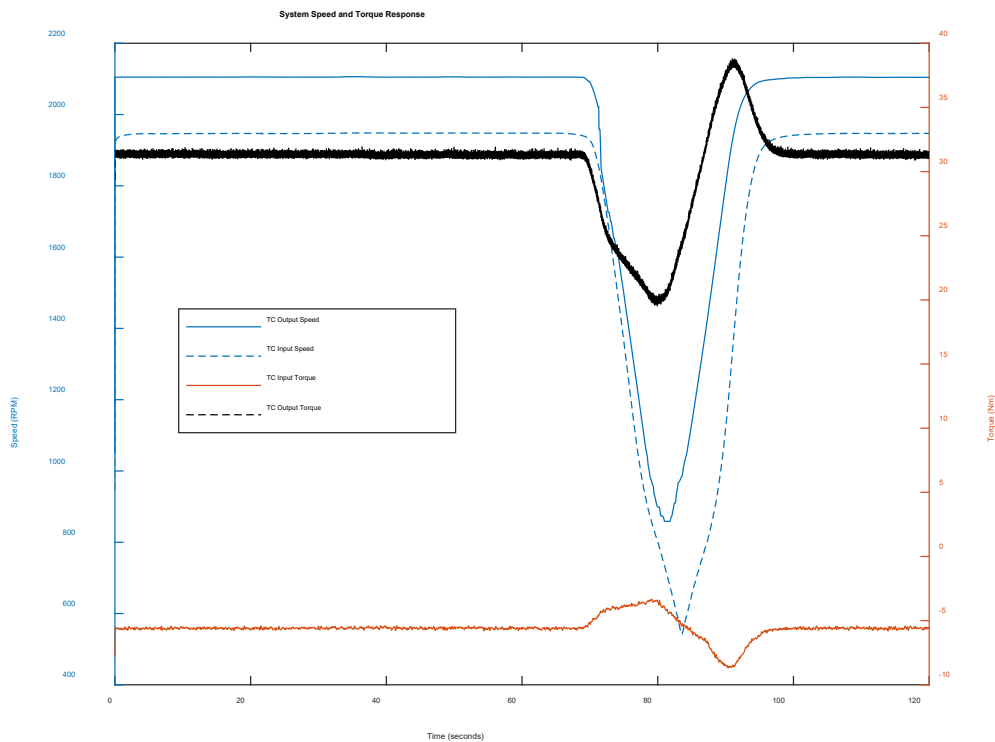
Figure 106: Torque converter speed and torque response for coast down test
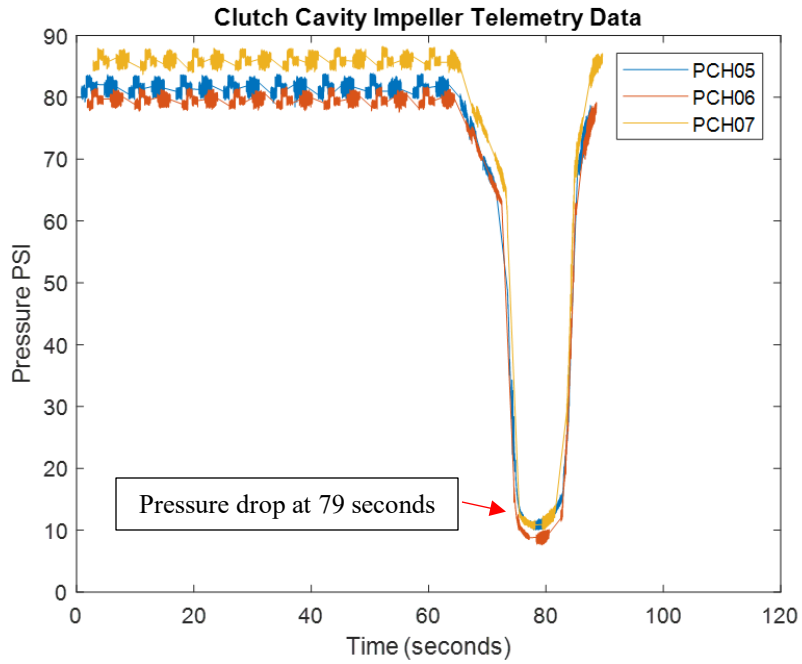
Figure 107: Clutch cavity impeller data during coast down test
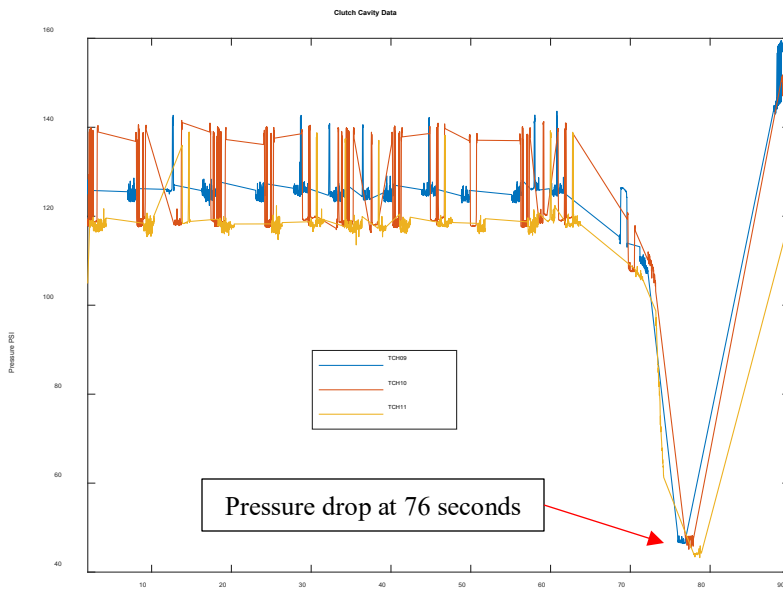
Figure 108: Turbine clutch cavity response data for coast down test

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5.2.4 Negative Input Torque with Slip

With the torque converter clutch locked, the input torque and output speed can be reduced much further than with the clutch open because the energy was being transferred mechanically and does not rely upon fluid momentum to spin the transmission. The test set-up was capable of 200 RPM of slip while applied -45 Nm input torque. 100 RPM was the target, but with open loop control, difficult to attain. There was a 1-second delay between commanding the TCC solenoid to soft lock and the pressure built to apply the TCC as shown in Figure 109.
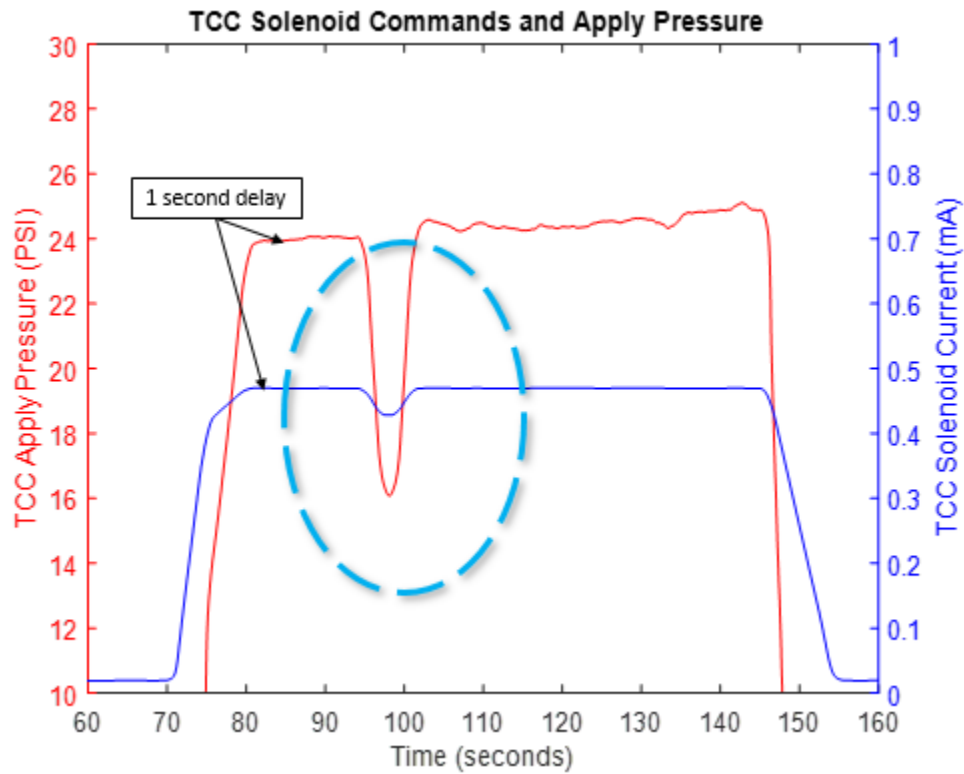
Figure 109: 1 second delay between TCC current command and TCC pressure built

During the locked condition, the pressure side of the stator was higher than the suction side of the stator as shown in Figure 110 and Figure 111. Restated, the pressure side, or the side closest to the impeller, had a higher pressure than the suction side, or the side closest to the turbine. This makes sense because the clutch plate is being applied by fluid pressure supplied from the impeller side.
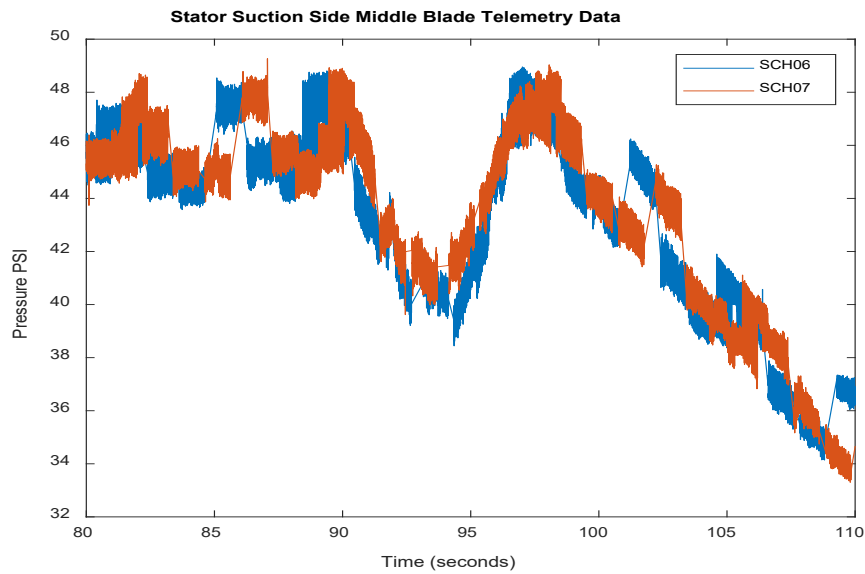
Figure 110: Stator suction side data from negative torque input with slip test
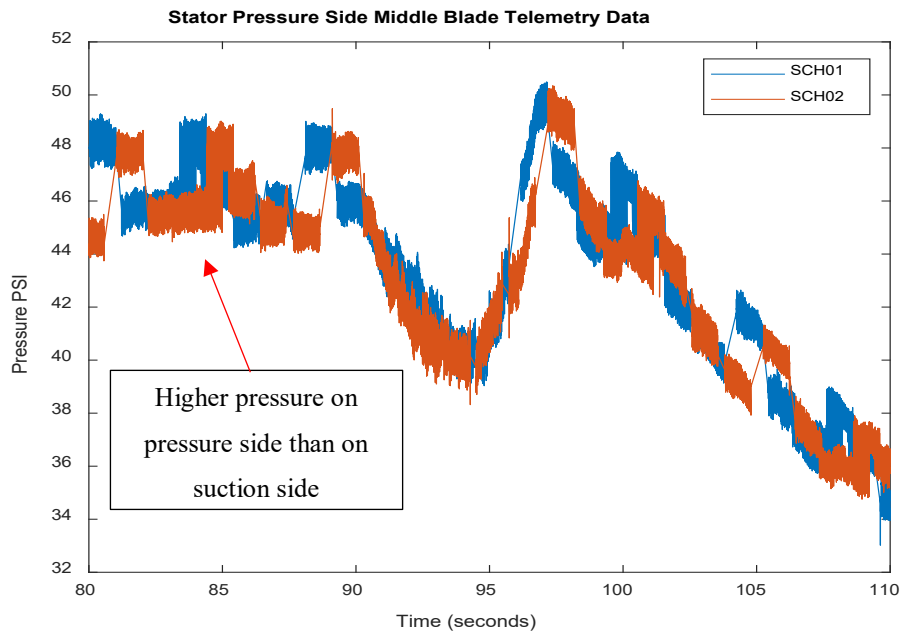
Figure 111: Stator pressure side data from negative torque input with slip test

It can also be seen that the pressure followed a radial trend. The pressure is highest at the core proximity which follows the physics as shown in Figure 112. The fluid will flow highest in the center to be redirected to apply pressure to the clutch plate. The channel locations are depicted in Figure 113.
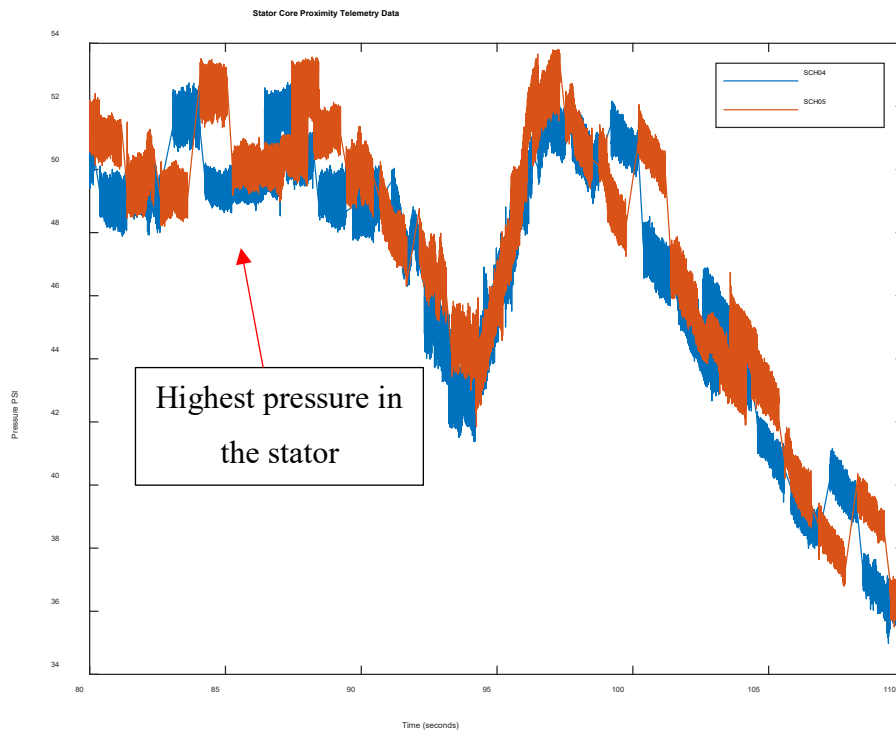
Figure 112: Stator core proximity telemetry data from negative torque input with slip test
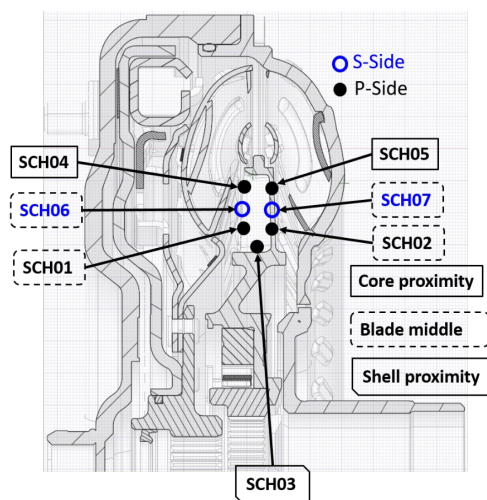
Figure 113: Stator channel locations

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There was less than 0.1 second delay between the initial command for the solenoid to slip the torque converter clutch in Figure 109 and the slip response shown at 97 seconds in Figure 114 which is derived from subtracting the input and output speed of the torque converter shown in Figure 115.
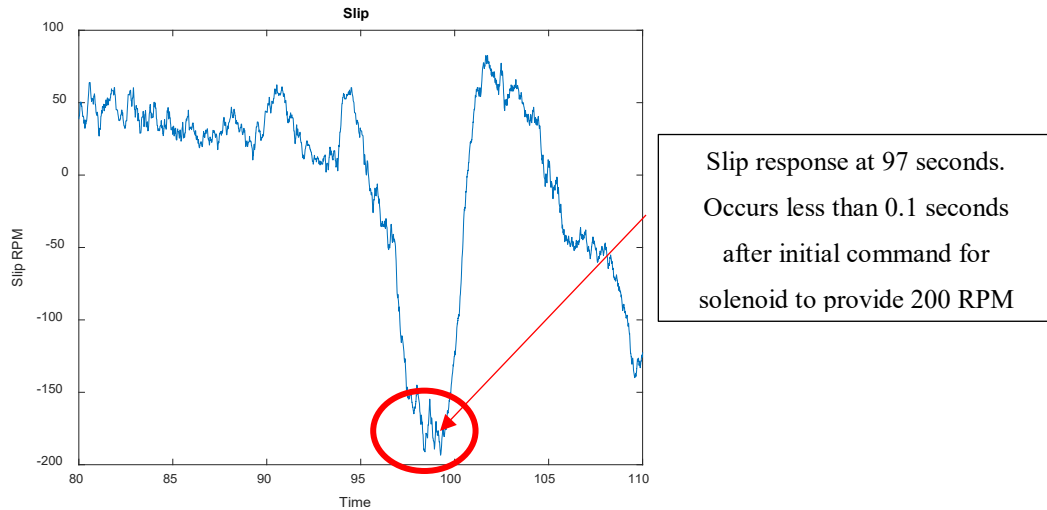
Figure 114: Slip was controlled at 200 RPM for negative input torque with
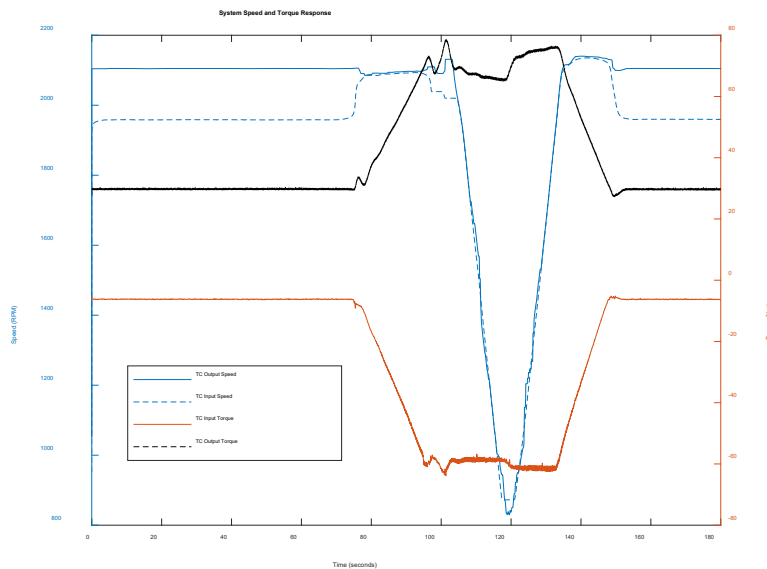
Figure 115: Torque and speed system response from negative input torque
with slip scenario

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There were no vibration issues associated with this maneuver or strange fluid behavior. The only controllability issue was with slip targeting 100 RPM and reaching 200 RPM. This could be adjusted with multiple test runs since it is an open loop control. The behavior in the stator pressures followed the physics of the maneuver.

There are some discrepancies to note in data in this test and the coast down test. The straight lines between data points represent areas where no data was recorded. It is extremely important to start each test at precisely the same time or the data between channels will not line up properly. Channel 15, nearest to the marker channel, contained a significant amount of noise and sometimes interfered with starting the data at the correct time (See Figure 116 and).
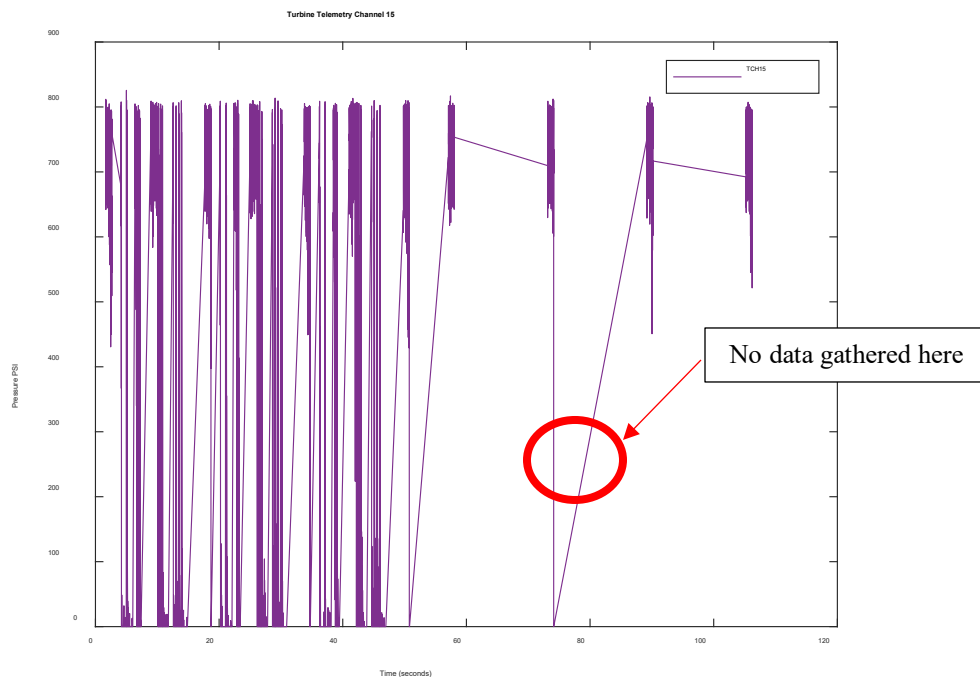
Figure 116: Channel 15 issues on turbine channel
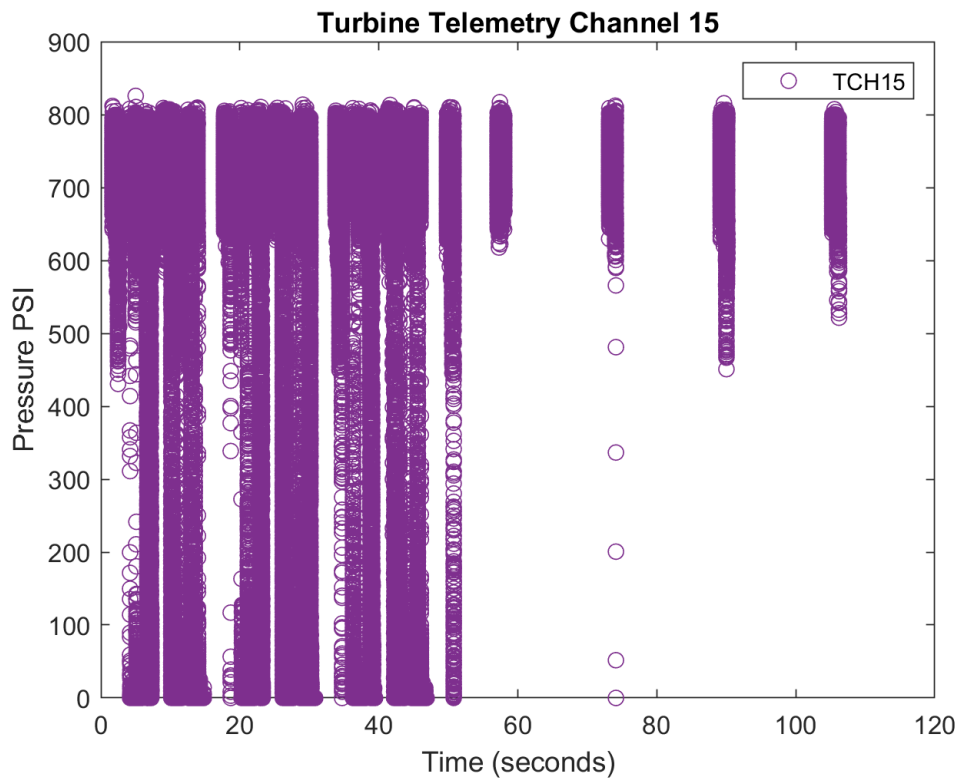
Figure 117: Turbine Telemetry Channel 15 data shown as individual points

This can be alleviated two ways: by filtering the signals before parsing the data or by running the entire test twice and then plotting data sets for each channel directly on top of one another to fill in the gaps of data. The signals were filtered before parsing the data using a low-pass filter, but this did not solve every dropout or discrepancy. Running the entire test twice could have been done, however, this may not work every time due to Channel 15. As can be seen from Figure 118 and Figure 119, Channel 12, 13, and 14 are also affected due to continued wear on the components. The best solution is to bring the hardware in for repair.

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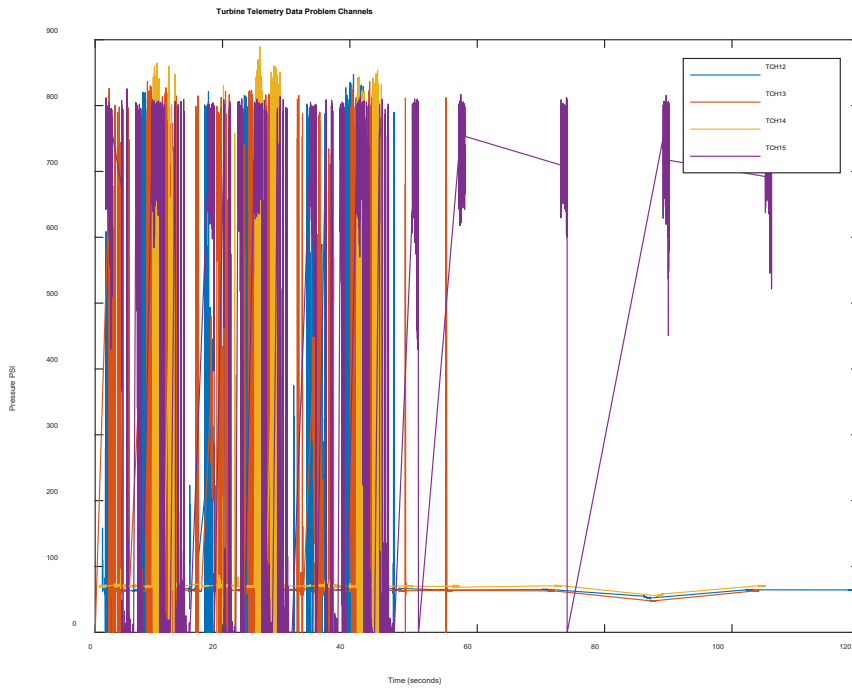
Figure 118: Problematic channels for turbine telemetry data
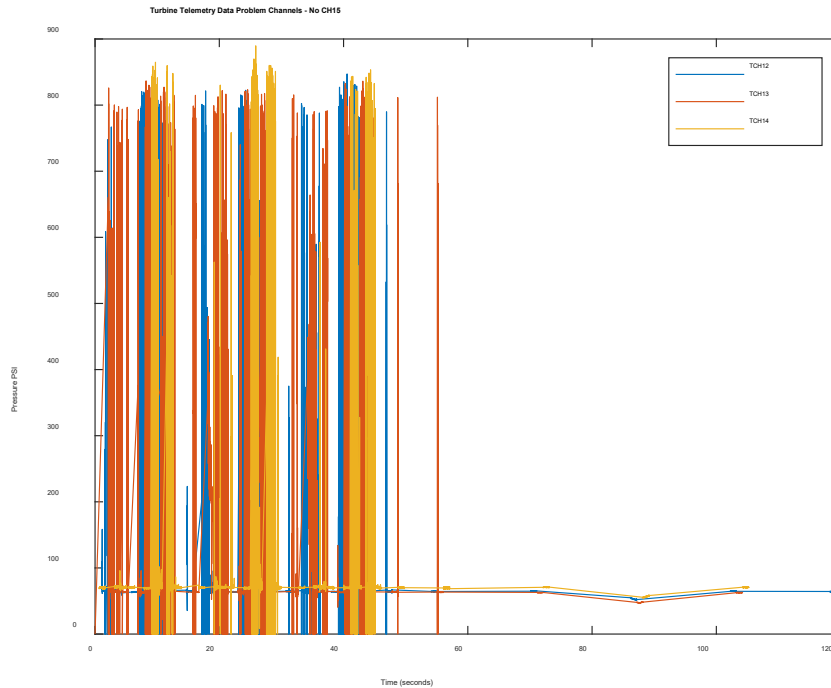
Figure 119: Affect of channel 15 on neighboring channels

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Furthermore, the ability to trigger recording data automatically was lost before obtaining this data. Therefore, the impeller, stator, and turbine data sets were all gathered separately and triggered manually. This could add to further discrepancies in the data. General cause and effect relationships can be drawn; however it is inaccurate to draw any conclusions about frequency content of the signals.

6 Summary and Conclusions

- The BorgWarner electric motor set-up can provide a constant negative input torque to the system

- Performance testing was complete on both test set-ups and results validated the repeatability and consistency of measurements and test cell capability. Difference in performance varied no more than 3% between tests except for speed ratios above 0.9 with a difference of 11%. This difference can be attributed to the difference in speed ratios reached between tests.

- An average ATF temperature difference of 50 °F changes performance testing values by 2.7% within the same test cell set-up. Because the performance tests between set-ups varied by no more than 3%, this test is not conclusive.

- Transient clutch apply and release testing was completed and the system control was able to reach a fully locked state and the telemetry system was able to accurately capture the event for the turbine/clutch channels.

- The limit for negative input torque while operating the torque converter clutch in an open state is -5 Nm with output speed at 300 RPM

- The limit for AC output speed while operating the torque converter clutch in an open state is 100 RPM while the input is at 10 Nm

- The responses of the telemetry pressures to changes in speeds and torques of the system follow the physics of the torque converter

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7 Recommendations

7.1 Testing Recommendations

- Oscillating torque scenarios should be investigated. With the added capability of the smaller inertia input motor, it would be conducive to recreate more detailed engine behavior in future testing. Adding a dynamic torque trace on top of a negative torque input may also be of interest

- During the duration of this research, the non-instrumented transmission was used to develop test profiles and practice runs. When the profiles and test script were finalized, the instrumented transmission was installed and non-instrumented transmission removed. This process should continue if this hardware is to be used for future research. The antennae and hardware have a limited life and many hours have already been run on the system.

- If there is interest in looking at performance characteristics as a function of ATF temperature, there should be an ATF temperature control loop to keep it at a cool starting temperature throughout the test.

7.2 Instrumentation Recommendations

- Wiring behind the "gmtorque" and "Hydraulic" computers inside the test cell should be updated. Connectors were added for ease of removal during the dynamometer swap, but the terminal strips are unreliable for transmitter signals and more noise was introduced to the system because of the inverter and electric motor. The terminal strips should be converted to a few large plugs running directly to the wall and to their respective destination inside the cabinet. The wiring upstairs in the AC drive cabinet should also be examined.

- Wiring from the transmission instrumentation to the Scadas III DAQ should be updated. The wires currently run via unshielded BNCs to a panel box on the wall and then through conduit out of the test cell to another panel box which breaks out

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into more unshielded BNCs to the Scadas III DAQ. The added EMI from the BorgWarner machine and inverter caused many of the signals to become unstable and several were re-routed with shielded BNCs outside of the conduit. The wiring inside the conduit should have ribbon cable and all the BNCs should be RG58 shielded cable.

- The IR Telemetrics hardware should be sent in to repair Transmitter A. The receivers are currently unable to lock onto Transmitter A's frequency likely because of the life of the hardware. If any future testing requires information about the impeller, this should be examined.

- IR Telemetrics hardware should be updated to 4 transmitters to better identify Transmitter C data. Currently turbine data does not show trends effectively because data does not line up perfectly every time since Channel 15 interferes with the marker signal. This issue has bled into other turbine channels and can be avoided, sometimes, by running the Transmitter C tests twice to take an average or see the data trend more clearly but it takes up a large amount of time.
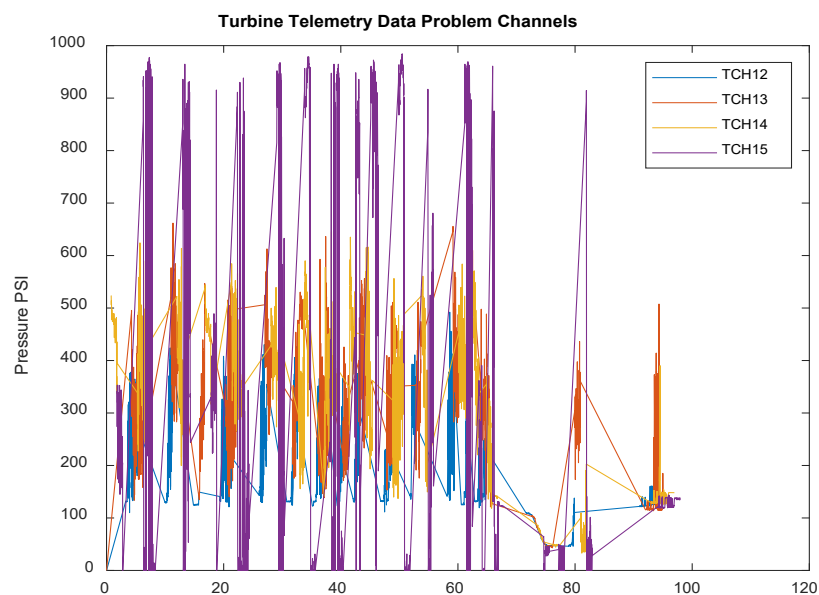
Figure 120: Transmitter C telemetry problem channels

- The IR Telemetrics software should be updated to include:
  - Renewed use of the "On Sync" function for obtaining data automatically

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- The custom LabView software used to operate the input motor and absorbing dynamometer should be updated to include:
  - A safety check for torque ramp rates. Currently the default torque ramp rate is the same as the RPM ramp rate: 100 Nm/s. This can be dangerous if a user mistakenly believes they are in speed mode, when really they are operating in torque mode and enter 500 thinking they are commanding a speed when it is commanding a torque instead. This could be accomplished by either changing the default torque ramp rate to 10 Nm/s or having a dialogue box open when a user accidentally enters a high torque number.
  - A speed limit on the input motor. Currently the AC dynamometer has a speed limit of 5000 RPM. The DC dynamometer used to have the same speed limit, but the BorgWarner motor does not have this as a current feature. The e-stop will suffice for emergencies but because of the incredibly quick ramp-rates, it can be hard to react in time. A speed limit could help in avoiding troublesome situations.
  - A fail safe if the program crashes. Typically, if the program crashes, the dynamometers continue at the same speed or torque point they were at prior to the crash. This can be troublesome if the crash happened in the middle of a test script and the user cannot recall the exact speed and torque point which they were commanding. This could be resolved by spinning down the input and output dynamometer to stop and the user could re-open the program.

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A Supplementary Graphs for Transient Tests

A.1 Negative Torque Sweep

The negative torque sweep examines a situation where the input is switched from positive to negative. The input torque was commanded from 15 Nm to -5 Nm and then the input speed reacted to this change.
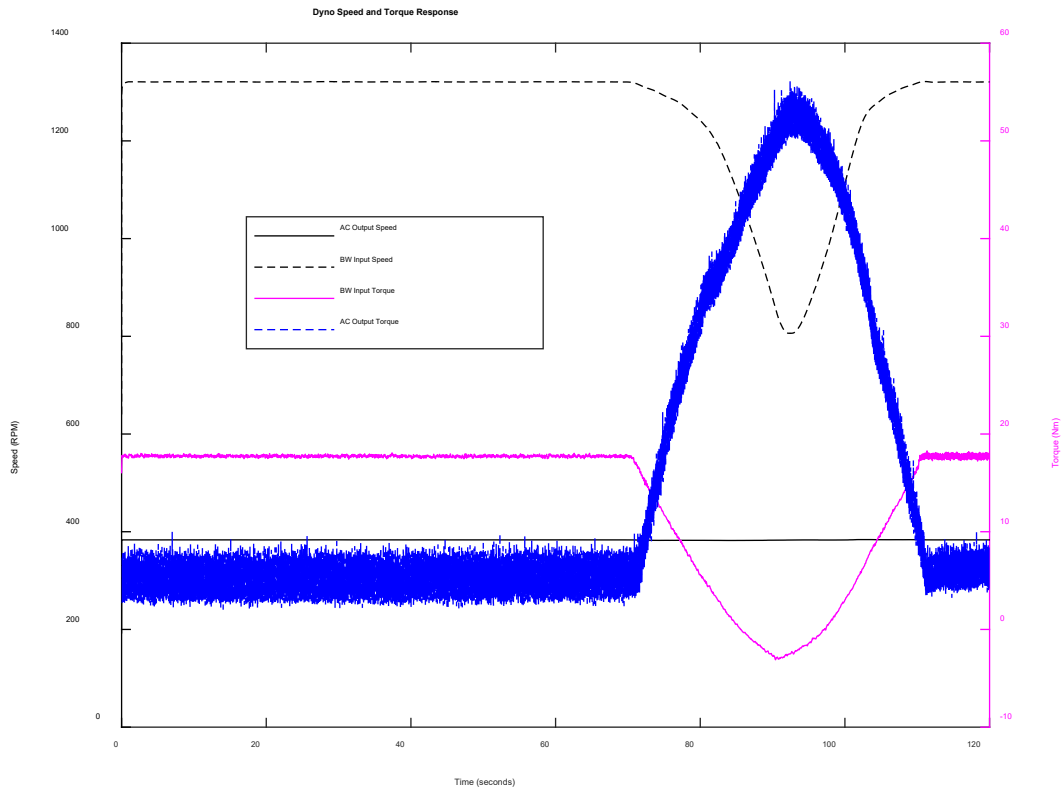

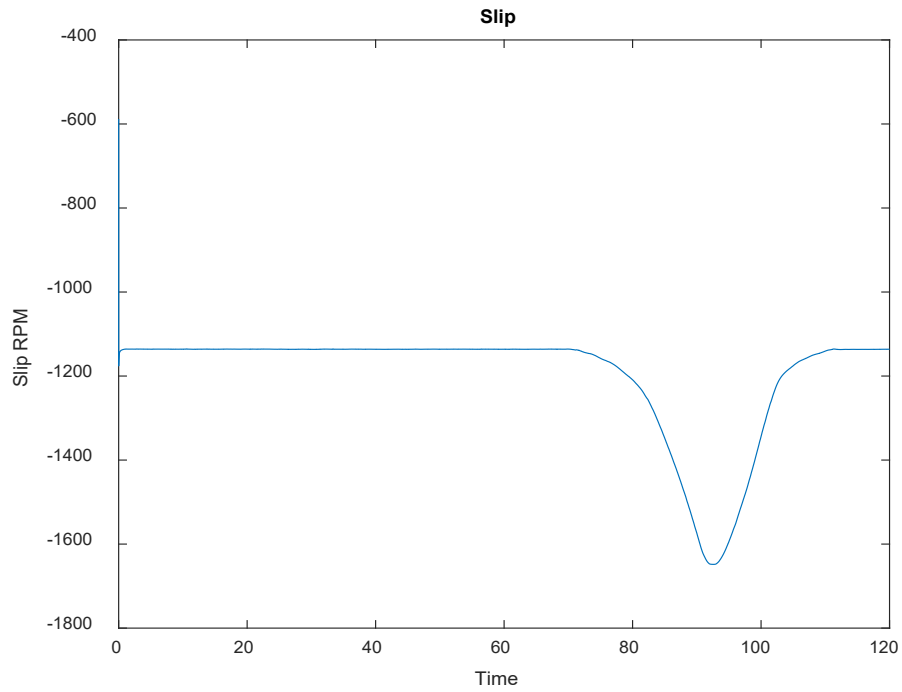*Figure 121: Dyno speed and torque responses for negative torque sweep test*

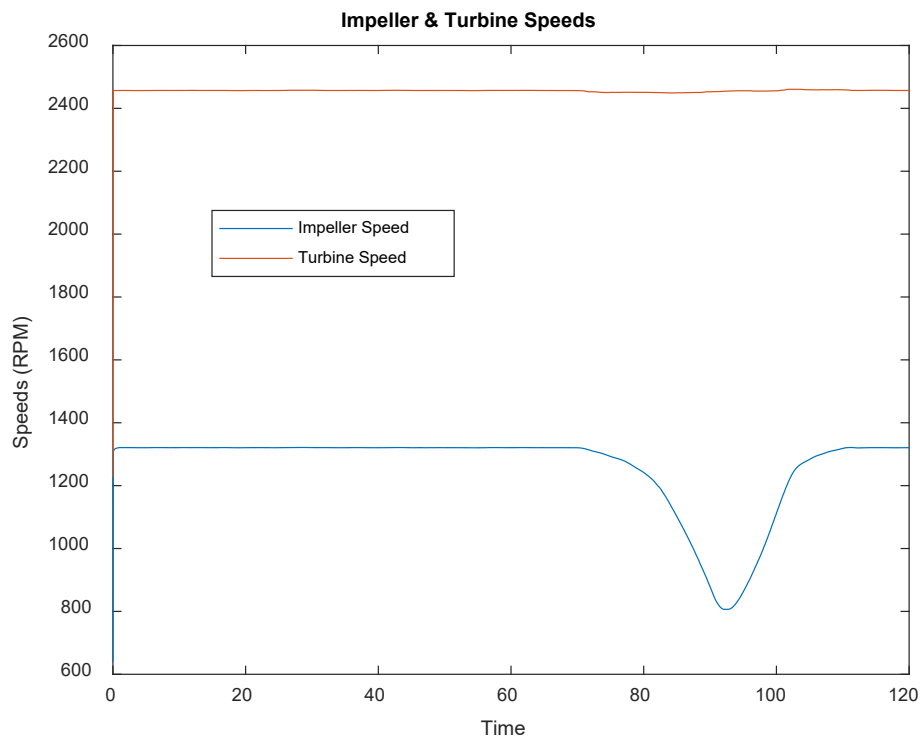*Figure 122: Slip response for negative torque sweep test*

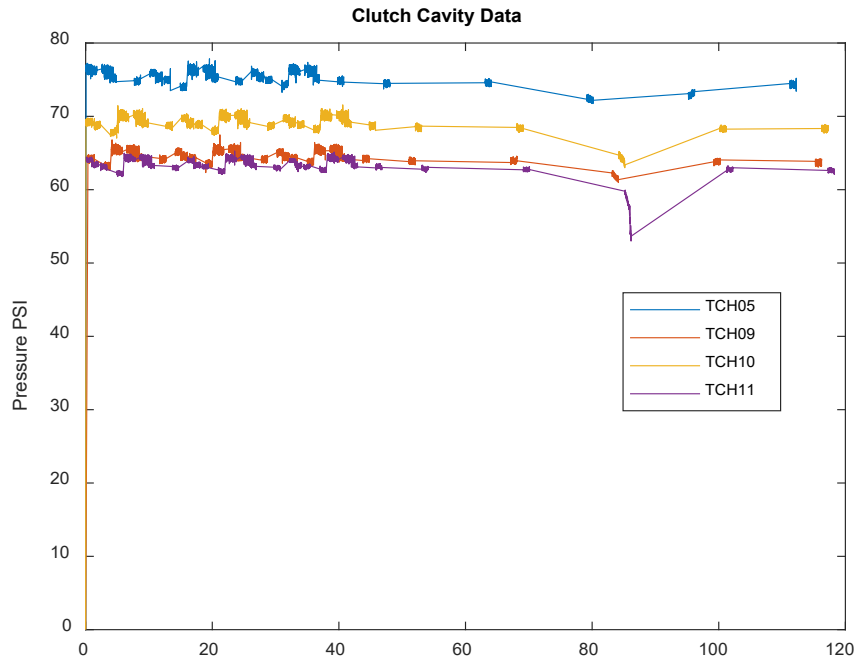*Figure 123: Impeller and turbine speed response for negative torque sweep test*

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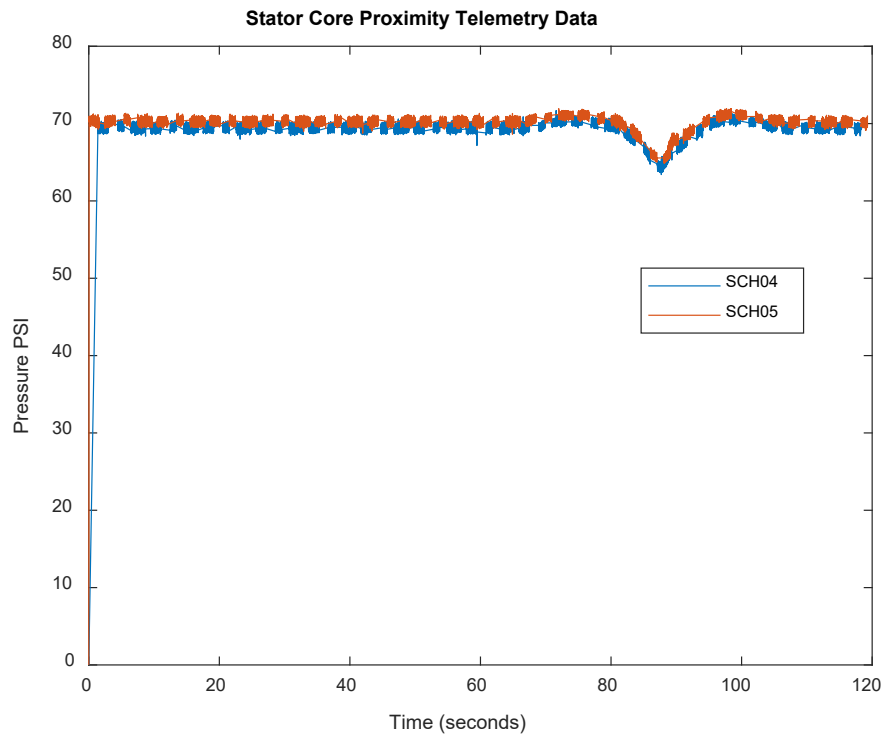*Figure 125: Turbine clutch cavity response for negative torque sweep test*

Figure 124: Stator core response for negative torque sweep test
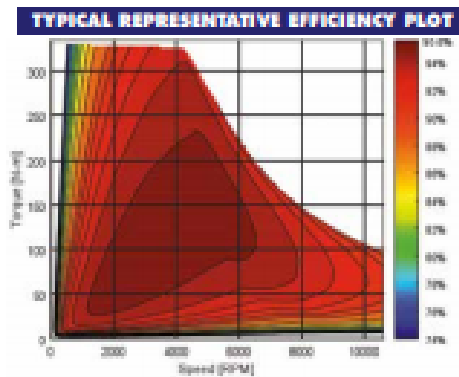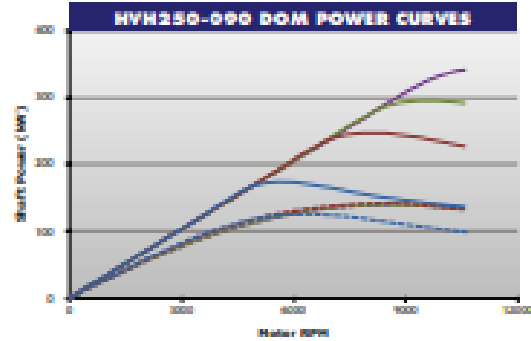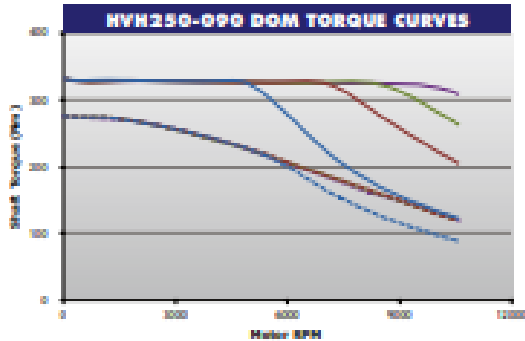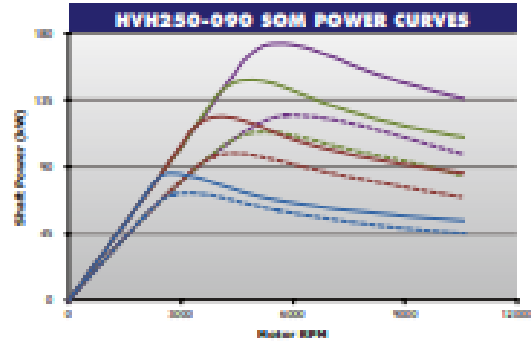
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B   Troubleshooting

If the "gmtorque" computer is shut down or re-started, both the contactors for the TCC cell and ADAPT cell will close. It is important to turn off the AC dynamometer drive cabinet before re-starting the software or resuming testing so as not to weld the contactors shut. Then turn on and off the contactors in the NI Max software before re-starting.

If there are any issues with NI channels reading improperly, LabView needs to be closed and open NI Max to examine sensor calibration by hitting "Run" and closing after examining the value.

C BorgWarner Electric Motor Data Sheet

HVH250-090 Electric Motor

D   Calibrating the Inverter Cart

- Open Phoenix utility software and hit "play", select 'user defined', and click "read" to obtain the current position offset
- Enter new position (197.9 for the Ford test cell side) and hit "write", and click 'stop'
- Turn off the inverter power switch (black button) for 10 seconds
- Turn back on inverter power switch (black button)
- Enter Phoenix Utility software again and hit "read" to confirm new position.
- Exit Phoenix Utility and Enter Remote Desktop
- Remove Vector tool
- Turn on TCC Contactors and then AC Cabinet
- Open Labview
- Test spin in manual mode to verify test cell function, tacho gaps, etc
- Proceed with acquiring test data

E   Telemetry Post Processing

For more information on telemetry post-processing, see the reference below:

[1] M. T. Woodland, "Characterization of Hydraulic Interactions Between Torque Converter and Transmission During Transient Events," Michigan Technoloical University, Houghton, 2019.

One large change was made to the post-processing code used in this research. For identifying marker channels on Transmitter C a low-pass filter was applied to the raw data in order for the Telemetry_Organizer code to pick up the data. In order to apply this filter, Line 68 in the Telemetry_Stitcher code needs to change to Dropout_ResampleA.

Telemetry_Stitcher

```
    % Commanding subroutine to remove dropouts and resample the data
set
    [ty,y] = Dropout_Resample(Data(:,1),Data(:,2),fs);
    % Dropout_Resample was created by Mark Woodland in previous
research.
    % For high noise data from Transmitter C, use Dropout_ResampleA,
    % which has a low pass filter prior to re-sampling the data to help
    % more effectively remove dropouts near the marker channel
    % Commanding subroutine to organize the data by channels and 3D
matrix
```

Dropout_ResampleA

```
function [ty,y] = Dropout_ResampleA(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 specifically for problem channels in turbine speed
%% Removing Dropouts
B = hampel(A, 30000);
% p = 5, upsampling parameter, q = 10, downsampling parameter
q = resample(B,t,fs,5,10);
lpFilt = designfilt('lowpassfir', ...
```

```matlab
        'StopbandFrequency',90,...
        'PassbandFrequency',25,...
        'StopbandAttenuation',70,...
        'SampleRate',fs);
y = filtfilt(lpFilt, q);
ty = 1/fs:1/fs:length(y)*1/fs;

end
```

To change the threshold level if there are still any troubles identifying marker channels with Transmitter C, see Telemetry_Organizer code Line 19.

Telemetry_Organizer

```matlab
%% Finding Marker
thresh = 10000;
% [Hz] threshold level for marker
```

F   Fill Procedure for Transmission

- Fill from the rubber port on top of the transmission with Mercon LV fluid obtained from the outdoor trailer.
- Fill until ATF flows from the sight port underneath the final drive outlet
- Close the sight port, and cover the rubber port
- Run the transmission at 500 RPM in Speed mode with AC dynamometer off in 5th gear until you see something read on the digital coolant flow meter. Shut off immediately.
- Check to see if ATF flows from the sight port. If not, fill until you see anything dripping and repeat the previous step.
- Once fluid is flowing, run the transmission at 500 RPM in Speed mode with the AC dynamometer off and shift into 6th gear, then step all the way down to 1st gear and step back up (^ 6th, 5th, 4th, 3rd, 2nd, 1st, ^ 2nd, 3rd, 4th, 5th).
- Check fluid. Refill if necessary
- Run at 1500 RPM for 5 minutes
- Check fluid. Refill if necessary

Typical amounts range from 3.5 - 5 quarts when the torque converter is somewhat full and there has been no changes to the final drive.

G   Checklist for Starting TC Cell

1. **AC Dyno to "Forward"**
2. **Turn on conditioner box for laser tachometers**
3. **Turn on power supply**
4. **Turn on solenoid controller box and power supply**
5. **Check that both dynos oil supplies are working**
6. **Check that both spin w/o issue**

<mark>Make sure to plug into the NI system for calibration and recording data.</mark>

Starting the Test Cell
1. Double check that vehicle dyno cell (ADAPT) contactors are not on
2. Turn on contactors using NI Max Software
3. Check coolant level
4. Turn on cart - make sure fans are running and coolant is flowing.
5. Double check NI box is on
6. Turn on main power upstairs
7. Double check gear state
8. Double check both dynos spin w/o issue
9. The inverter voltage can be viewed by clicking the "Startup" button on the VI. When the inverter is powered up, the display should show the inverter voltage around 718 - 719 V. The battery voltage is not a concern when operating on the cabinet power supply. In roughly a minute or so after the high voltage power switches are thrown, the "Inv. Fault" field should change from "Fault" to "No Fault". If the inverter stays in the fault condition well after this event, there is issue in system that must be corrected before operation.
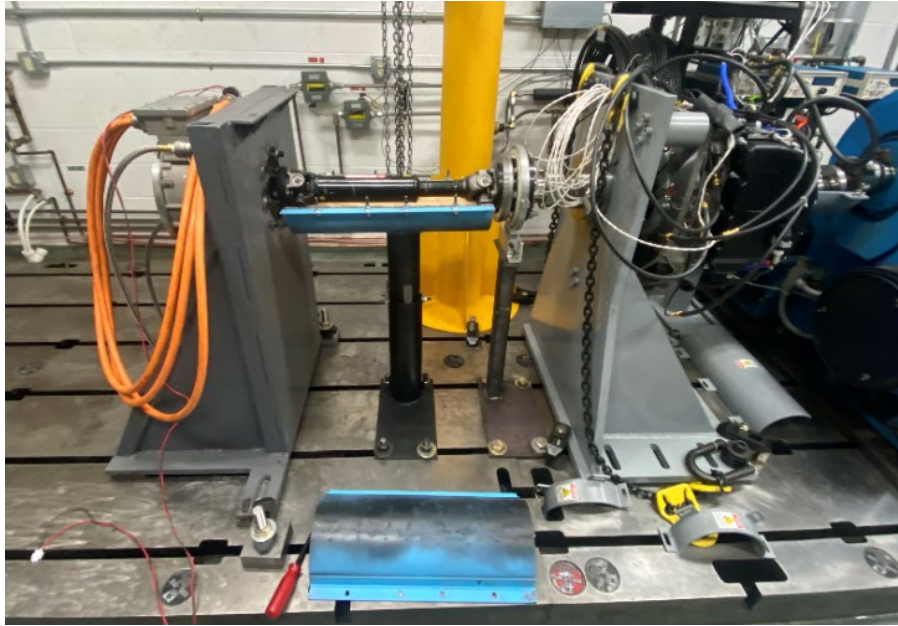10. Set System for Mode "Off" since we are not using the hydraulic system.

NOTES:

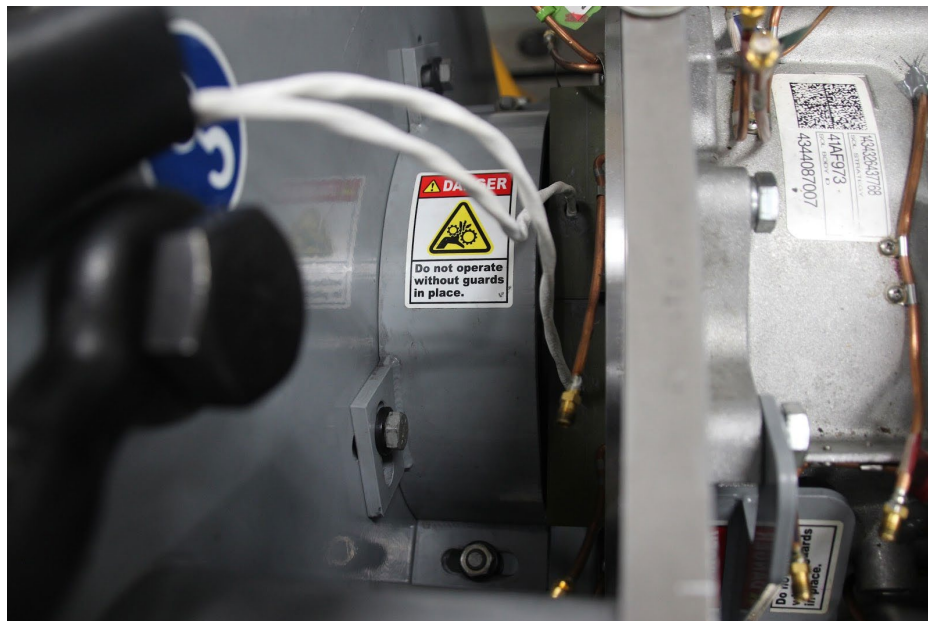CHECK INVERTER TEMPS PERIODICALLY THROUGHOUT THE DAY.

<mark>**ALWAYS START IN TORQUE/SPEED MODE. DO NOT SWITCH MODES IN MANUAL MODE**</mark>
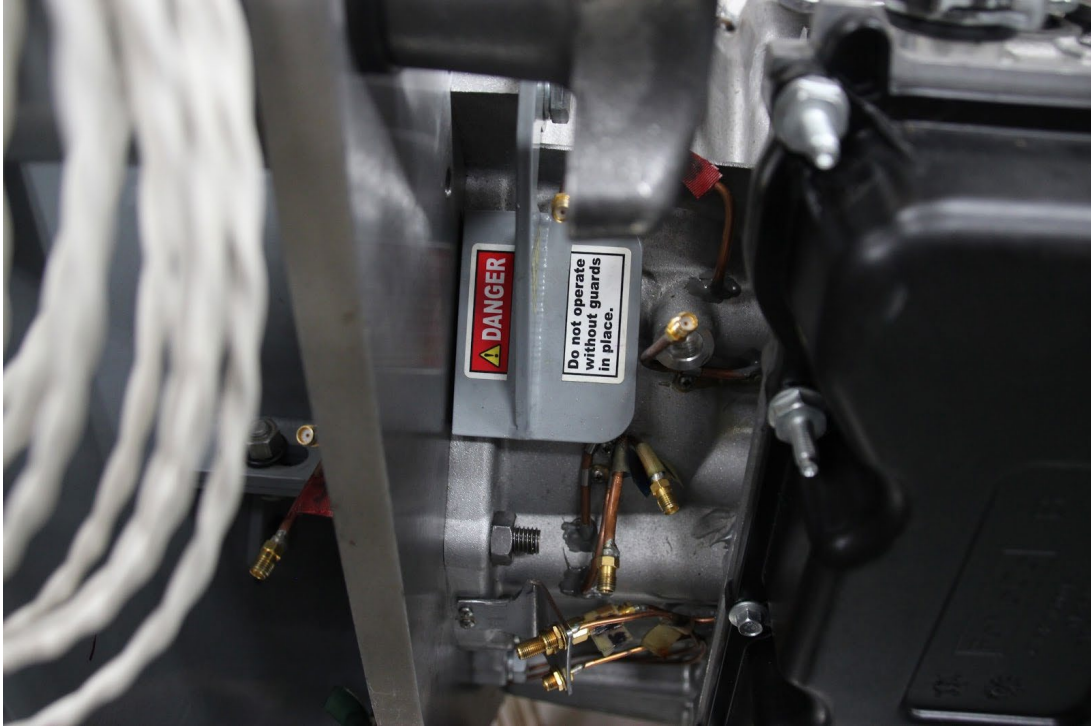
H   Transmission Swap Procedure
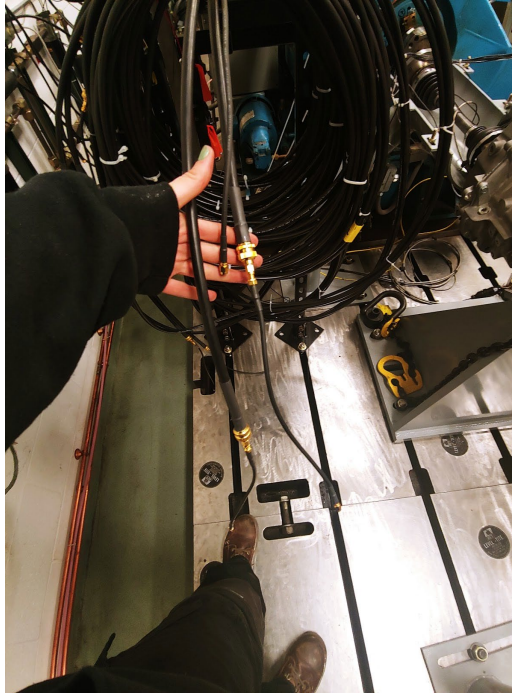

Figure 126: Remove guards and shafting

Figure 127: Remove guards and shafting
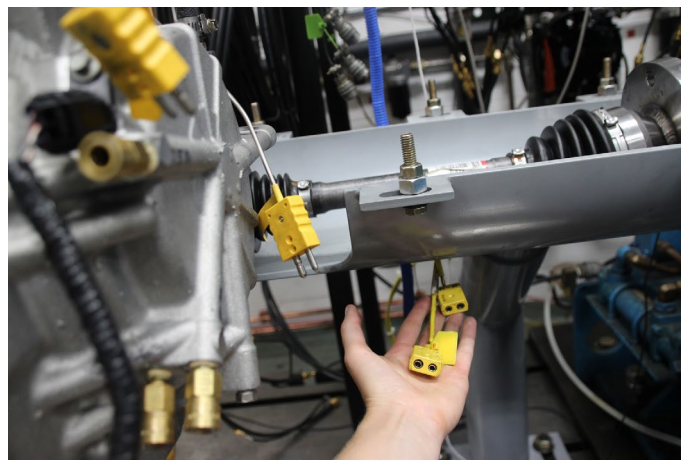
117
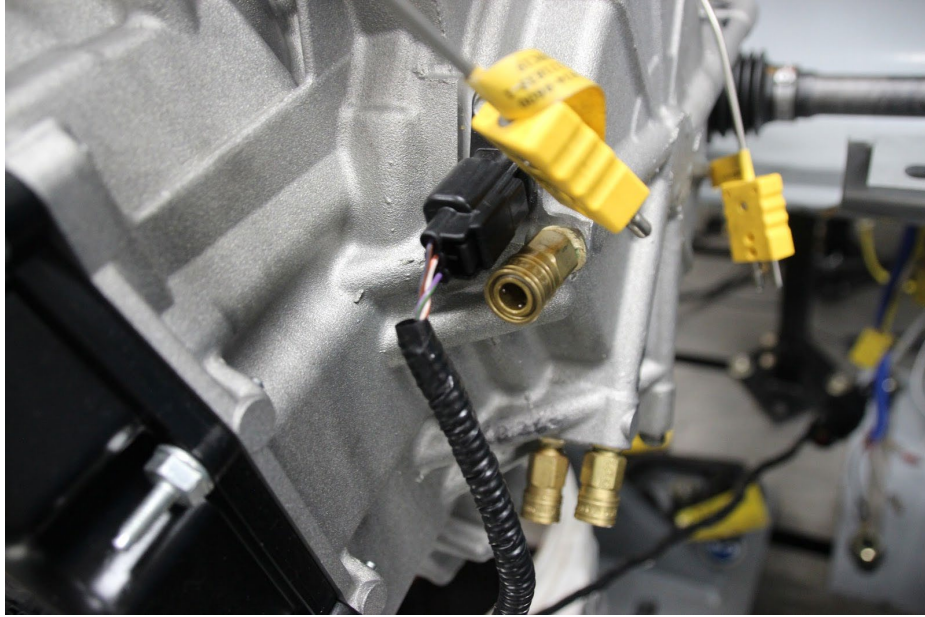
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Figure 128: Remove guarding

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Unplug sensors: telemetry, thermocouples, Kulite pressure sensors, Milspec pressure sensors, solenoid controller. Solenoid controller comes off easily if you push down on black piece with a screwdriver.
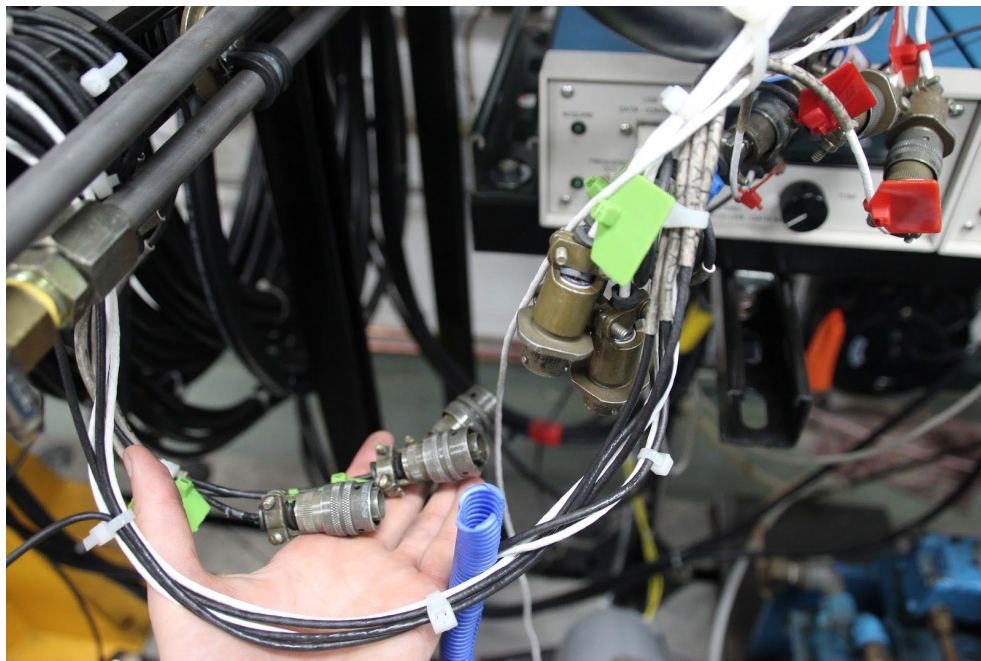

Figure 129: Unplug telemetry antennae

Figure 130: Unplg thermocouples

Figure 131: Transmission Kulite sensors and speed sensors unplugged

Figure 132: Milspec pressure sensors unplugged

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Figure 133: Transmission connector removal

Unplug ATF Lines (10 mm to remove metal retainers)
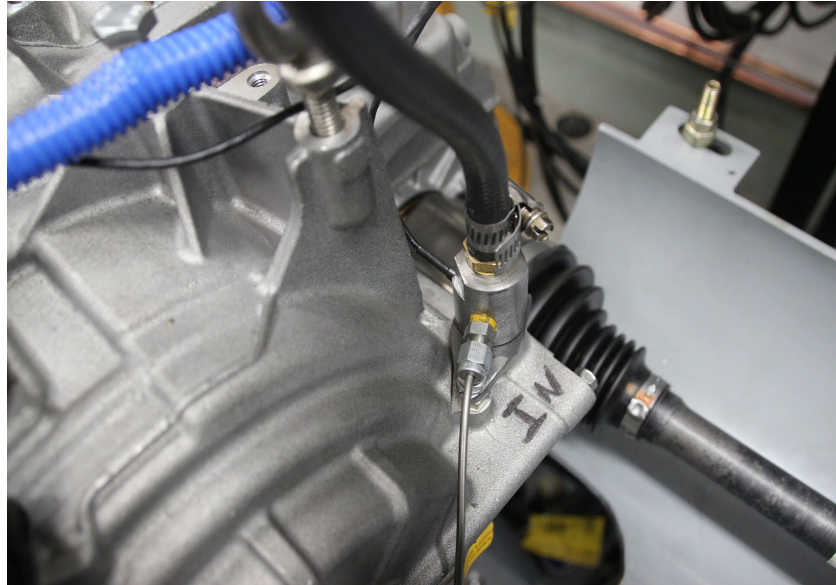
Figure 134: Inlet transmission ATF line

Figure 135: Outlet transmission ATF line
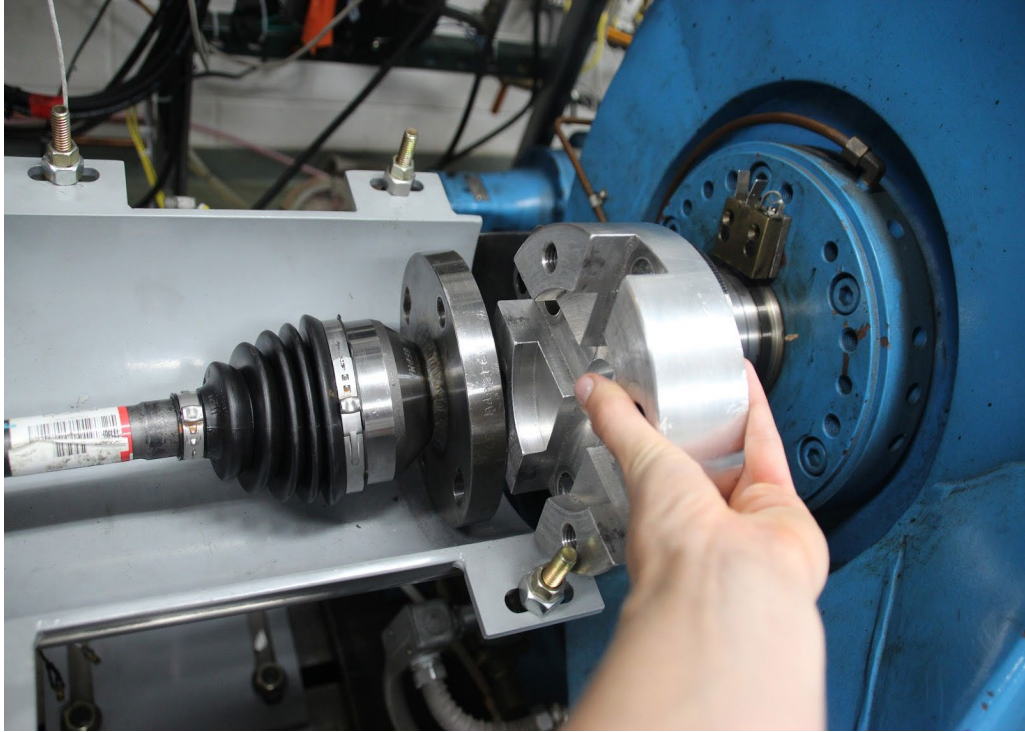
Figure 136: Remove driveshaft from dyno side with impact driver
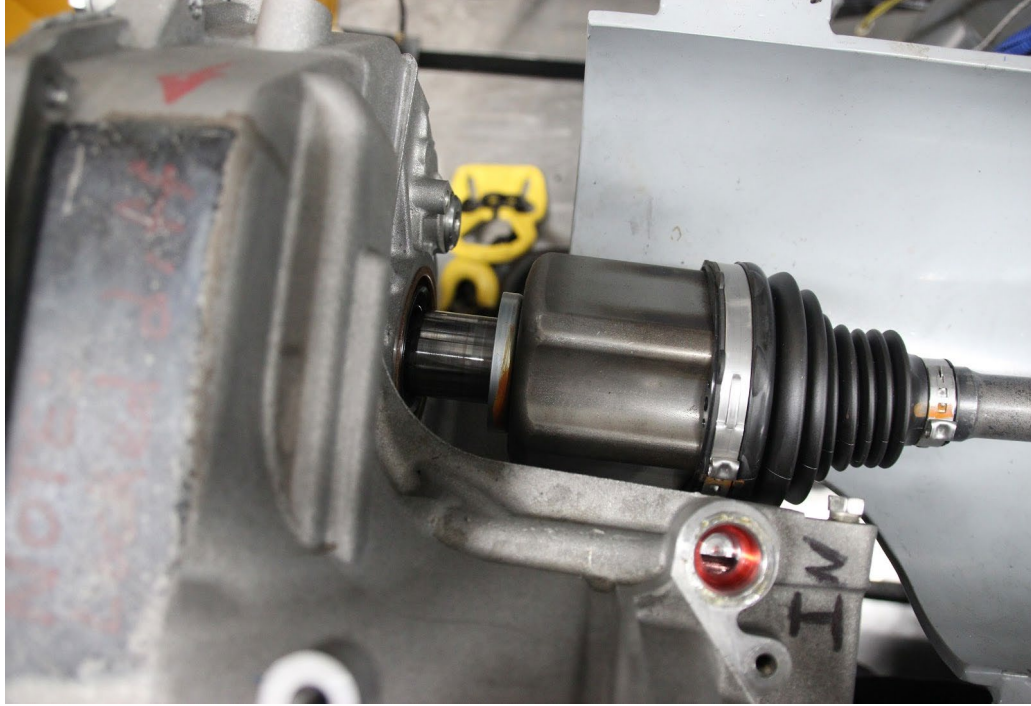
Figure 138: *Remove driveshaft. The transmission side should just slide out with some force*

Swing cover out of the way (Need a big adjustable wrench)
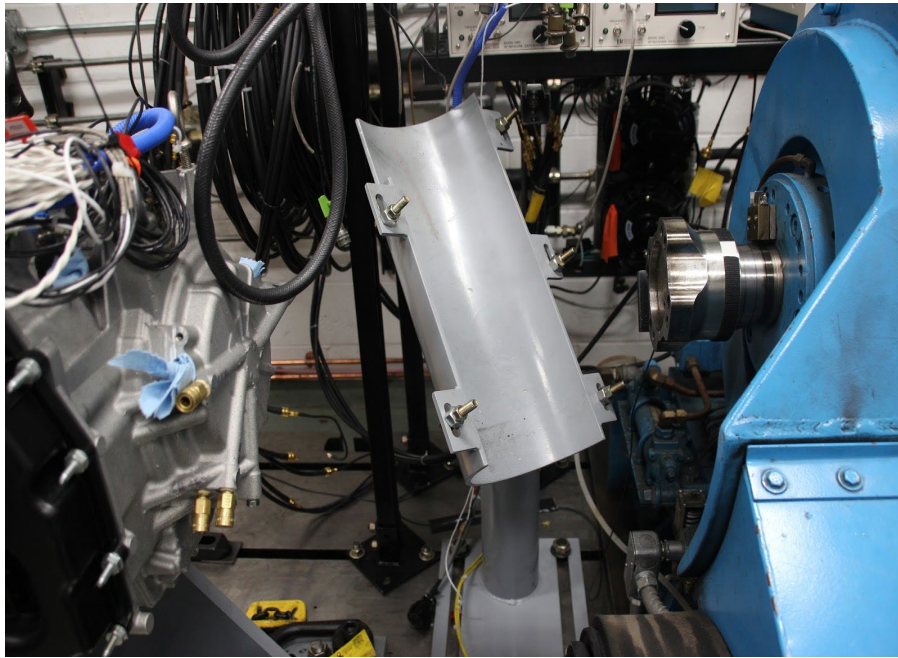
Figure 137: Moving driveshaft guard

Unbolt bearing cover (9/16). Make sure to have something to stop the transmission from spinning (use a long screwdriver on bolts on input side)
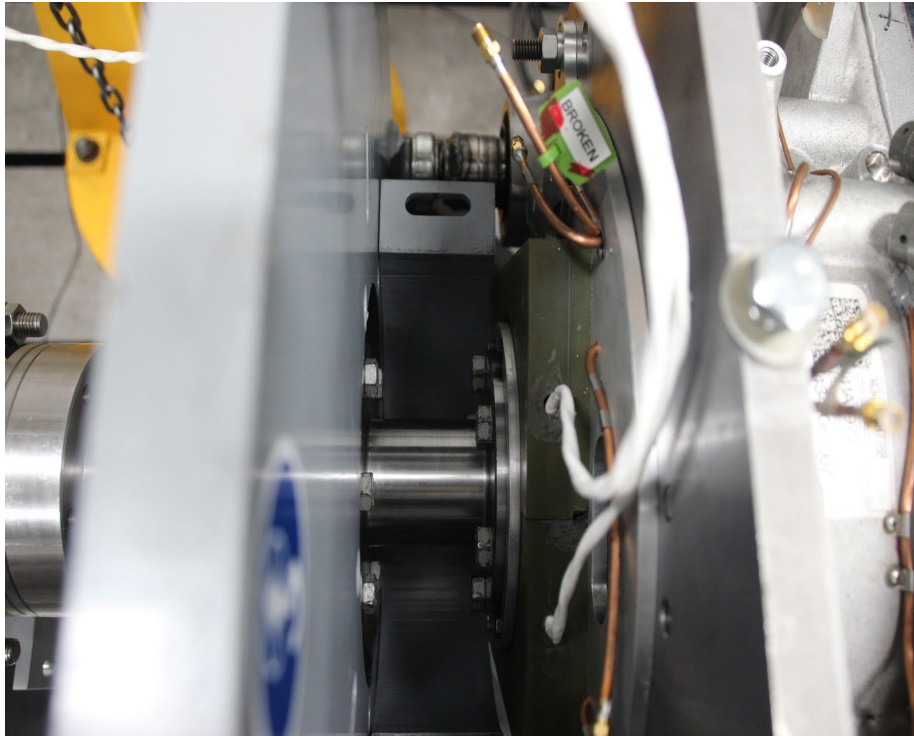
Figure 139: Remove bolts from bearing shaft

Figure 140: Bearing bolt up connection to headstand

Hook up eyelets to hooks on hoist to attach evenly to crane. First remove bottom bolt (¾") - 105 Nm. Put some tension on the chain before removing large knobs on the transmission headstand. Remove slowly!

Figure 141: ¾" bolt removal on bottom of headstand

Figure 142: Empty headstand and bolt up point

Put a retainer in to keep the torque converter from falling off. Remove the chair roller from the other side of the final drive and put it onto new transmission. Install head plate onto new transmission too - pay attention to which bolts go in which side.
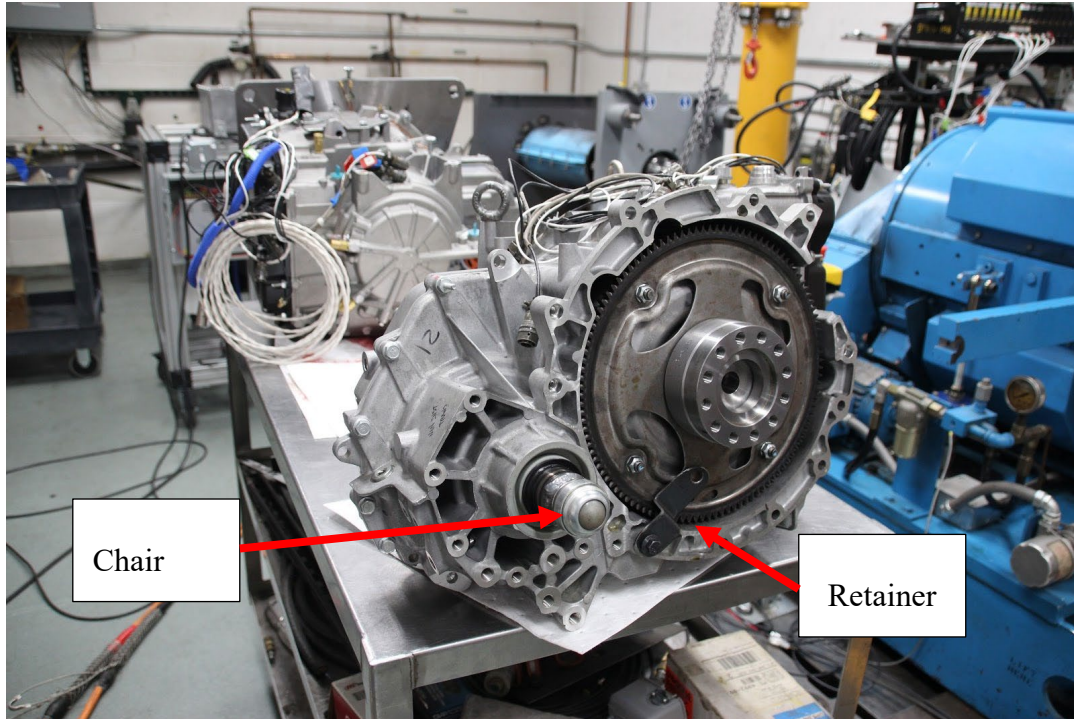
Figure 143: Flex plate on non-instrumented transmission with retainer

If swapping to/from telemetry system, make sure to remove telemetry plate.
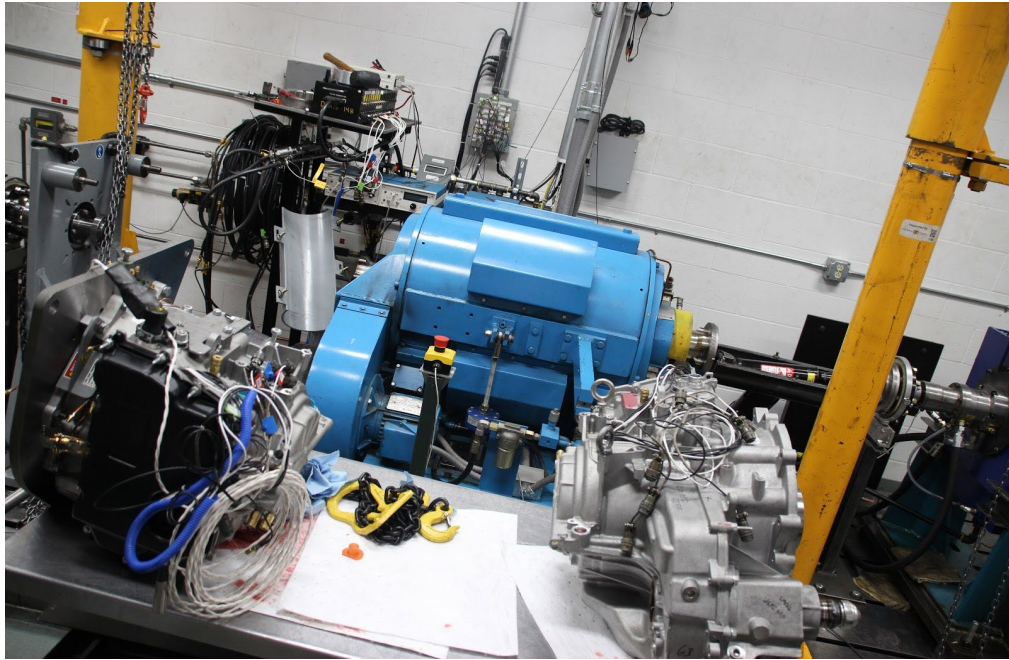
Figure 144: Instrumented transmission (left) and practice transmission (right)

Figure 145: Headstand plate for telemetry induction coil

Figure 146: Telemetry receiver coil

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I.1   Mark Woodland Thesis Reference Permission

Mark Woodland Thesis Reference Permission

2 messages

Abby Hempy <aahempy@mtu.edu>   Thu, May 28, 2020 at 11:40 AM
To: Mark Woodland <Mark.Woodland@paccar.com>, Mark Woodland <mtwoodla@mtu.edu>

Mark,

Do I have your permission to use your thesis as a reference in my thesis? Since this work is a continuation, I thought it would appropriate for you to be my key reference.
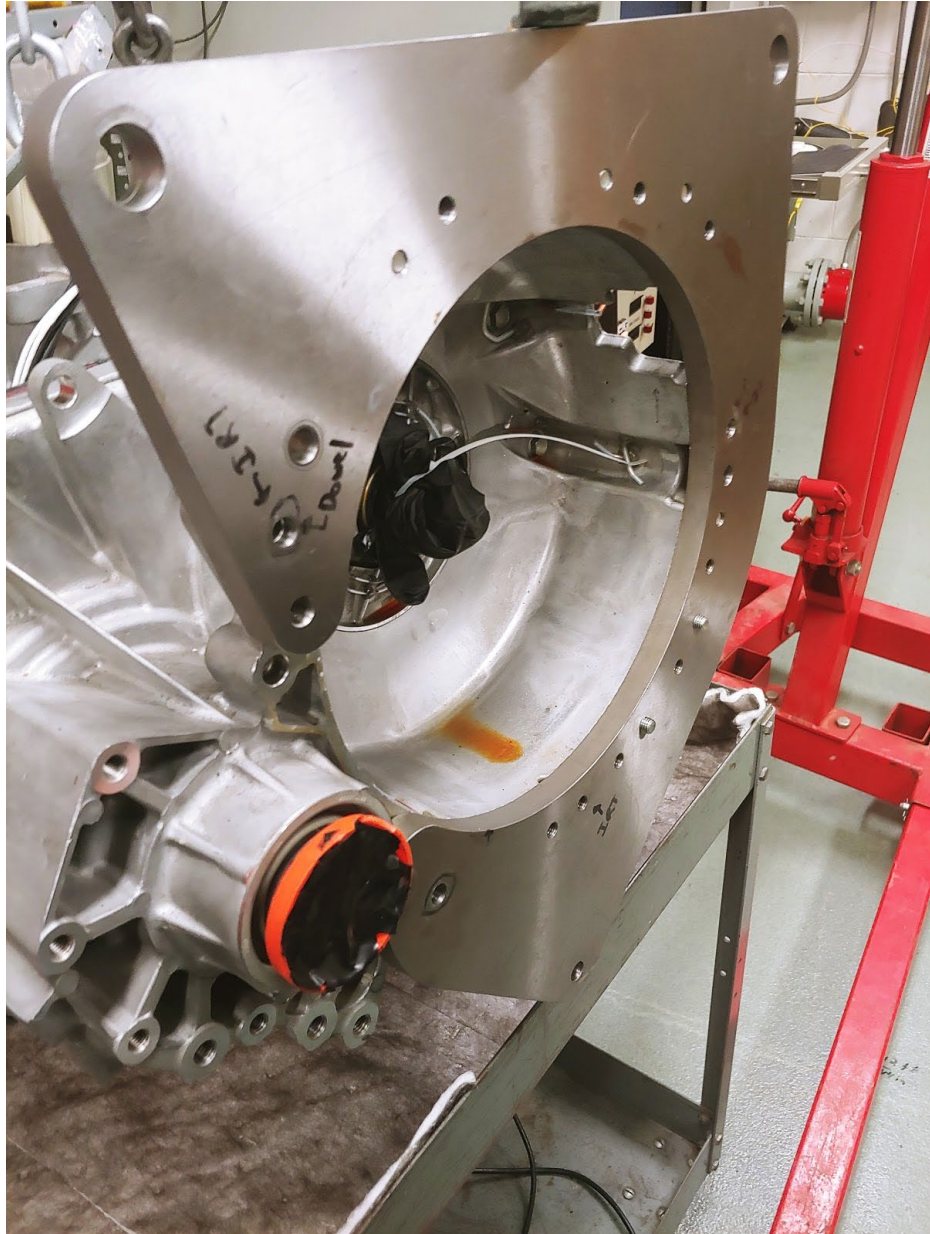
Thank you,
-Abby

--

Abby Hempy
Mechanical Engineering | *M.S. Student*
Michigan Technological University

Mark Woodland <Mark.Woodland@paccar.com>   Fri, May 29, 2020 at 1:29 PM
To: Abby Hempy <aahempy@mtu.edu>

Yes you can use my thesis as a reference.

Mark Woodland

OBD Calibration

PACCAR Technical Center

360-757-4713 | Mark.Woodland@PACCAR.com | 12479 Farm to Market Road, Mount Vernon, WA 98273

[Quoted text hidden]

I.2   Eric Mordorski Thesis Reference Permission

Michigan Tech   Abby Hempy <aahempy@mtu.edu>

Permission to Reference Eric Mordorski Thesis
3 messages

Abby Hempy <aahempy@mtu.edu>   Sat, May 30, 2020 at 9:27 AM
To: Eric Mordorski <ermordor@mtu.edu>

Hello Eric,

    I am a Michigan Tech graduate student working for Dr. Blough and Dr. Robinette on a Ford torque converter project - it is a continuation of Mark Woodland's research and I used some of your CAD files for the electric motor stand to make a new one for a Borg-Warner machine. I wanted to reference some of your work in my thesis, do I have your permission?

Thank you,

Abby

Abby Hempy
Mechanical Engineering | **M.S. Student**
Michigan Technological University

Eric Mordorski <ermordor@mtu.edu>   Sat, May 30, 2020 at 11:58 AM
To: Abby Hempy <aahempy@mtu.edu>

Hi Abby,

You have my permission to use any part of my master's thesis for your own thesis.

Thanks
Eric Mordorski

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I.3 Edward de Jesús Rivera Dissertation Reference Permission

Michigan Tech   Abby Hempy <aahempy@mtu.edu>

Thesis Reference Permission
2 messages

Abby Hempy <aahempy@mtu.edu>   Sun, Nov 22, 2020 at 8:20 PM
To: edejesus@mtu.edu

Edward,

I am writing my thesis about transient testing on the Ford Torque converter cell and I realized some of the figures I would like to use from Mark's thesis are originally from yours. Do I have your permission to use your figures in my descriptions of the telemetry hardware instrumentation?

Thank you,
-Abby

--

Abby Hempy
Mechanical Engineering | *M.S. Student*
Michigan Technological University

Edward De Jesus Rivera <edejesus@mtu.edu>   Mon, Nov 23, 2020 at 10:35 AM
To: Abby Hempy <aahempy@mtu.edu>

Hello Abby,

Of course. No problem. Use any pictures you need.

Thanks,

Edward De Jesús Rivera
01000101 01100100 01110111 01100001 01110010 01100100

[Quoted text hidden]

I.4   IR Telemetrics Calibration Sheet Reference Permission

![Michigan Tech] Abby Hempy <aahempy@mtu.edu>

IRT Permissions for Thesis
4 messages

Abby Hempy <aahempy@mtu.edu>   Fri, Nov 20, 2020 at 9:18 PM
To: Dan Kemppainen <dan@irtelemetrics.com>

Hello Dan,

   May I use the IRT calibration sheets for the impeller, stator, and turbine in my thesis?

Abby

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Abby Hempy
Mechanical Engineering | M.S. Student
Michigan Technological University

Dan Kemppainen <dan@irtelemetrics.com>   Mon, Nov 23, 2020 at 9:51 AM
To: Abby Hempy <aahempy@mtu.edu>, Glen Barna <irtel@irtelemetrics.com>

Abby,

I don't think this will be an issue, however I'll let Glen Barna give the final response.

Glen,

Do you see an issue letting Abby use the calibration sheets in her thesis?

Thanks,
Dan

   On 11/20/2020 9:18 PM, Abby Hempy wrote:
      Hello Dan,

         May I use the IRT calibration sheets for the impeller, stator, and turbine in my thesis?

      Abby

      --

      "Abby Hempy"
      "/Mechanical Engineering| M.S. Student/"
      "/Michigan Technological University/"

Glen Barna <irtel@irtelemetrics.com>   Mon, Nov 23, 2020 at 11:20 AM
To: Dan Kemppainen <dan@irtelemetrics.com>, Abby Hempy <aahempy@mtu.edu>

Abby,

I don't have an issue with that. I think it is common practice to mention who generated it.

https://mail.google.com/mail/u/0?k=ee0ebfb41e&view=pt&search=all&permthid=thread-a%3Ar3026305224009752498&simpl=msg-a%3Ar592371157...   1/2