1992

Validation of MTS testing system/preliminary study of crossarm behavior due to galloping conductors

Jawahar Muniyandi
Iowa State University

Recommended Citation

Muniyandi, Jawahar, "Validation of MTS testing system/preliminary study of crossarm behavior due to galloping conductors" (1992). *Retrospective Theses and Dissertations*. 17262.
https://lib.dr.iastate.edu/rtd/17262

Validation of MTS testing system/preliminary study of crossarm behavior due to galloping conductors

by

Jawahar Muniyandi

A Thesis Submitted to the
Graduate Faculty in Partial Fulfillment of the
Requirements for the Degree of
MASTER OF SCIENCE

Department: Civil and Construction Engineering
Major: Civil Engineering (Structural Engineering)

Signatures redacted for privacy.

Iowa State University
Ames, Iowa
1992

TABLE OF CONTENTS

NOMENCLATURE

F_y	Yield strength of steel
F_u	Specified minimum tensile strength of steel
I_{xx}	Moment of inertia about the x-x axis
S_{xx}	Sectional modulus about the x-x axis
A	Area of the cross section
r_{xx}	radius of gyration about the x-x axis
P_v	vertical component of the service load
P_t	transverse component of the service load
P_l	longitudinal component of the service load
L_a	Length of the crossarm
L_i	Length of the insulator
f_a	Computed axial stress
F_a	Pure axial compressive stress permitted in member
f_{bx}	Computed bending stress about the x-x axis
F_{bx}	Pure bending stress permitted in a member
f_t	Computed tensile stress
f_v	Computed shear stress
F_t	Allowable axial tensile stress
V	Static load due to the weight of conductor and ice from half span
v	vertical dynamic load due to galloping from half span
v(t)	vertical dynamic load due to galloping from half span
L	Span of the conductor

s_o	Static line sag
n	number of loops during galloping per span
a_o	galloping amplitude
k_e	equivalent stiffness of the system in the longitudinal direction
k_i	stiffness of insulator in the longitudinal direction
k_c	stiffness of conductor (= EA/L)
w	total conductor weight per unit length ($= w_c + w_i$)
w_c	weight of conductor per unit length
w_i	weight of ice on conductor per unit length
H	Horizontal component of static tension in the conductor
EA	longitudinal rigidity of the conductor
V_w	wind velocity
k	stiffness of a system pertaining to a degree of freedom
m	mass in a system
ω	natural frequency of a system
Ω	frequency of forcing function
W	total weight of the conductor (=wL)
W_i	Weight of the insulator

1. INTRODUCTION

1.1 General Background

1.1.1 Galloping conductors

"Galloping conductors", also called "dancing conductors", is an unusual aerodynamic phenomenon characterized by vertical oscillations of very large amplitude and very low frequency. This usually occurs when there is an asymmetric ice deposit of 0.1 to 0.5 inch of equivalent radial thickness combined with an average wind speed of between 3.0 and 35.0 mph at a temperature of approximately 32 degrees Fahrenheit. The duration of galloping varies from a few hours to 24 hours. The observed amplitude reported in the literature vary from a few feet to 20 feet depending on the span of the conductors [1]; and the frequency of the oscillations is normally 1 Hz or less.

The motion of the galloping conductor is very complex. Field observations show that the motion is predominantly in the plane of the sag (vertical direction). This motion is sometimes idealized as a narrow elliptical path. The profile of the conductor normally assumes a single or double loop in the span. The amplitude of galloping varies with the wind speed and line frequency. This motion causes stretching of the conductor and proportionally a time-varying tensional force in the conductor. The increase of tensional force in the conductor and the corresponding steeper slope of the conductor at the conductor attachment point during galloping will result in dynamic vertical loads at the support. Figure 1.1 shows a laminated wood pole with the various structural and hardware components. Figure 1.2 illustrates the galloping of the conductor and the various load components acting on the structure.

1.1.2 Results of galloping and damage to structures

The results of galloping ranges from temporary line outages due to phase-to-phase and phase-to-shield wire flashovers to damage to the conductor strands, insulators, connections, hardware and support structures [2]. The failure of the conductor or the connections to the crossarm can trigger the failure of a series of towers because of an unbalanced longitudinal load on the tower. Such a failure is called a cascading or domino effect.

If the structure has a bending frequency close to the galloping frequency of the conductor, the resonance of the conductor and the tower motion will produce large amplification of the loads. Observations by utilities in Japan, New Zealand, the United States, Canada and Europe show that the most common damage caused by galloping are failure of the crossarm due to the large dynamic vertical force. In single post towers the failure of the welded or the bolted

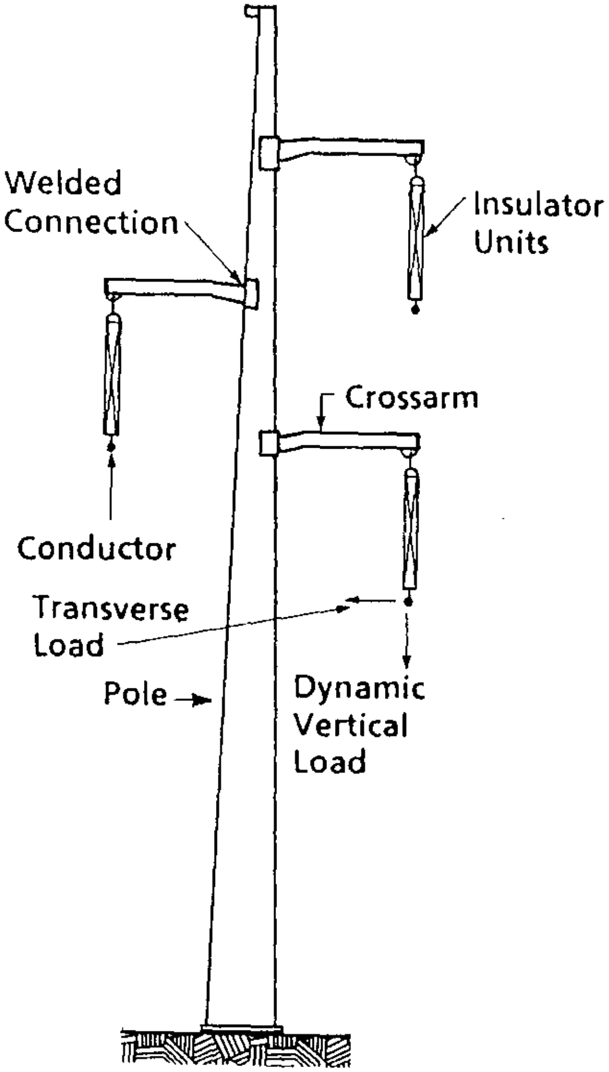


Figure 1.1. Laminated wood pole

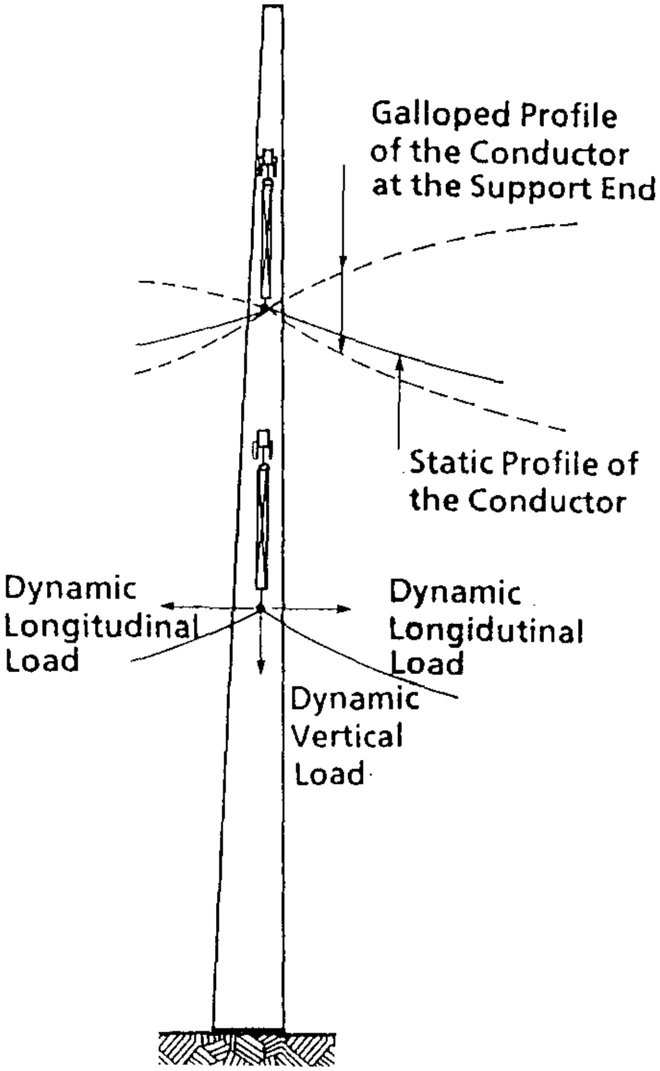


Figure 1.2. Galloped profiles of conductor and the associated dynamic forces

connection of the crossarm with the pole has been observed. In lattice type structures, typically buckling of the crossarm members has been observed. Several galloping occurrences and subsequent failure of the welded connections of the crossarm in single pole structures have been reported by Iowa Electric Light & Power Company [3]. The failure of the bolted connections have been reported by other electrical utilities.

One objective of this research is to study the behavior of a crossarm in a single pole structure when subjected to forces from the galloping conductors.

1.1.3 Present design practice

While the current National Electricity Safety Code (NESC) [4] provides for loading due to combined ice and wind, heavy ice, high wind and stringing. It addresses the dynamic loads through the provision of an overload capacity factor only in a general sense. It does not specify a factor for galloping load nor does it explain how such a factor can be determined. From the failures observed over the past, these overload factors do not seem to provide the required safety to safeguard the structure during galloping.

This situation necessitated research to quantify the loads due to galloping conductors, taking into account the meteorological, aerodynamic, geometric and material factors of a given system.

1.1.4 Background

An analytical study conducted at Iowa State University (ISU) by Dr. Mardith Thomas (Civil and Construction Engineering) and Dr. William James (Aerospace Engineering) addressed the problems due to galloping conductors and considered the various factors which affect the behavior of the complete system. The final task of their project quantified the dynamic loads due to galloping in a single pole tower system which was subsequently validated with wind tunnel testing by using a model of a conductor [5]. The vertical dynamic loads calculated for a given system using this force-time algorithm have been proved to agree well with the dynamic loads recorded during galloping in the field.

1.1.5 MTS dynamic and pseudodynamic testing system

The Civil and Construction Engineering department of Iowa State University recently acquired a dynamic and pseudodynamic testing system of MTS Systems Corporation. This system consists of an electro-hydraulically operated equipment with an on-line computer control which is capable of performing real-time dynamic and pseudodynamic testing of structural elements. It was proposed that this system might be suitable to simulate the dynamic loads due to galloping which would enable a study of the behavior of the crossarm subject to these dynamic loads.

1.2 Objectives

1.2.1 Major objective 1

As the system was only recently acquired, the first major objective was to validate the testing capability of this equipment, document trial tests and to determine its suitability for the experimental study presented. In addition, the production of an example manual to provide guidance to the future users of the testing facility was needed. The specific tasks defined in achieving these objectives consisted of the following.

Task 1: Learn how to use the testing equipment.

Task 2: Conduct a series of dynamic and pseudodynamic trial tests.

Task 3: Study the limitations and capability of the testing system and determine its suitability for the experimental study.

Task 4: Produce the Example Manual.

These tasks are discussed in detail in Chapter 2.

1.2.2 Major objective 2

The second major objective was to perform an experimental study of the structural behavior of a crossarm subjected to the vertical dynamic forces from galloping conductor using a single specimen of the crossarm. It was not within the scope of this project to perform a large number of tests; only to demonstrate the capability of performing such tests and make recommendations on the accuracy of the experimental method to characterize the interaction of the wind-induced dynamic forces and the transmission line single pole structure. The specific tasks defined in accomplishing this major objective consisted of the following.

Task 1: Definition of a typical single pole tower system.

Task 2: Design of a crossarm as per the National Electricity Safety Code guidelines.

Task 3: Fabrication of the crossarm and setting up of the experimental testing system.

Task 4: Computation of the vertical galloping load for an assumed environmental condition.

Task 5: Execution of tests.

Task 6: Discussion of the test results and conclusions.

Tasks 1, 2 and 3 are discussed in detail in Chapter 3; task 4 in Chapter 4; tasks 5 and 6 are discussed in Chapter 5.

1.3 Research Program

1.3.1 Major objective #1

The first part of the research program consisted of performing the tasks associated with the first major objective which has been listed in Section 1.2.1. Initially, it consisted of getting acquainted with the system software and hardware. As the software itself was a recently developed one, the initial task consisted of attempting to identify the defects in the software and requesting MTS to correct the software. After adequate practice in using the software to define a test, trial tests were conducted. This included a training program given by MTS. The trial tests consisted of running a series of dynamic and pseudodynamic tests on simply supported beams. Both harmonic and non-harmonic loads were used to test the capability of the testing system. These points are discussed in detail in Chapter 2. The last phase in achieving the first major objective consisted of selecting example tests, documenting them and preparing the user's manual. This manual is available in Appendix A of this thesis.

1.3.2 Major objective #2

The second part of the research consisted of performing the tasks associated with the second major objective. At first, a single pole transmission tower structure system was defined and the crossarm was designed based on the guidelines specified in National Electricity Safety Code of 1981. The crossarm was then fabricated and the experiment was set up. This phase is discussed in detail in Chapter 3. Environmental conditions which have produced galloping in the past were assumed for this tower system. The magnitude of the vertical galloping force was calculated for the defined material, geometric and environmental conditions using the algorithm mentioned in Section 1.1.4. Dynamic analysis was made to study the effect of the dynamic load on the crossarm. The computation of the load is discussed in detail in Chapter 4. Finally, the tests were conducted and results noted. These are discussed in Chapter 5. The summary and the conclusions are also available in Chapter 5.

1.4 Literature Review

1.4.1 Crossarm behavior to galloping conductors

A review of the existing literature on this topic was made and no such work was found. However, the following observations were made.

Two articles revealed the existence of the extensive damage to the supporting structure due to galloping conductors [1,2]. These had reported that the failure of the welded and bolted connections in the crossarm were very common during galloping. References 1 and 5 had agreed on the inadequacy of the overload factors currently specified by NESC. There was a consistent agreement among these reports that the vertical dynamic force was the most significant load due to the predominant vertical motion of the conductor during galloping. Li Li [5] had predicted the potential fatigue loading of the support structure during galloping.

It was learned that Iowa Electric Light and Power Company has in the past experienced failures of the weld (of the crossarms) due to galloping. It was also learned [6] that in the case of crossarms using channels as arm base, the web of the channels had yielded by bending. In the recent (Spring 1990) ice storms in the central Iowa region, a transmission line covering a distance of 18.0 miles failed by a domino effect. The cause of the failure is currently being investigated at Iowa State University [7]. It is suspected that galloping could be one of the possible causes of failure.

1.4.2 Pseudodynamic testing methods

The report by Mahin and Shing [8] with regard to pseudodynamic testing was reviewed with the objective of understanding the procedure and its advantages and disadvantages for the purpose of validation of the MTS Dynamic and Pseudodynamic Testing System and the possible use of this experimental technique in the study of the behavior of crossarms.

From this report by Mahin by Shing it was understood that this technique was originally developed to evaluate the seismic performance of structural elements. The significant advantages of this testing methods are: it allows the testing of large scale structural systems which cannot be tested realistically by conventional methods; and it allows the test to be conducted at slower rates thereby allowing a better study of the seismic behavior. Verification tests in the elastic and inelastic range have been conducted on a SDOF steel cantilever system with a concentrated load at the top for El Centro 0.1g, El Centro 0.8g and Miyagi Oki 0.45g ground motions. The results of these tests have correlated well with the analytical simulations. Successful tests have been conducted on prototype multi-storied steel and reinforced concrete structures in the United States and Japan. These results have correlated well with equivalent analytical results.

2. VALIDATION OF THE TESTING SYSTEM

2.1 Introduction

2.1.1 Testing system

The testing system consists of an electro-hydraulically operated dynamic and pseudodynamic test system with an on-line computer control designed by MTS Systems Corporation. MTS seismic and pseudodynamic test systems are capable of investigating the characteristics of specimens undergoing simulated dynamic loads. This simulation is controlled through Seismic Test Execution (STEX) software.

2.1.2 Test system configuration

Figure 2.1 shows the hardware configuration of the test system. As illustrated in the figure, the hardware consists of an on-line control computer, digital console, analog console, hydraulic distribution system and hydraulic actuators. Figure 2.2 shows a test setup with the actuator and the test specimen mounted in a testing frame. Figure 2.3 shows the consoles and the on-line control computers available in the Structures laboratory at Iowa State University. The on-line control computer is a Microvax II computer system with a LVP 16 plotter attached. The test to be conducted is defined in STEX, which sends the electronic signals to the analog console through the digital console. The analog console in turn develops the servovalve control signals to control the

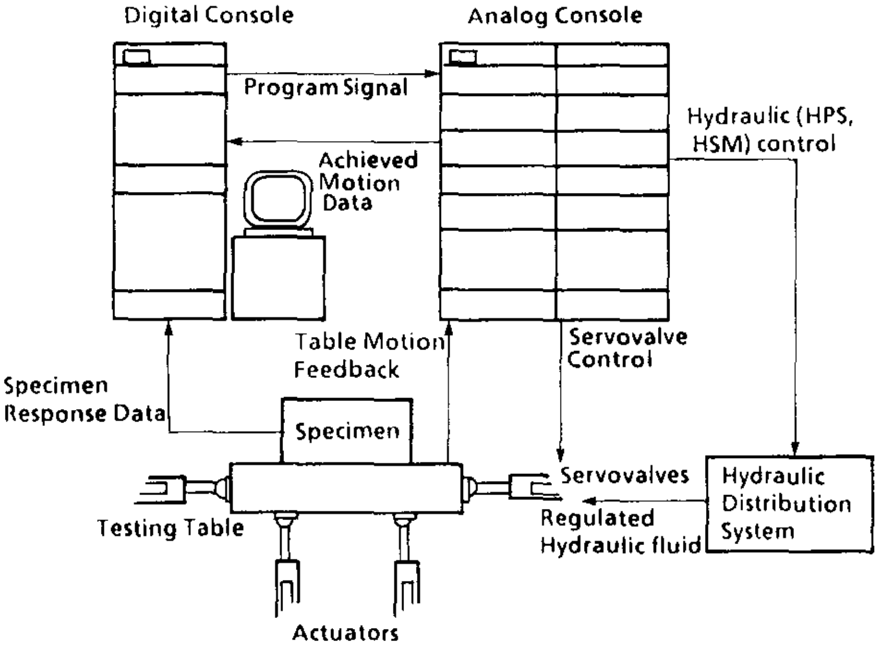


Figure 2.1. Test system configuration

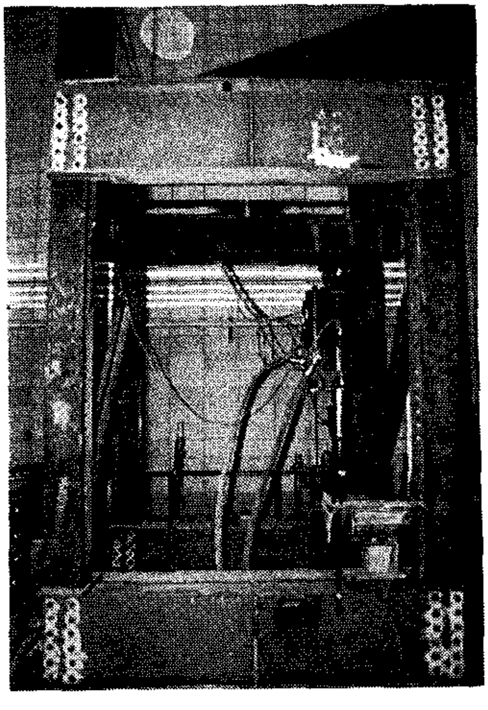


Figure 2.2.

Setup for trial tests

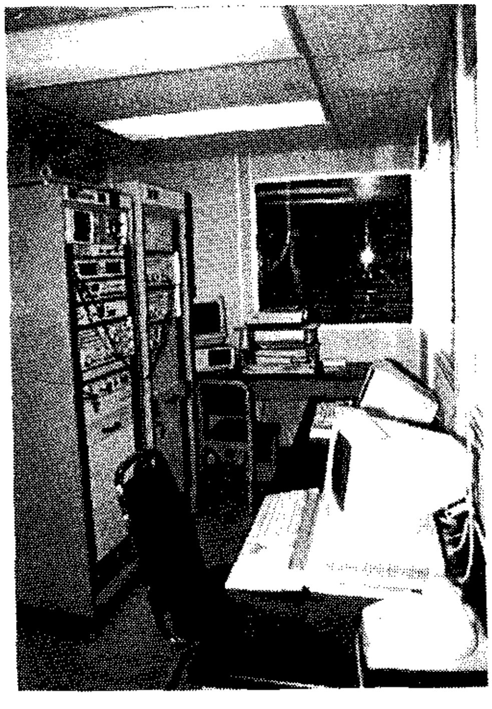


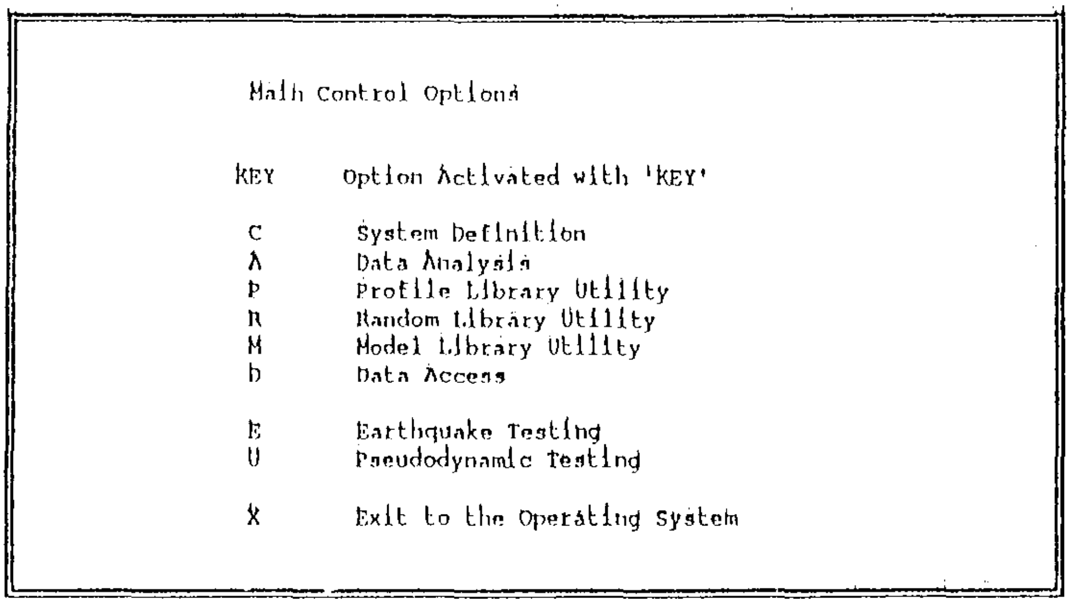
Figure 2.3.

Consoles and on-line control monitors

servovalve located in the actuators. In addition to this, the analog console also controls the hydraulic distribution system to regulate the flow of hydraulic fluid to achieve the desired motion or load of the actuator. The analog console also receives the feedback signals from the load and displacement transducers contained in the actuator which are later acquired by the test processor of the digital console. STEX receives the feedback signal from the test processor contained in the digital console.

2.1.3 STEX software capabilities

STEX is a menu driven software which provides control of multi-channel loads and motions. The software at ISU currently accommodates two channels only. It allows the definition and execution of seismic (dynamic) and pseudodynamic tests. These are discussed in detail in Sections 2.2 and 2.3. It also allows the storage and analysis of test definitions and test results. Its analysis library allows the import, creation, modification and analysis of different types of forcing functions. It allows the choice of either load or displacement control of the test. The entire software is made up of eight libraries with a specific function attached to each library. These eight libraries together aid in performing the above-mentioned tasks. Figure 2.4 shows the main control menu which provides access to the



```
   Main Control Options

  KEY      Option Activated with 'KEY'

   C         System Definition
   A         Data Analysis
   P         Profile Library Utility
   R         Random Library Utility
   M         Model Library Utility
   D         Data Access

   E         Earthquake Testing
   U         Pseudodynamic Testing

   X         Exit to the Operating System
```

Figure 2.4. Main control options menu

different libraries.

2.1.4 Objectives for the validation of MTS system

The objectives set for the process of validation of the testing system are listed below.

1. To check the correctness of the software.
2. To recognize the capability and limitations of the software and the hardware.
3. To demonstrate the capability of executing dynamic and pseudodynamic tests by conducting simple trial tests.
4. To study the suitability of the testing system for the experimental study of the crossarm.
5. To document the procedure of using the system for the purpose of preparing a user's manual with example tests.

The validation process involved a sensitivity study of the capability of the testing system for a few parameters of the forcing functions.

2.1.5 Test setup for the trial tests

The testing frame used for conducting the dynamic and pseudodynamic trial tests is shown in Figure 2.2. The trial tests were run on simply supported beams. The setup in the frame was made such that the loads exerted by the actuator are self-contained in the frame itself. The actuator was attached to a support beam near its end to keep any error due to the bending of this beam to the minimum. The same frame was later used for the experimental study on the crossarm.

2.2 Earthquake or Dynamic Test

2.2.1 Introduction

This is one of the options in the main control options menu shown in Figure 2.4. This option can be used to (i) define a new test and execute it; (ii) select an already defined test and execute it; or (iii) modify an existing test and execute it. This option allows the execution of an uncompensated test or a compensated test.

2.2.2 Compensated and uncompensated tests

When running a dynamic test, the achieved signal (measured specimen response) may not always be the same as the desired forcing signal. This depends on: the forcing function used, the dynamics of the test setup used, the capability of the servovalve, the calibration of controller present in the analog console and calibration of certain other electronic devices in the analog and digital consoles. The dynamics of the test setup may have an effect leading to a decreased desired amplitude of the control signal. These can be in the form of frictional forces in actuator-specimen connection, movement of the specimen support, or movement of the actuator support. Hence depending on the desired signal, the drive signal may need to be adjusted. This procedure generally calls for an over-programming of the drive signal to achieve the desired specimen motion. However, this procedure may not fully achieve the desired motion as the capability to compensate ultimately depends on the limitations of the hardware. A test which has its drive signal adjusted for the system dynamics is called a compensated test and the one which does not have its drive signal adjusted is called an uncompensated test.

2.2.3 Uncompensated test

2.2.3.1 Introduction In this test the drive signal is not adjusted for the system dynamics of the test specimen and test setup. There are two different types of uncompensated tests:

(i) Uncompensated Profile test and
(ii) Uncompensated Random test.

The uncompensated profile test is run as a step to understand the capability of the system to apply the specified forcing function. The random test is run when compensation of the drive signal is anticipated. The random test collects the data from the system necessary for the compensation procedure.

2.2.3.2 Test procedure There are five basic steps involved in the definition and execution of an uncompensated test. These steps are shown in the flow chart in Figure 2.5.

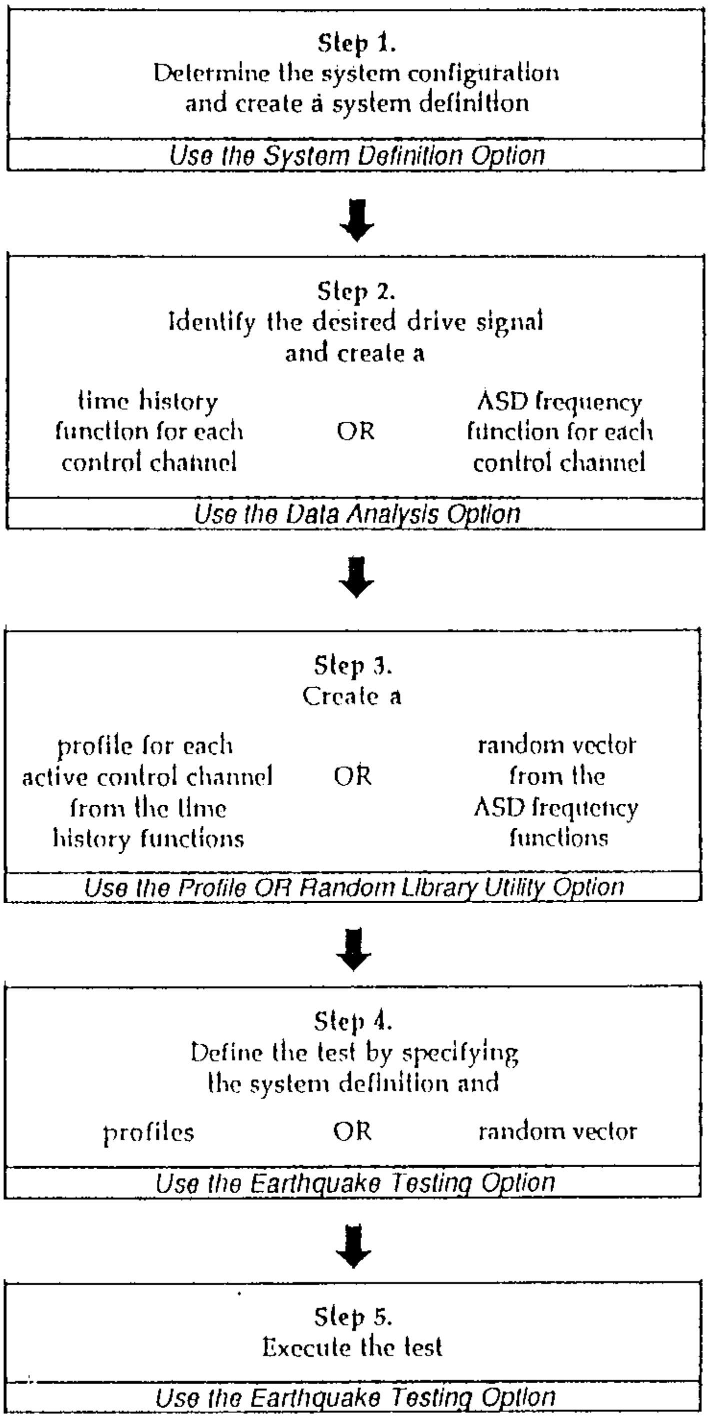


Figure 2.5. Uncompensated earthquake test execution flowchart

After the execution, the data analysis option is used to analyze the specimen response data from the uncompensated test. Each of the steps shown in the figure is described in detail with an example test in Parts I and II of the User Manual in Appendix A.

2.2.3.3 Trial tests A series of trial tests were run on simply supported steel beams (W 10 * 22 and W 12 * 14) with forcing functions consisting of both time history functions (rectangular, ramp) and waveforms such as sinesweeps.

The simply supported beams were analyzed as undamped single degree of freedom systems considering a negligible weight for the beam. The forcing functions considered are listed below.

1. Rectangular pulse
2. Ramp function
3. Sinesweeps with varying amplitude and frequency.

The definition and execution of the tests using the testing system with comparison to the analytical results are discussed in detail in Appendix A.

2.2.3.3.1 Rectangular pulse Rectangular pulses with a constant peak load with varying duration were used. Relatively fast pulses with durations of 0.06, 0.2 and 0.3 seconds were chosen to illustrate the limitations of the system. Figure 2.6 shows the applied drive signals considered in the tests on one of the beams. Figure 2.7 shows a typical

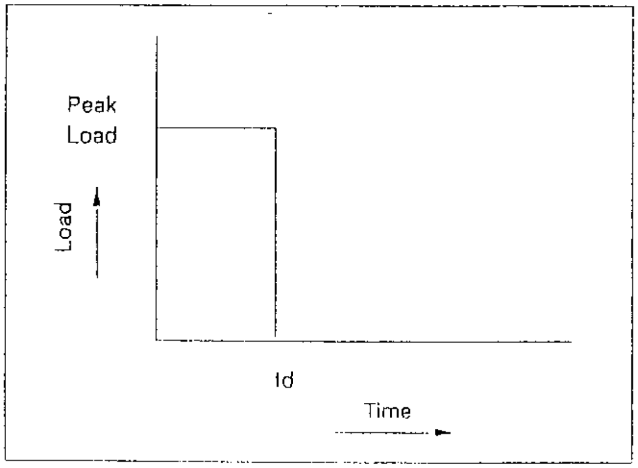


Figure 2.6. Rectangular pulse

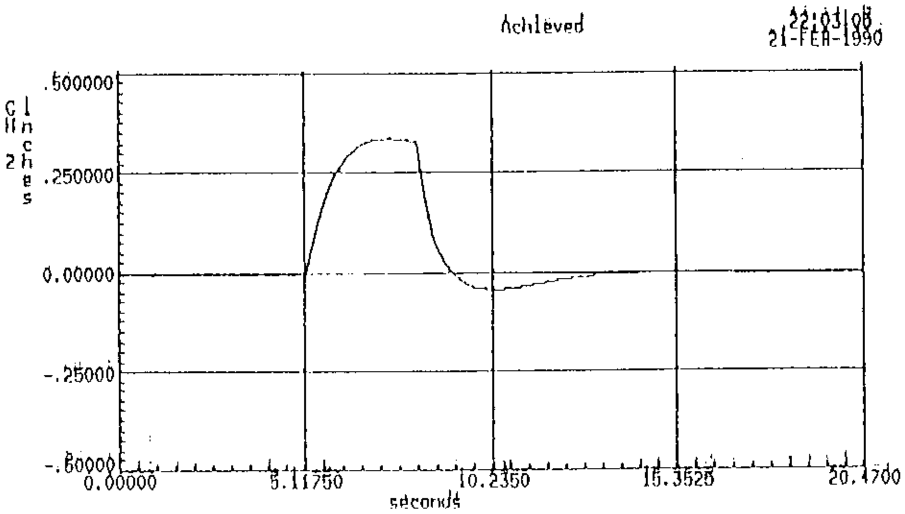


Figure 2.7. Typical response to rectangular pulse

Table 2.1. Results of trial tests

Test number	Peak load	td	td / t	Theoretical		Actual	
				X	tm	X	tm
	kips	secs.	-	Inches	secs.	Inches	secs.
1	1.5	0.06	1.26	0.562	0.024	0.025	0.128
2	1.5	0.20	4.19	0.562	0.024	0.080	0.307
3	1.5	0.30	62.9	0.562	0.024	0.338	2.431

achieved motion. Based on the results summarized in Table 2.1, the following inferences and conclusions can be developed.

The peak response increases with the duration of the rectangular pulse. Also, the time of peak response is more than the theoretical value. But these results correspond well with the achieved load. This indicates that the hardware, in general, does not respond swiftly to apply the defined load on the specimen which is a performance limitation of the hardware. These example tests used a servovalve with a peak capacity to pump 20 gallons of oil per minute. The performance can be increased by using a higher capacity servovalve or an additional servovalve of the same capacity. In either of these cases the system can be made to respond more swiftly. Trial tests with higher capacity servovalves need to be conducted to arrive at the particular capacity of the servovalve that would give good results. A compensated test cannot be performed on a non-frequency function such as rectangular, triangular and ramp signals. It can also be noted that the free response is quickly damped. The damping in these cases consist of a combination of viscous and coulomb damping. The viscous damping was present by virtue of the molecular friction in the material of the beam. The coulomb damping was due to the friction offered by the piston of the actuator and the connection between the actuator and the test specimen.

2.2.3.3.2 Ramp pulse Ramp pulses with a constant peak load with varying ramping periods as shown in Figure 2.8 were used. The results have been summarized in Table 2.2. A typical response is shown in Figure 2.9. The results indicate that the peak dynamic response matches the theoretical results. But the period of response was several times higher than the theoretical. This again is a performance limitation of the system as observed in the responses to rectangular pulses. The response also indicates that the portion of the response immediately following the peak is quickly damped out by a combination of viscous and coulomb damping. The free response after the load becomes zero is also quickly damped out.

2.2.3.3.3 Sinewave Tests with sinesweeps involving variation in frequency as well as in amplitude were conducted. One of the examples is shown in Figure 2.10. The frequency varies exponentially from 0.1 to 10 Hz and the amplitude varies linearly from 4 kips of single amplitude at the start to 0.8 kips in the middle. The achieved signal of the load is shown in Figure 2.11 from which it is understood that the defined frequency has been maintained during the execution, while the amplitude decreases as the frequency increases. This suggests that compensation of the drive signal (forcing signal) would be necessary to improve the

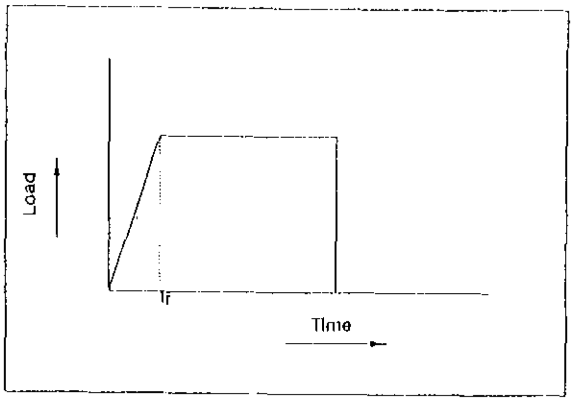


Figure 2.8. Ramp pulse

Table 2.2. Results of trial tests

Test number	Peak load	t_r	t_r / T	Theoretical		Actual	
				X	t_m	X	t_m
	kips	secs.	-	inches	secs.	inches	secs.
1	1.5	0.070	1.50	0.228	0.057	0.225	2.45
2	1.5	0.117	2.50	0.206	0.055	0.219	2.35
3	1.5	0.140	3.00	0.187	0.057	0.221	2.18

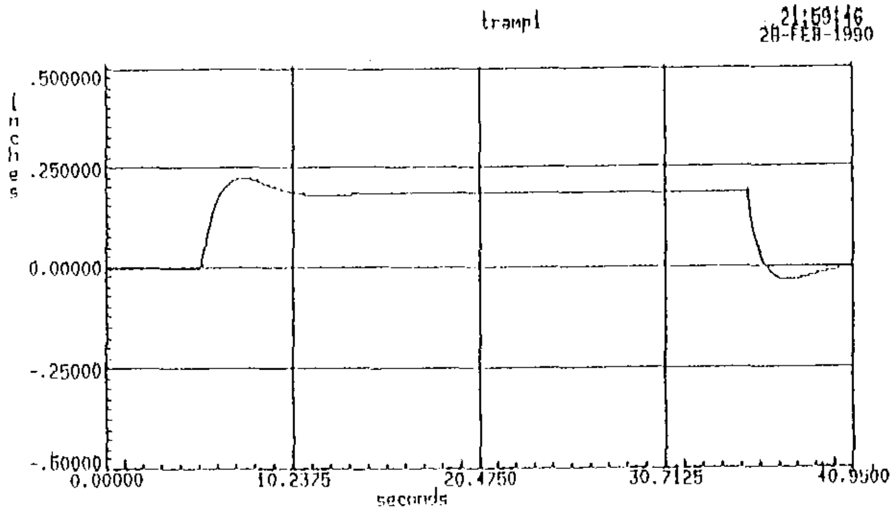


Figure 2.9. Typical response to ramp pulse

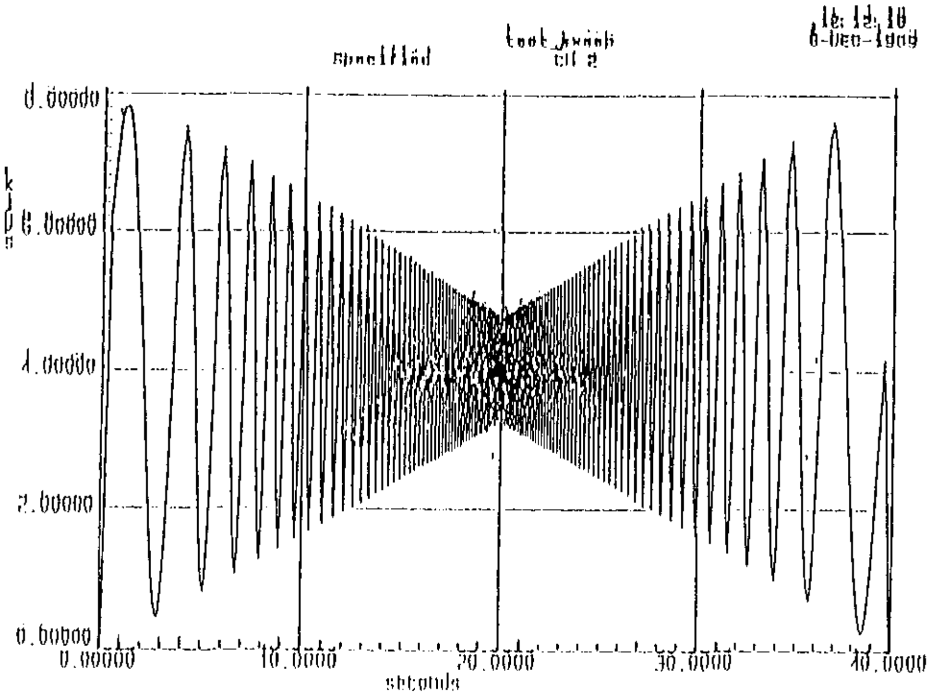


Figure 2.10. Specified forcing function

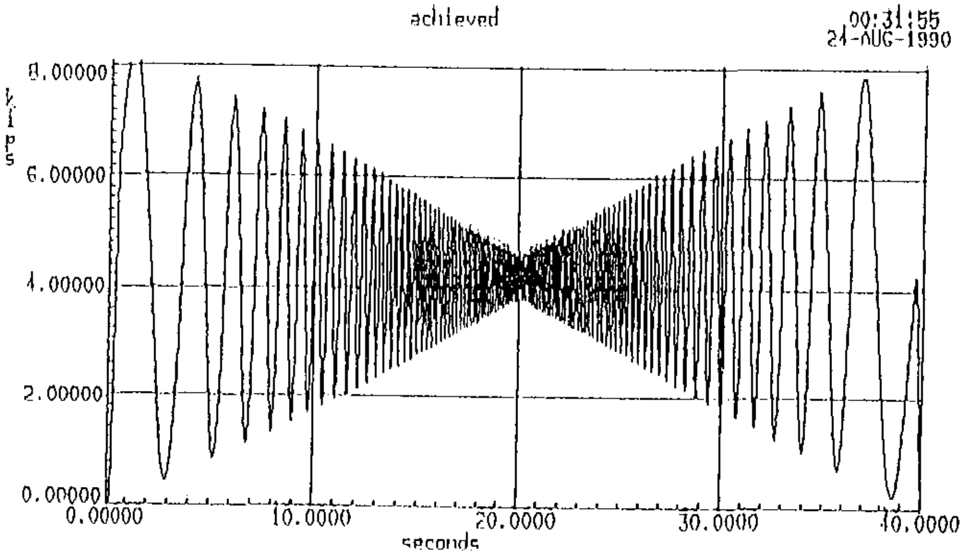


Figure 2.11. Achieved load in the test

signal.

The achieved displacement signal is shown in Figure 2.12. It can be observed that the signal starts from 0.705 inches instead of zero. This indicates that the displacement channel was not zeroed completely at the start of the test, but had a voltage corresponding to 0.705 inches. It can be observed that the displacement signal has followed the pattern of the forcing function closely. The maximum theoretical response (at the first peak) of the forcing signal agrees well with the achieved displacement. The achieved displacement at the first peak is equal to 0.0275 inches and the calculated displacement at the first peak is equal to 0.026 inches.

Part I of Appendix A illustrates with an example test the procedure adopted in STEX for setting up a test and executing the same.

2.2.4 Compensated tests

The procedure adopted in STEX for conducting a compensated test is outlined by the flow chart shown in Figure 2.13. The procedure calls for running an uncompensated random vibration test to collect information from the specimen about its response at different amplitude. This information is later used in the Model library of STEX to create an Expanded Inverse function. At the test phase, this Expanded Inverse function is used to produce a suitable drive function which is

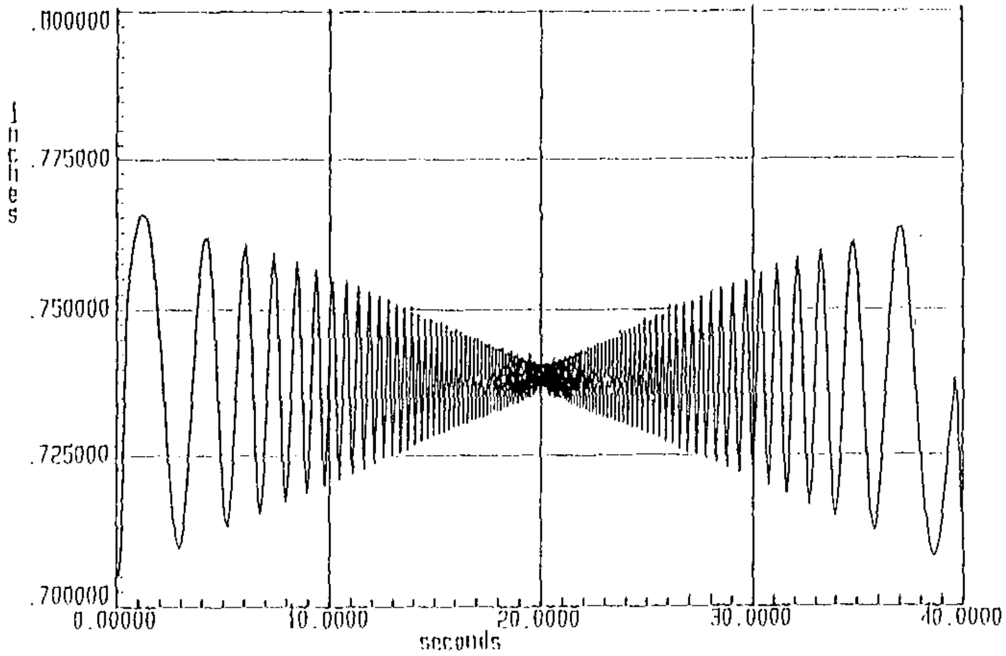


Figure 2.12. Displacement response

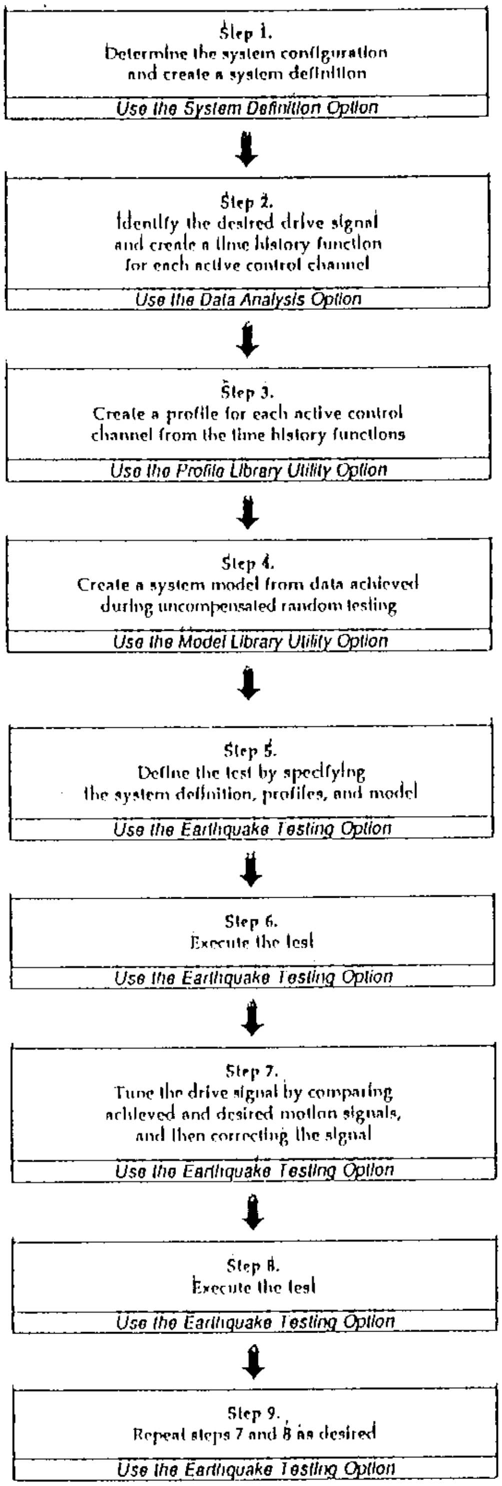


Figure 2.13. Compensated test execution flowchart

compensated to obtain the desired function when executed. The forcing function of an example of a compensated test is shown in Figure 2.14a. The frequency of this function varies exponentially from 0.1 Hz to 5 Hz and the single amplitude varies from 1.0 inch at 0.1 Hz to 0.4 inch at 5 Hz. During this test the drive signal was compensated twice. An overlay plot of the achieved signals corresponding to the desired, uncompensated test and first compensated test is shown in Figure 2.14b. The initial 5 seconds of this plot corresponds to a test start up delay which is defined earlier in the software during the test setup. It can be noted from this plot that the system is able to maintain the required amplitude of 0.7 inches at 0.71 Hz corresponding to the time of 21.5 seconds. This can be better observed in the enlarged plot in Figure 2.14c. From Figure 2.14d it can be observed that the first compensated test (compen_ach) has performed better in the region beyond 21.5 seconds. From Figure 2.14e it can be observed that the second compensated (ach_it_1) has only performed as much as the first compensated test. This is because of the performance limitation of the hardware.

The following conclusions can be drawn from the results:

1. The system provides priority to the frequency than to the amplitude.
2. The system performs best at low frequencies due to the limitations of the hardware.

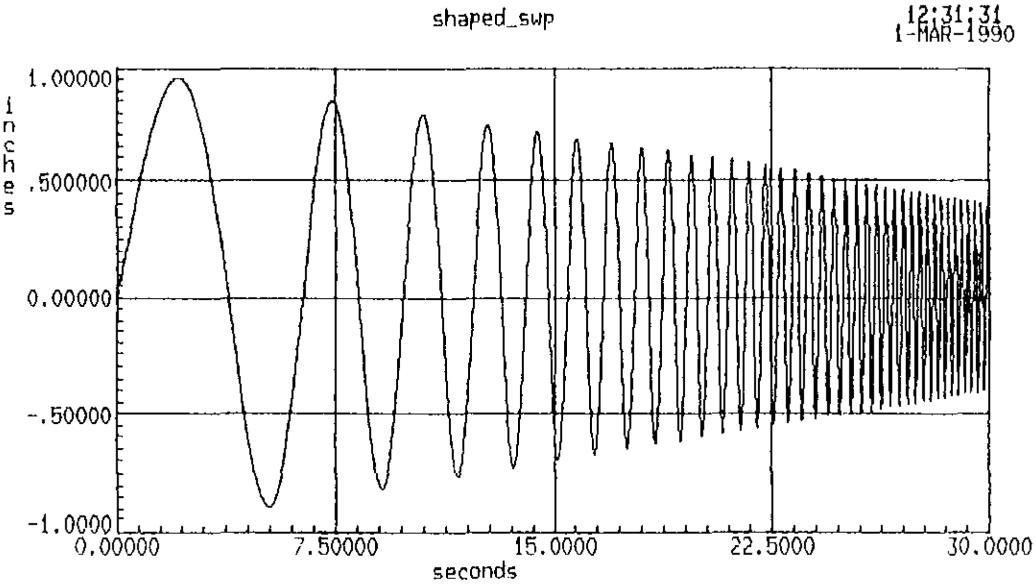


Figure 2.14a. Specified forcing function

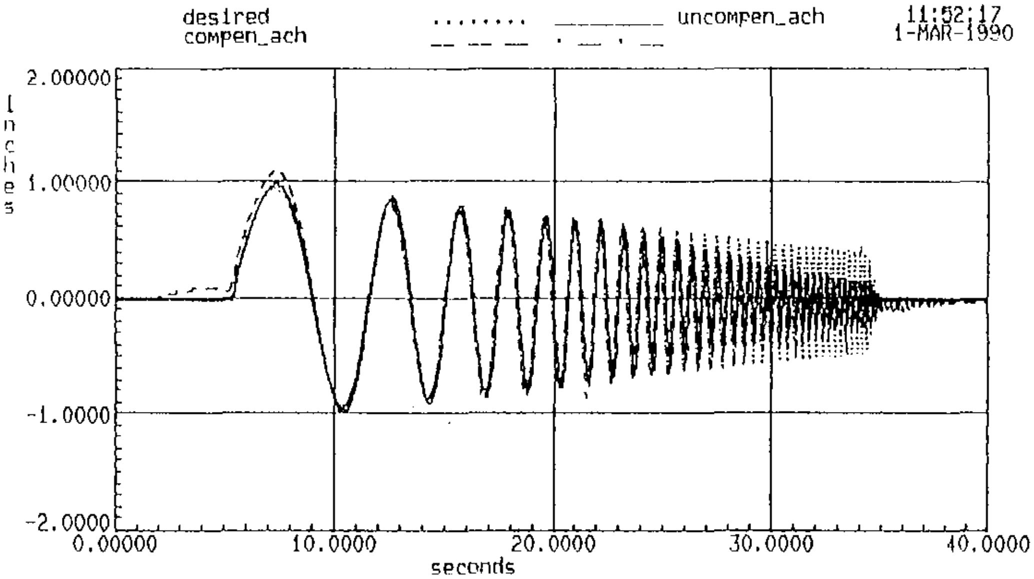


Figure 2.14b. Overlay plot of achieved functions

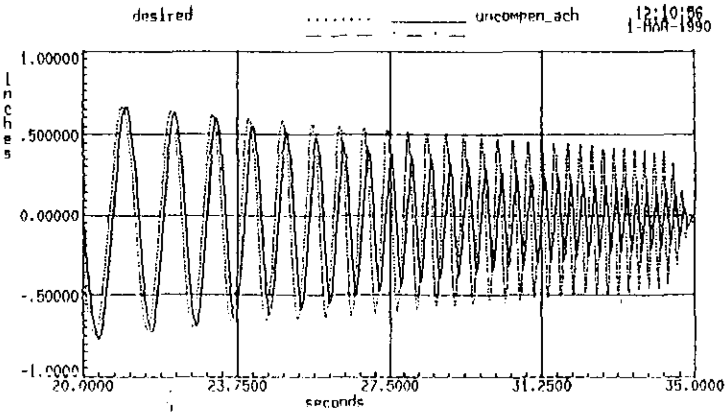


Figure 2.14c. Overlay plot of desired and achieved function of uncompensated profile test

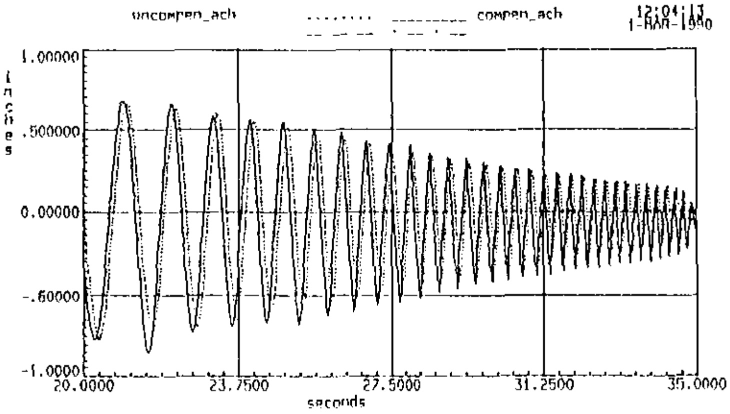


Figure 2.14d. Overlay plot of achieved functions of uncompensated and first compensated tests

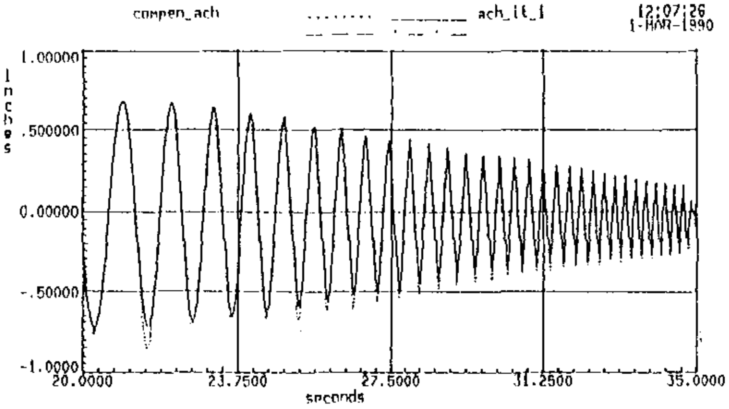


Figure 2.14e. Overlay plot of achieved functions of first compensated and second compensated tests

3. Compensation helps to overcome the various factors which decrease the amplitude of the achieved signal only within the frequency-amplitude capability of the system hydraulics.

Part II of Appendix A illustrates in detail the procedure followed in STEX for the definition and execution of this example test.

2.3 Pseudodynamic Test

2.3.1 Introduction

The pseudodynamic test method is a relatively new testing method which was originally developed for evaluating the seismic (or dynamic) performance of structural models in a laboratory by an on-line computer controlled testing. This technique combines the realism of real time testing with the economy and convenience of the quasi-static testing. In a quasi-static test, an inelastic computer analysis is performed for the structure in question. The displacements calculated at different locations of the structure are used to control the test. Such tests utilize conventional static testing systems and allow for a detailed observation of the structural behavior during the tests.

Pseudodynamic test allows the testing of large-scale structural models which cannot be tested realistically and efficiently by conventional methods [8]. Another significant advantage is that it allows the test to be conducted at a slower rate, thereby, allowing a better study of the behavior of the test specimen as the test progresses. Pseudodynamic tests have been successfully performed in Japan and the United States and the results have correlated well with the analytical and shaking table results [8].

However, this procedure has its own limitations. It works well with the structure which can be realistically characterized by lumped masses and fewer degree of freedoms (DOF). In general, structures with significant distributed masses or masses that can influence the local modes of failure or those constructed with materials which are sensitive to the rate of loading may not be suitable for this method.

2.3.2 Pseudodynamic test procedure

The pseudodynamic test procedure is similar to the quasi-static test except that the displacements being applied on the structure at each step are computed by the on-line control computer based on the dynamic response of the specimen. The test procedure is explained by the schematic diagram shown in Figure 2.15. The test procedure can be outlined as follows: The structure is modeled analytically, with the damping and the inertial characteristics determined prior to the testing. These values together with the acceleration of the forcing function form the input to the test. An initial prescribed displacement is imposed on the structure through the hydraulic

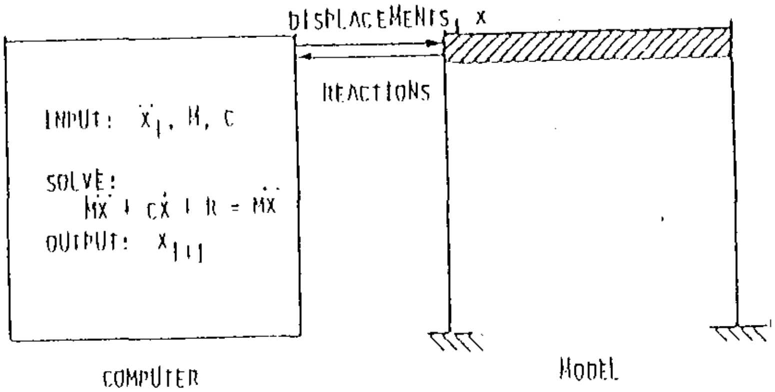


Figure 2.15 Schematic diagram of Pseudodynamic testing method

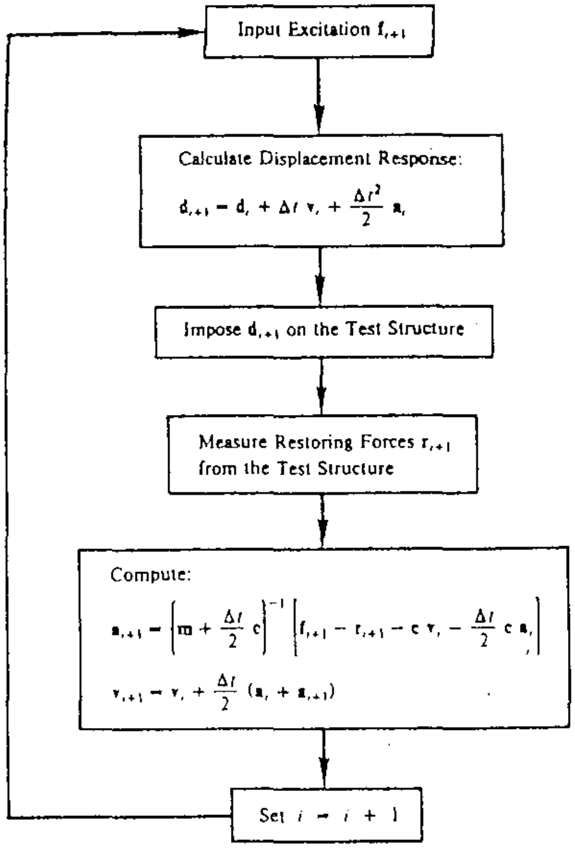


Figure 2.16 Flow chart of Explicit Newmark algorithm

actuators located at each degree of freedom (DOF). The load cells, present within the actuator, monitor the restoring forces produced at each DOF due to the imposed displacement. These forces are retrieved by a high speed on-line data acquisition system. The restoring forces become the input to the software which solves the system of differential equations associated with the structure to arrive at the displacements at each DOF. These displacements are then applied at the next time step and the process repeated. The flow chart on Figure 2.16 (Figure 2.2c of Shing & Mahin (8)) illustrates the steps involved in a pseudodynamic test using Explicit Newmark Algorithm (for solving the differential equation of motion).

2.3.3 Test procedure in STEX

The entire test procedure consists of several steps. These are described in Figure 2.17.

2.3.4 Trial tests

A series of tests were conducted in the elastic range on a simply supported beam. Trial tests consisted of using a ramp forcing function shown in Figure 2.18 with varying damping coefficients. The results of the tests have been summarized in Table 2.3. It can be seen from the results, that the actual achieved values generally agree well with the theoretical values. A sample of the response (obtained for

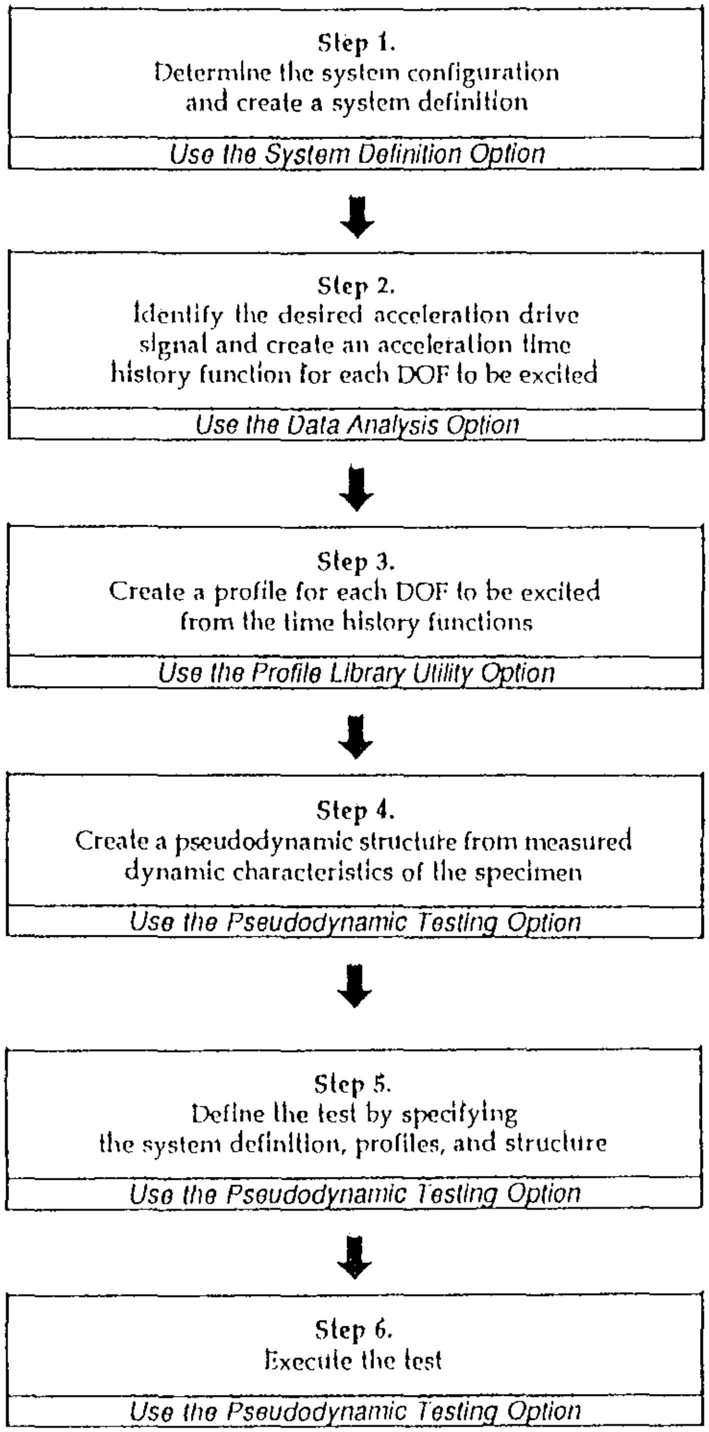


Figure 2.17 Flowchart of Pseudodynamic testing procedure

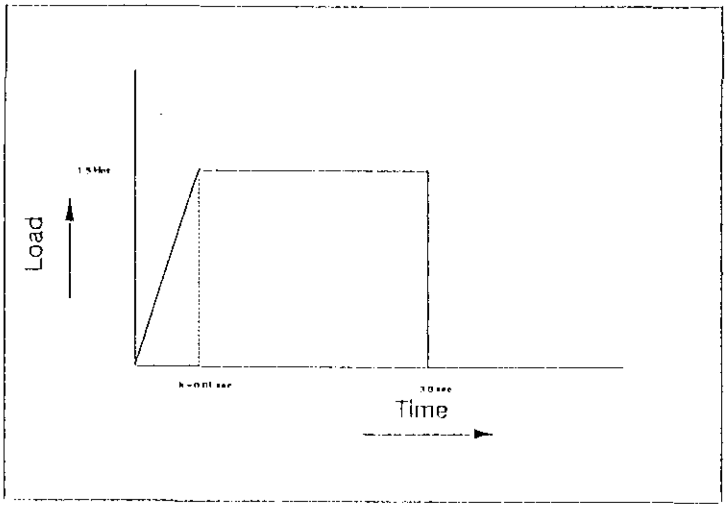


Figure 2.18 Specified forcing function

Table 2.3. Results of pseudodynamic tests

Test number	Peak load	Damping factor	tr / T	Theoretical X	Theoretical tm	Actual X	Actual tm
	kips	%	-	inches	secs.	inches	secs.
1	1.5	0	0.05	0.556	0.1	0.54	0.09
2	1.5	1	0.05	0.505	0.08	0.575	0.105
3	1.5	10	0.05	0.486	-	0.475	-

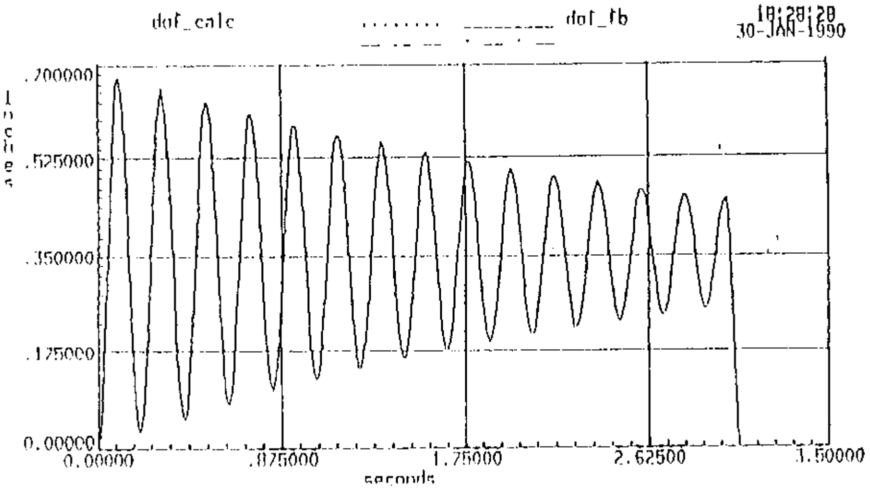


Figure 2.19 Achieved displacement function

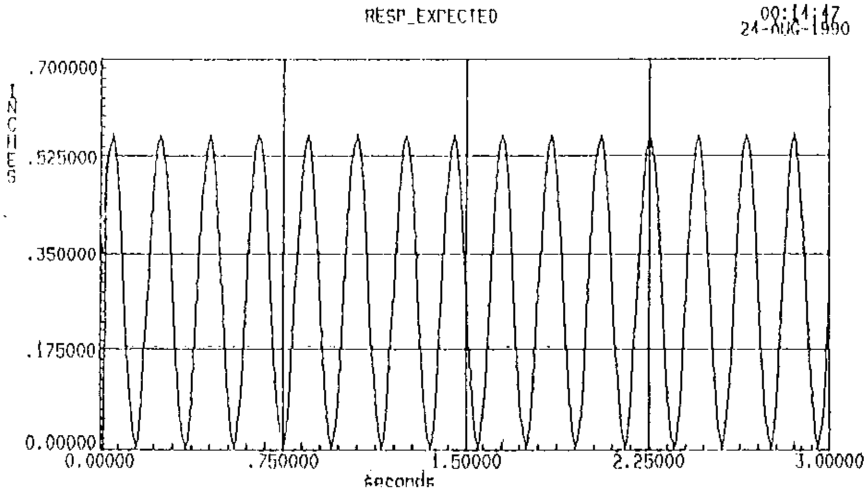


Figure 2.20 Theoretical displacement function

the test with 0% damping) is shown in Figure 2.19. The corresponding theoretical response is shown in Figure 2.20.

Part III of Appendix A illustrates with an example the definition and execution of the pseudodynamic test with 0% damping using STEX.

2.4 Example Manual for STEX

The production of the Example Manual was one of the primary tasks associated with the first major objective. This is available in Appendix A.

The Example Manual was made with the following objectives:

1. To guide the user to learn how to use the Testing System.
2. To provide the user with the information provided by MTS on a personal level, which is available neither in the STEX manual nor in the software. This includes Cautions and Notes to the user provided throughout the example tests for the different types of testing.
3. To provide illustrations for the definition, execution and post-test analysis of a test through the example tests. This was essential because the STEX software does not have a Help Menu and the documentation of the STEX user's manual does not discuss some of the theory involved.
4. To provide the user some basic knowledge of the functions of the hardware and the settings which are required to be made

in the process of executing a test.

5. To provide the user the current status of the software.
6. To provide some idea of the limitations of the hardware.

The contents of the Example Manual is given below.

Part I. Uncompensated Dynamic Test.

Part II. Compensated Dynamic Test.

Part III. Pseudodynamic Test.

Each of the above parts illustrates the procedure involved in detail with an example test.

3. PROBLEM DEFINITION AND DESIGN OF THE CROSSARM

3.1 Introduction

This chapter corresponds to the tasks 1 and 2 of the second major objective, as explained in Section 1.2.2 of Chapter 1. These tasks involve the definition of a single pole tower system and the design of the crossarm as per NESC [1987], and Manual of Steel Construction, Eighth edition [9].

3.1.1 Single pole support system

Figure 3.1 (Figure 3.1 of Li Li, reference 5) shows the schematic diagram of a pole transmission line system. A pole tower system consists of four basic elements: pole support structure, crossarm, insulators and the conductors. The pole structure is usually made of either timber or steel. The wooden poles may have either steel or wooden crossarm while the steel poles usually have metal crossarms only. The insulators may be either suspended or fixed with the conductors attached to their ends.

The steel crossarms are usually welded to a plate or to the web of a channel, which in turn is bolted to the pole structure. Figure 3.2 shows a typical laminated wooden pole in a single circuit 161 KV transmission line which uses such a connection detail for the crossarm. Iowa Electric has observed that such connections have failed, most likely due to galloping. These were mostly failures of the welds rather

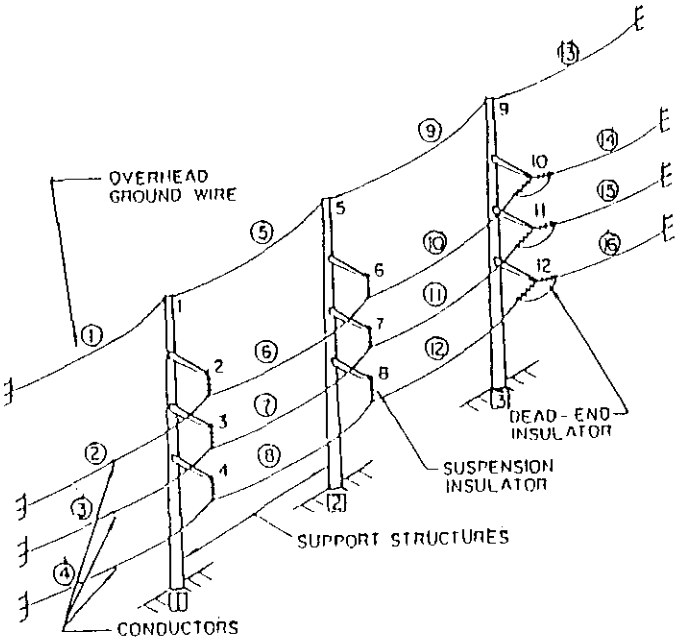


Figure 3.1. Schematic diagram of pole transmission line system

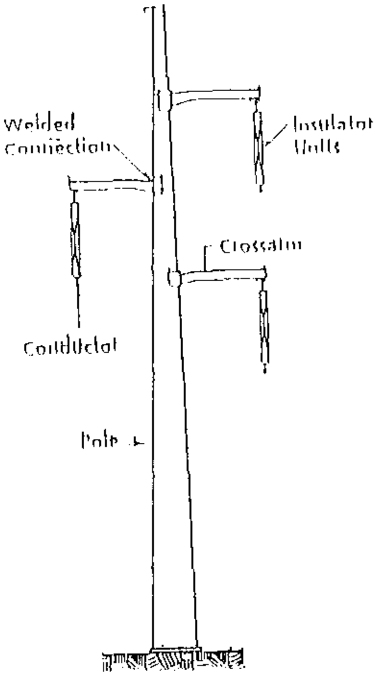


Figure 3.2. Typical laminated wood pole

than of the bolts.

The experimental study being reported here was directed at defining a typical pole tower system and designing a steel crossarm for a wooden pole support with a connection detail as discussed in the previous paragraph.

3.1.2 Experimental studies

There were two experimental studies undertaken in this research. In the first trial study, a wooden pole tower system with a 600 feet span was defined and a steel crossarm designed. The prototype crossarm consisted of a 5 inch square structural tube (constant section) with a wall thickness of 1/4 inch made of A 500 (designation of the American Society of Testing Materials) cold formed steel. The tube was welded to a channel made of plates and the channel was in turn bolted to the support beam.

Prior to applying galloping load, static loads approaching 1.75 kips were applied to the structure and strains were measured close to the weld (approximately 1/4 inch away) at the top and the bottom, in the middle of the section. In addition, strains were measured at the top of the tube at a location one foot from the welded joint. It was observed that while the strains one foot from the joints were in agreement with the theoretical strains, the strains at the top of the section close to the weld ranged between 2.0 to 3.0

times the theoretical strains and permanent strains of approximately 980 micro-strains were noticed. The theoretical strain values were calculated with the beam idealized as a fixed cantilever. It was also observed that a vertical stiffness of approximately 25% of the theoretical stiffness was obtained at the end of the crossarm where the insulator is attached.

It was suspected that this behavior of the cantilever could be due to the effect of welding of the cold formed section. When a cold formed metal is welded, the portion of the metal next to the weld (in the zone of fusion) may undergo recrystallization [10]. The recrystallized metal tends to be weaker and more ductile than the original cold-worked metal. It was also felt that this material does not reflect the field conditions, in which ASTM A 588 weathering steel plate is used to fabricate the crossarm. For these reasons the use of this specimen for the experimental study was suspended.

The second experimental study involved the use of a prototype crossarm obtained from Iowa Electric. This is very similar to the crossarms which failed due to forces from galloping conductors a few years ago in the Central Iowa. The definition of the pole structure system for this crossarm was done by working backwards from the sectional details and the weld details of the crossarm. It is this experimental study on this crossarm which is being reported in this thesis.

3.2 Definition of Pole Support System

3.2.1 Design data

The following data were assumed for the pole structure system.

Location: Central Iowa.

Location in the transmission line: Intermediate span.

Average span of the line: 400.0 feet.

Material of the pole: Wood (Douglas Fir).

Height of the pole: 70.0 feet above the ground.

Material of the crossarm: Steel.

Type of Insulator: Suspended.

Length of the Insulator: 6.0 feet.

Weight of the Insulator: 200 lbs.

Conductor type: Bittern (45/37 ACSR)

Number of conductors: One.

NESC Grade of construction: Grade B.

3.3 Computation of Design Loads

The loads acting at the end of the crossarm are normally from the weight of the conductor, the weight of the suspended insulator and stringing loads applied during construction. These loads act together with ice and wind loads in various combinations.

3.3.1 Loading conditions

The general loading requirements are specified in section 25 of the NESC. This section specifies ice, wind and temperature conditions for different loading situations. The different loading conditions recommended by NESC are as follows.

1. Combined ice and wind loading.
2. Extreme wind loading
3. Loading due to stringing.

However, in practice the following loading condition is also considered [11].

4. Heavy ice loading.

The ice, wind and temperature conditions for the Loading conditions 1 and 2 are specified under rule 250 B and 250 C respectively. NESC recommends a suitable allowance for stringing load, which is only a minor load. These data for loading conditions 3 and 4 have been assumed from reference [11]. The ice, wind and temperature data adopted for each of the above loading conditions are summarized in Table 3.1.

It is noted that while NESC generally recommends consideration of loads due to other effects such as stringing etc., it is not specific on the magnitude of loads to be considered. It does not seemingly address the loads due to galloping conductors.

Table 3.1. Ice, wind and temperature data

Load Case	Loading Condition	Ice Thickness	Wind Pressure	Temperature	Remarks
		inches	lbs/ sq.ft	degrees F	
1	Combined Ice and Wind	0.5	4	0	NESC 250 B
2	Extreme Wind	0	16.0	+ 60	NESC 250 C
3	Heavy Ice	1.0	0	0	Adopted from ref.
4	Stringing	0	0	+ 60	

3.3.2 Loading components

The different loading components and the method of calculation of the static service loads are specified in rule 251 A and B of NESC. The different loading components considered are as given below.

1. Vertical loading component
2. Transverse loading component and
3. Longitudinal loading component.

The specified directions are with respect to the conductor as illustrated in Figure 3.3. All these components are assumed to act at the end of the connection point of the conductor with the suspended insulator.

3.3.3 Overload capacity factors

The overload capacity factors, which act as safety factors, for metal crossarms of Grade B construction are given in Table 262-2 of NESC which are reproduced below.

Vertical strength: 1.5
Transverse strength: 2.5 (wind load)
Longitudinal strength: 1.1 (non-dead ends)

3.3.4 Strength requirements of NESC

Section 26 of NESC specifies the strength requirements of the crossarm. The strength requirement of the metal crossarm are specified as follows.

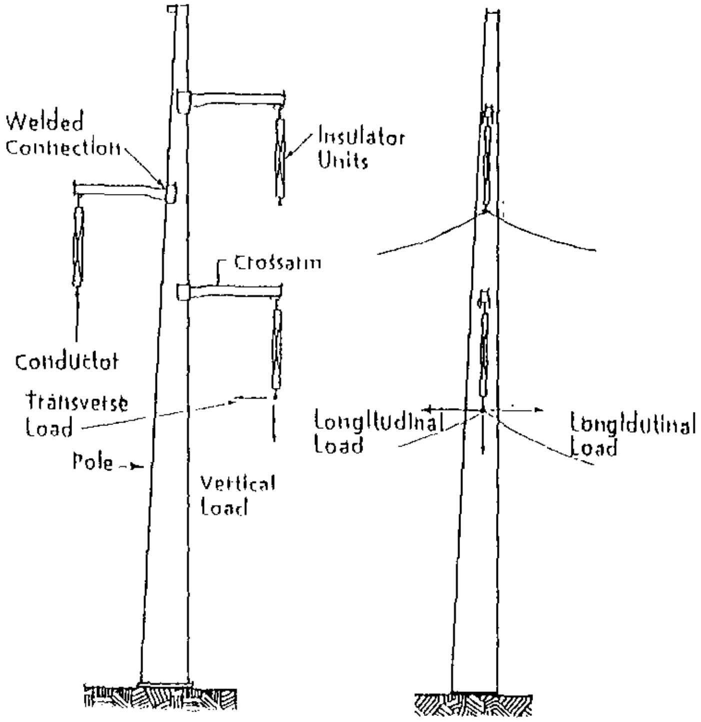


Figure 3.3. Loading components as specified by NESC

3.3.4.1 Vertical strength The crossarm shall withstand the service static loads without exceeding 50% of the ultimate strength. It shall also withstand the service static loads multiplied by the overload capacity factors.

3.3.4.2 Longitudinal strength The crossarms shall withstand the greater of the static service loads as specified in Rule 252 and 700 lbs without exceeding the ultimate strength of the material. Rule 252 allows for a suitable assumption of this load.

3.3.4.3 Transverse strength The crossarm shall withstand the service static loads multiplied by the overload capacity factors.

3.3.5 Design loads The design loads calculated as per rule 252 of NESC for the various loading conditions with the appropriate overload capacity factors are tabulated in Table 3.2.

3.4 Check on the Strength of the Crossarm

While NESC specifies the strength requirements for each of the three different loading components on the crossarm in Section 26, it does not appear to clearly specify the design method to be adopted in such cases of loading or in a combination of such cases. For example, it does not specify the design procedure to be adopted for the combined axial and

Table 3.2. Factored loads

Load Case	Loading Condition	Vertical	Transverse	Longitudinal
		Load in Kips		
1	Combined Ice and Wind	1.863	0.795	0
2	Extreme Wind	1.161	1.84	0
3	Heavy Ice	2.937	0	0
4	Stringing	1.161	0	1.0

Note: The weight of the insulator has been included in the vertical load.

Table 3.3. Service loads

Load Case	Loading Condition	Vertical (P_v)	Transverse (P_t)	Longitudinal (P_l)
		Load in Kips		
1	Combined Ice and Wind	1.242	0.318	0
2	Extreme Wind	0.774	0.737	0
3	Heavy Ice	1.958	0	0
4	Stringing	0.774	0	0.91

Note: The weight of the insulator has been included in the vertical load.

bending effects of the transverse loading component for the extreme wind case.

In the strength checks made on the crossarm obtained from Iowa Electric Light and Power Company, Ceder Rapids, the Allowable Stress Method, as per the American Institute of Steel Construction (AISC) requirements, has been adopted. However, the check for the strength adequacy as per NESC has been made in load cases where no combined loading condition is present. Such a situation is present only in the 'heavy ice' case where the vertical load alone acts. A strength check for the loading case of the stringing load has not been done as this is only a minor load.

The service loads for the different loading conditions calculated as per rule 252 of NESC are shown in Table 3.3. The crossarm is idealized as a fixed cantilever in the elastic analysis. The following checks have been made for the section at the pole end:

Description of the crossarm

The crossarm is shown in Figure 3.4.

Length: 6.5 feet.

Angle of inclination (to the horizontal): 3 degrees.

Material: Fabricated out of ASTM A 588 plate.

Wall thickness: 3/16 inch.

Section: Tapering from square at the pole end to a

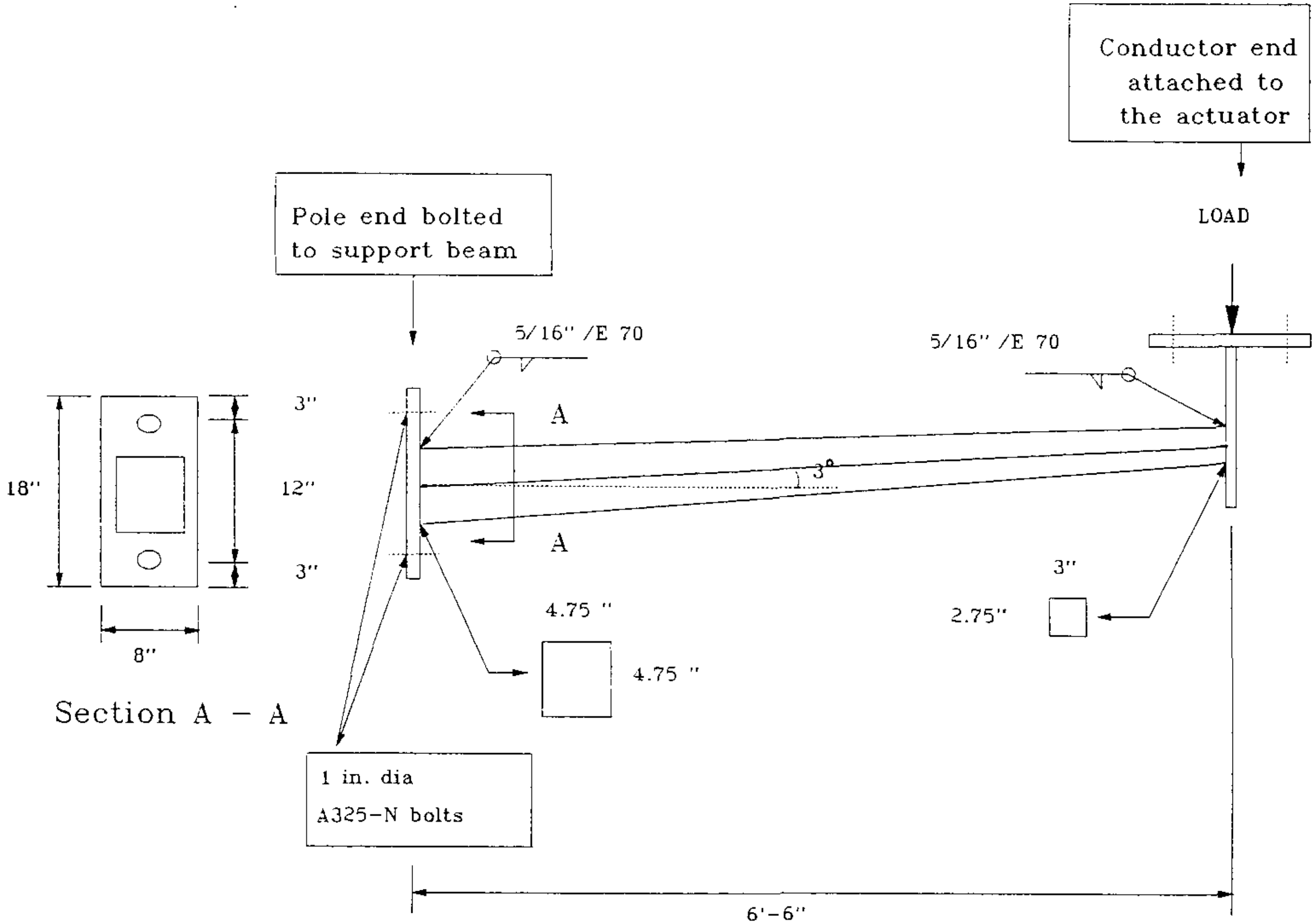


Figure 3.4. Details of the crossarm used in this study

rectangle at the conductor end.

Size at pole end: 4.75 inch * 4.75 inch.

Size at the conductor end: 3.00 inch * 2.75 inch.

For ASTM A 588, F_y = 50 ksi ; F_u = 70 ksi.

3.4.1 Properties of the crossarm at the pole end

$I_{xx} = 11.892\ in^4$; $S_{xx} = 5.007\ in^3$;

$A = 3.562\ in^2$; $r_{xx} = 1.827$ in.

3.4.2 Check for combined ice and wind loading

This is a case of combined bending and axial loading where the vertical loads from the weight of the insulator, conductor and the ice produce a bending effect. The transverse load due to the wind acting on the conductor also produces a combined bending and axial effect. For combined stresses, this cross section needs to comply with clause 1.6.1 of AISC.

Bending moment at the pole end = $P_v * L_a + P_t * L_i$

= 1.242*6.5*12 + 0.318*6*12

= 119.772 in-kips.

Total service axial load = P_t = 0.318 kips (Table 3.3)

The summary of the design is given below.

f_a = 0.3486 ksi

F_a = 18.210 ksi

f_{bx} = 23.920 ksi

$F_{bx} = 0.66\ F_y = 33$ ksi.

It must be noted here that this cross section satisfies the conditions for the use of $F_y = 0.66\ F_y$ as per clause 1.5.1.4 of AISC.

$$\frac{f_a}{F_a}+\frac{f_{bx}}{F_{bx}}=0.698<1 \qquad (3.1)$$

Hence O.K.

3.4.3 Check for extreme wind loading

This is also a case of combined bending and axial loading at the end of the crossarm. The weight of the conductor produces bending effect. The high wind acting on the conductor produces a combined bending and axial effect. The check for the combined stresses as per clause 1.6.1 of AISC was done. The summary of the design check is given below.

Bending moment at the pole end = $P_v * L_a + P_t * L_i$

= 0.774*6.5*12 + 0.737*6*12

= 113.436 in-kips.

Service axial load = 1.840 kips (Table 3.3)

$f_a = 0.2173$ ksi

F_a = 18.210 ksi

f_{bx} = 22.655 ksi

F_{bx} = 0.66 F_y = 33 ksi.

$$\frac{f_a}{F_a}+\frac{f_{bx}}{F_{bx}}=0.7439<1 \qquad (3.2)$$

Hence O.K.

3.4.4 Check for heavy ice loading

This loading produces a pure bending in the crossarm. This section is checked for compliance with 1.5.1.4 of AISC.

Moment at the pole end (service load) = $P_v * L_a$

= 1.958 * 6.5 * 12

= 152.78 in-kips.

Moment at the pole end (factored as per NESC) = 205.69 in-kips. The summary of the design check is given below.

The sectional modulus required at the end of the crossarm as per AISC and NESC are given below.

S_{xx} required as per AISC = 4.628 in^3

S_{xx} required as per NESC (rule 261 D) = 4.363 in^3

S_{xx} required as per NESC (rule 261 E) = 4.582 in^3

S_{xx} provided = 5.0063 in^3

Hence O.K.

It can noticed from the strength checks made for compliance with AISC that the load cases 1 and 2 are not as critical as load case 3 (Heavy Ice loading).

3.5 Check on the Strength of the Weld and Bolts.

These checks have been made only for the Heavy Ice load case which is the most critical case.

3.5.1 Check on the strength of the weld

The specifications of the weld are as follows:

Nominal size: 5/16 inch.

Type of the weld: Fillet weld all around the section.

Electrode specification: E 70 electrode.

Effective length of the fillet weld = 19 in.

From Table 1.5.3 of AISC, Allowable shear stress = 21 ksi.

Shear stress, $f_y' = 0.468$ ksi.

Bending tensile stress, $f_y'' = 20.64$ ksi.

Resultant stress, $f_r = 2.064$ ksi < 21 ksi.

3.5.2 Check on the strength of the bolts

Two, 1 inch diameter A 325-N bolts are provided at 12 inches apart. The holes provided are 1.25 inches in size. From Table 1.5.2.1 of AISC manual, allowable shear capacity, F_v = 21 ksi. The allowable tension capacity of bolts subject to shear and tension must be the least of F_t = 44 ksi (Table 1.5.2.1 of AISC manual) and F_t'.

$$f_t=\frac{My}{\Sigma Ay^2}=16.21ksi \tag{3.3}$$

$$f_v=\frac{P}{A}=1.247ksi<21ksi \tag{3.4}$$

Hence O.K in shear.

$$F_t=55-1.4*f_v=53.254ksi. \tag{3.5}$$

The allowable tension capacity = 44 ksi > f_t. Hence O.K in tension also.

The available crossarm has now been checked for the loads specified by NESC adopting the design specifications of AISC for the assumed pole structure system defined in Section 3.1.

3.5.3 Maximum static vertical loads

The maximum allowable static vertical load at the conductor end for the available strength of the crossarm, weld and bolts have been calculated. These values are given below:

For the crossarm = 2.118 kips.

For the weld = 1.992 kips.

For the bolts = 5.314 kips.

It can be understood from the above information that the weld is the most critical component of the system since it allows the application of the least load.

4. COMPUTATION OF THE GALLOPING LOADS AND TEST SETUP

4.1 Algorithm for Vertical Galloping Force

The force-time algorithm for quantifying the vertical component of the galloping load has been reported in reference [5] and has been reproduced below.

According to this study, the dynamic load due to galloping can be idealized as a sinusoidal function. This dynamic load is considered to be acting in the vertical direction at the point of attachment of the conductor to the insulator. The dynamic load contributed by half of the span of the conductor is given by (V+v). The total dynamic load at the tip of the insulator is the response from two half-spans on either sides of the pole. The worst case of both the spans galloping in phase is given by 2*(V+v).

Assuming only one mode is excited and the mode shape is approximated by a sine function, then

$$V+v(t)=\frac{1}{L}(4s_o+n\pi a_o\cos\omega t)\left(\frac{2a_o k_e wL}{n\pi H}\cos\omega t+H\right) \quad (4.1)$$

The worst case occurs when both the spans gallop in phase with the first mode. The peak dynamic load, $(V+v)_{max}$ is obtained when cos t is unity. The weight of the insulator is added to $2*(V+v)_{max}$ to arrive at the peak load on the crossarm due to conductor galloping. The dynamic vertical galloping force on the crossarm is shown in Figure 4.1. Please refer to Chapter 6 for the definition of the terms.

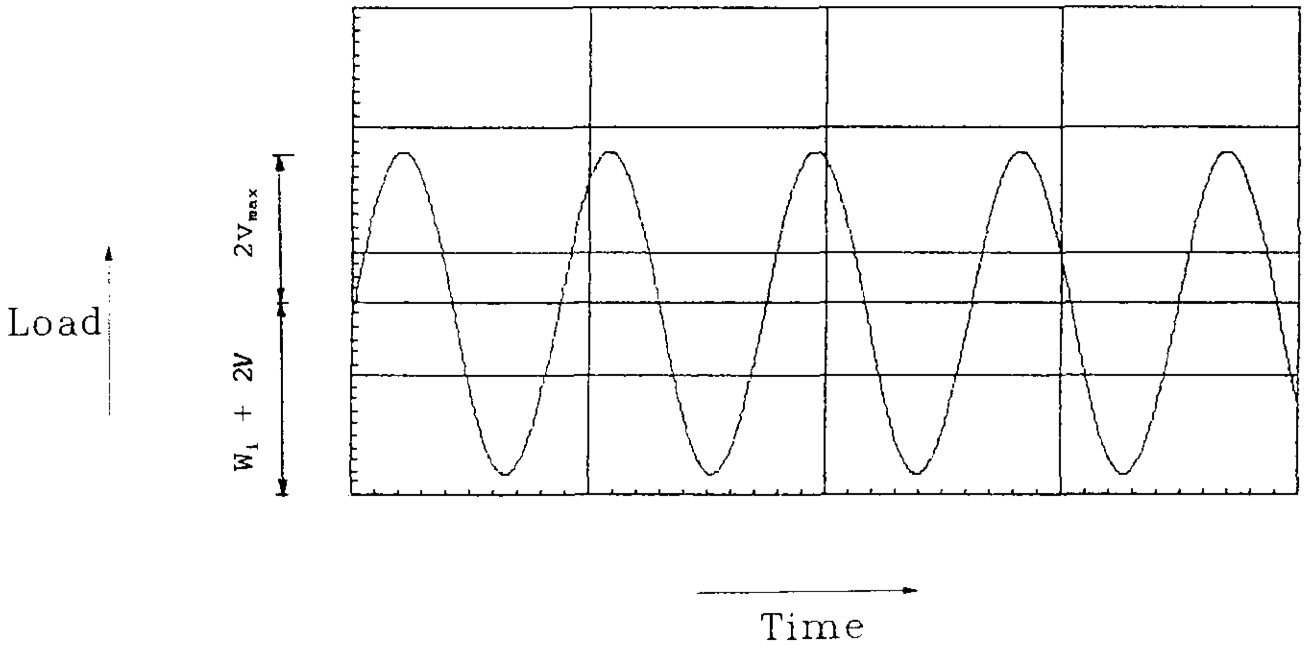


Figure 4.1. Idealized force due to galloping

The galloping amplitude, a_o is given by,

$$a_o=0.5\left(\frac{0.26V_w}{f}\right) \tag{4.2}$$

The equivalent stiffness, k_e is given by

$$k_e=\frac{1}{\frac{1}{k_i}+\frac{1}{k_c}} \tag{4.3}$$

where $k_i = (W + 0.5W_i) / L_i$.

The natural frequency, ω_n is given by

$$\omega_n=\left[\frac{H}{m}\left(bL+\left(\frac{n\pi}{L}\right)^2\right)\right]^{\frac{1}{2}} \tag{4.4}$$

where bL is given by

$$bL=\frac{8s_ok_ew}{H^2L^2} \tag{4.5}$$

The static load due to the weight of half the span is given by V.

$$V=\frac{4s_oH}{L} \tag{4.6}$$

4.2 Computation of the Galloping Load

4.2.1 Introduction

The parameters required for the computation of the galloping load using this algorithm are given below.

1. Geometry and material information of the conductor.
2. Geometry of transmission line system.
3. Initial tension in the conductor and temperature at stringing.
4. Ice, wind and temperature data during galloping.

The computation of the galloping load on the crossarm involves the following steps.

1. Computation of static line sag, s_o and horizontal load, H.
2. Computation of the equivalent stiffness, k_c.
3. Computation of the natural frequency, ω_n .
4. Computation of the galloping amplitude, a_o.
5. Computation of $(V+v)_{max}$.
6. Computation of dynamic load on the crossarm.

In this experimental study the worst case of the adjacent spans galloping in the same phase was assumed. The static load of the insulator is added to this load to arrive at the peak dynamic load acting on the end of the crossarm.

4.2.2 Input parameters for the computation of galloping load

The parameters that are required for the computation of the galloping load in this study are given below:

1. Geometry and material information for the conductor

The conductor adopted in this study is Bittern (name of the conductor). The properties of this conductor is available reference 12 which has been reproduced below.

Diameter of the conductor = 1.382 inches.

Total area of the conductor = 1.068 in^2.

Area of aluminum strands = 0.069 in^2.

Area of steel strands = 0.999 in^2.

Conductor weight = 1.434 lbs/ ft.

2. Geometry of the transmission line system The geometry of the transmission line system assumed is given below.

Span between the towers = 400 ft.

Difference in elevation of the conductor attachment points = 0.0 ft.

3. Initial tension and temperature at stringing

The initial tension assumed = 4500 lbs.

Temperature at stringing = 60 degrees F.

4. Ice, wind and temperature during galloping

Galloping is generally associated with the formation of glaze, which is the densest among the types of ice. The favorable temperature for the formation of this ice is approximately 32 degree Fahrenheit which has been assumed in this study.

In order to fully understand the effects of the variation of the ice and wind on galloping and subsequently their effects on the crossarm, a sensitivity study was made by varying each of these parameters individually while keeping the other one constant.

In the first case the radial ice thickness was kept constant at 0.3 inch and the wind speed was varied from 4 mph to 26 mph. The range of wind speed chosen was observed during the icestorm of Spring, 1990 in Central Iowa. The radial ice thickness was adopted from a galloping event data reported [13] for a site at Nanticoke, Canada. In the other case, the wind speed was kept constant at 10 mph and the radial ice thickness was varied from 0.1 to 0.7 inch.

4.2.3 Example computation of the dynamic load on the crossarm

1. Computation of line static sag and horizontal force

The line static sag refers to the sag of the conductor loaded with ice under static conditions. The horizontal force corresponds to the static state. This force acts at the connection point of the conductor with the insulator. The static analysis was performed using the computer program CABLE [14]. The input for this program consists of the following information.

1. Geometry and material properties of the conductor.

2. Geometry of the line transmission system.

3. Initial tension and temperature at stringing.

4. Ice thickness and temperature during galloping.

An ice thickness of 0.3 inches was assumed. The rest of the data is available in the previous subdivision. The result of the analysis is given below.

Static sag of the line = 5.86 feet.

Static horizontal force = 6997 lbs.

2. Computation of equivalent stiffness, k_e This is calculated using the Eq. (4.3).

Length of the insulator = 6.0 ft.

Weight of the insulator = 200 lbs.

$w = w_c + w_i = 1.434 + 0.616 = 2.050$ lbs/ft.

$k_i = 153.03$ lbs/ft; $k_c = 76649.99$ lbs/ft.

$k_e = 153.33$ lbs/ft.

3. Computation of the galloping frequency The first mode shape is assumed for galloping. The frequency is calculated using Eq. (4.4). All the inputs for this equation have been previously calculated.

Natural frequency for the first mode = 2.6196 rad/sec

= 0.4169 Hz.

It must be noted that the natural frequency does not depend on the wind speed but it does depend on the ice load.

4. Computation of galloping amplitude It can be noted from Eq. (4.2) that the galloping amplitude is directly

proportional to the wind speed. For a wind speed of 10 mph the galloping amplitude is calculated as 4.545 feet.

5. Computation of $(V+v)_{max}$ This is calculated by using Eq. (4.1). All the inputs to this equation have been calculated in the previous steps.

$(V+v)_{max} = 666.10$ lbs.

6. Computation of the dynamic load on the crossarm The total dynamic peak load on the crossarm is the sum of $2*(V+v)_{max}$ and the weight of the insulator.

Total static load $= 2 * V + W_i$

$= 2 * 410 + 200 = 1020$ lbs.

Maximum load $= 2(V+v)_{max} + W_i$

$= 2 * 666.10 + 200.0 = 1532.2$ lbs.

Minimum load $= W_i + 2(V+v)_{max} - 2v_{max} = 507.8$ lbs.

This load is shown in Figure 4.2.

4.3 Sensitivity Study

4.3.1 Case 1: Constant ice thickness with varying wind speeds

In this case, a constant ice thickness of 0.3 inch was assumed and the wind speeds were varied from 4 MPH and 26 MPH. The results have been tabulated in Table 4.1.

It can be seen from the table that as the wind speed increases the peak dynamic load on the crossarm increases and hence the dynamic load factor also increases. This is because

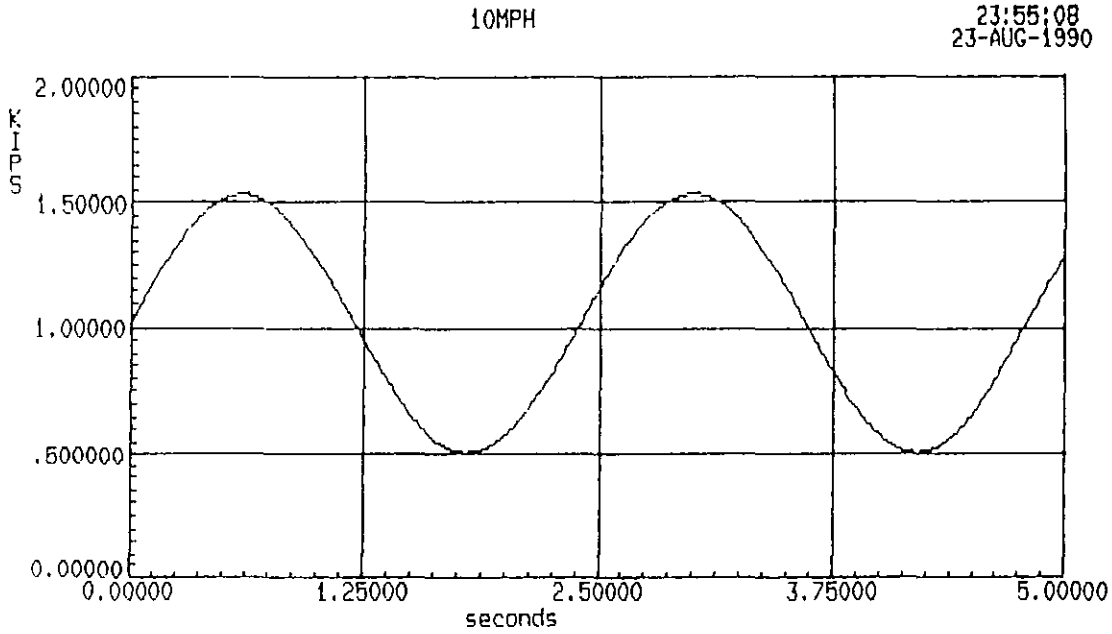


Figure 4.2. Galloping force for the example for a constant ice thickness, the effective stiffness and the natural frequency remain constant while galloping amplitude increases with increasing wind. As the amplitude increases the conductor exerts a greater force at the end of the insulator and hence a greater load on the crossarm. This analysis emphasizes the need for the assumption of a suitable design wind speed for a safe and economical design of the crossarm.

4.3.2 Case 2: Constant wind speed with varying ice thickness

In this case a constant wind speed of 10 MPH was chosen and the radial ice thickness was varied from 0.30 inch to 0.70 inch. The results of the analysis is available in Table 4.2.

It can be observed that as the ice thickness increases k_e increases rapidly. This is because the stiffness of the insulator increases with the ice load whose contribution to the equivalent stiffness is more than the conductor stiffness which is a constant. Also, it can be observed that the galloping amplitude increases marginally due to the change in natural frequency. Hence, there is only a marginal increase in the dynamic load factor. But the magnitude of the peak dynamic load increases with the increase of the static load due to an increase of the ice load.

These two sensitivity studies emphasize the need for the use of a suitable wind speed and radial ice thickness for a safe and economical design of the crossarm.

4.4 Dynamic Analysis

Dynamic analysis was performed to understand the dynamic effect on the crossarm for the harmonic load function due to galloping. The crossarm can be idealized as a fixed cantilever with the static lumped mass due to the static weight attached to its conductor end. In comparison to the static weight at the end, the weight of the crossarm can be considered negligible. Hence, the crossarm is idealized as a single degree of freedom lumped mass system. It must be noted that for all practical purposes, the decrease of the natural frequency due to damping can be neglected. It must also be noted that for a continuing state of vibrations, it is reasonable to assume that any small damping present in the system will eliminate the transient response.

The natural frequency of the single degree of freedom system is calculated as shown below.

K = 1.497 kips/inch.

$$\omega=\sqrt{k/m}=\sqrt{1.497/.00264}=23.813 rad/\mathrm{sec}$$

This corresponds to a natural frequency of 3.79 Hz. It must be recalled that the frequency of the forcing function has been calculated earlier as 0.4169 Hz.

The $(\mathrm{DLF})_{\max}$ for the forced part is then calculated as shown below.

$$(DLF)_{\max}=\frac{1}{1-(\frac{\Omega}{\omega})^{2}}=\frac{1}{1-(\frac{0.4169}{3.79})^{2}}=1.012$$

It can be observed from the above equation that as the frequency of the forcing function and the natural frequency of the crossarm are very different there is negligible amplification of the dynamic load due to galloping. Hence it can be concluded that galloping produces cyclic loading on the crossarm.

4.5 Test Setup

The test setup for the experimentation was made as shown in Figure 4.3. The testing frame in which the actuator and the crossarm are located is a self-contained frame. The pole end of the crossarm was connected to the web of a support beam consisting of W 21 * 68 and the conductor end was connected to the actuator as shown in Figure 4.4. A front view of the connection is shown in Figure 4.5.

Table 4.1. Results of case 1

WIND VELOCITY	GALLOPING AMPLITUDE	(V +v)max	vmax	MAXIMUM LOAD ON CARM	MINIMUM LOAD ON CARM	(DLF)max
mph	feet	lbs.	lbs.	lbs.	lbs.	
4.00	1.83	512.03	102.03	1224.06	815.94	1.20
6.00	2.74	563.26	153.26	1326.52	713.48	1.30
8.00	3.66	614.64	204.64	1429.28	610.72	1.40
10.00	4.57	666.17	256.17	1532.34	507.66	1.50
12.00	5.49	717.85	307.85	1635.70	404.30	1.60
14.00	6.40	769.68	359.68	1739.36	300.64	1.71
16.00	7.31	821.66	411.66	1843.32	196.68	1.81
18.00	8.23	873.79	463.79	1947.58	92.42	1.91
20.00	9.14	926.07	516.07	2052.15	-12.15	2.01
22.00	10.06	978.50	568.50	2157.01	-117.01	2.11
24.00	10.97	1031.08	621.08	2262.17	-222.17	2.22
26.00	11.89	1083.82	673.82	2367.63	-327.63	2.32

Notes: 1. Total static weight on the crossarm = 1020 lbs.
2. Constant Ice thickness = 0.30 inch.

Table 4.2. Results of case 2

Ice Thickness	Effective Stiffness K_e	Natural frequency f	Galloping amplitude a_o	Maximum load on crossarm	(DLF)max
inches	lbs/ft.	Hz	ft.	lbs.	_
0.30	153.33	0.42	4.55	1530.14	1.50
0.40	170.40	0.41	4.59	1534.61	1.50
0.50	189.00	0.41	4.64	1539.76	1.51
0.60	209.23	0.40	4.68	1545.02	1.51
0.70	231.08	0.40	4.73	1550.33	1.52

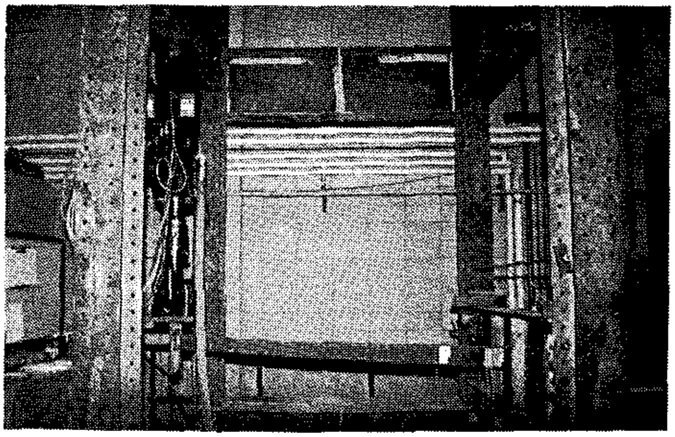


Figure 4.3. Photo showing the test setup

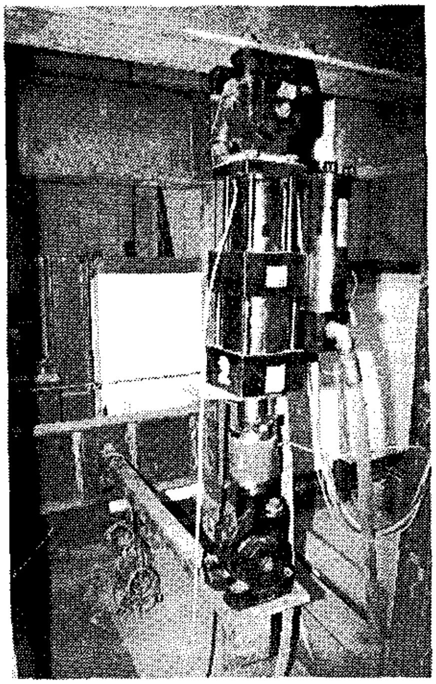


Figure 4.4. Another view of the test set up

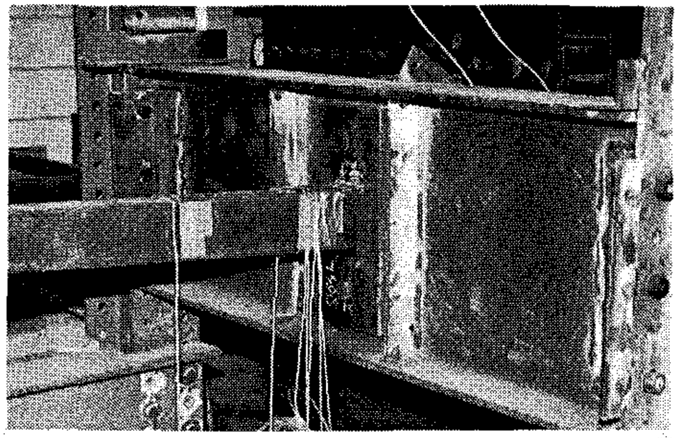


Figure 4.5. Front view of the connection at the pole end

5. TESTS AND TEST RESULTS

5.1 Testing Program

5.1.1 Objectives

The two main objectives of the testing program are listed below:

1. To use the MTS system to run an application test.

2. To conduct a preliminary study of the behavior of a crossarm to galloping forces which will provide preliminary information for more detailed testing on the crossarm in the future.

5.1.2 Scope of the Preliminary Study

The scope included for the preliminary study of the crossarm are stated below:

1. Demonstration of a simulation of the wind induced galloping force acting on the crossarm, for increasing wind speeds.

2. Study of the magnitude of stresses at the welded connection of the crossarm.

3. Preliminary investigation of the mode of failure of the connection.

5.2 Preliminary Static Loading

5.2.1 Introduction

It is understood from the dynamic analysis performed in Section 4.4 that the loading on the crossarm due to galloping of the conductors is cyclic in nature thus causing fatigue stresses. Hence, the performance of the welded connection under cyclic loading is an important consideration. The very nature of the fillet weld, transverse to the stress field, provides an abrupt change in the section. This abrupt change causes stress concentration which limits the fatigue strength and hence the fatigue life of the base metal [15]. Apart from this detrimental factor, there is also the possibility of the presence of residual tensile stress in the transverse direction to the weld.

Iowa Electric has in the past observed failures at the weld during suspected galloping. It is suspected that these failures could have been due to the fatigue stresses and the possible stress concentration at the welded connection. The experimental study was aimed at understanding the fatigue behavior of the member and the stress concentration at the welded connection.

Preliminary static tests were conducted prior to the application of galloping loads. The objectives of these tests were to: 1) measure the magnitude of the stresses in the elastic range at the welded connection to quantify the stress concentration factor; concern existed regarding the existence of residual stresses in this vicinity from the welding process, and 2) determine the member stiffness of the cross arm.

5.2.2 Instrumentation

A total of seven electrical resistance strain gages were mounted on the arm as shown in Figure 5.1. Three strain gages (gages 1,2 & 3) were mounted 0.25 inch away from the weld on the top flange across the width of the section. One strain gage (gage 4) was mounted at the bottom of the section next to the weld directly below gage 3. Two more strain gages (6 & 7) were mounted at locations approximately 6 inches and 12 inches away from the weld in line with the center of the section on top. Another one (gage 5) was mounted on the arm base plate midway between the top of the arm and the bolt in line with the vertical axis of the section.

The strains were measured using a strain indicator. A photograph of the strain gauges mounted at the connection is shown in Figure 5.2. Displacements were measured using the direct current displacement transducer (dcdt) housed in the actuator.

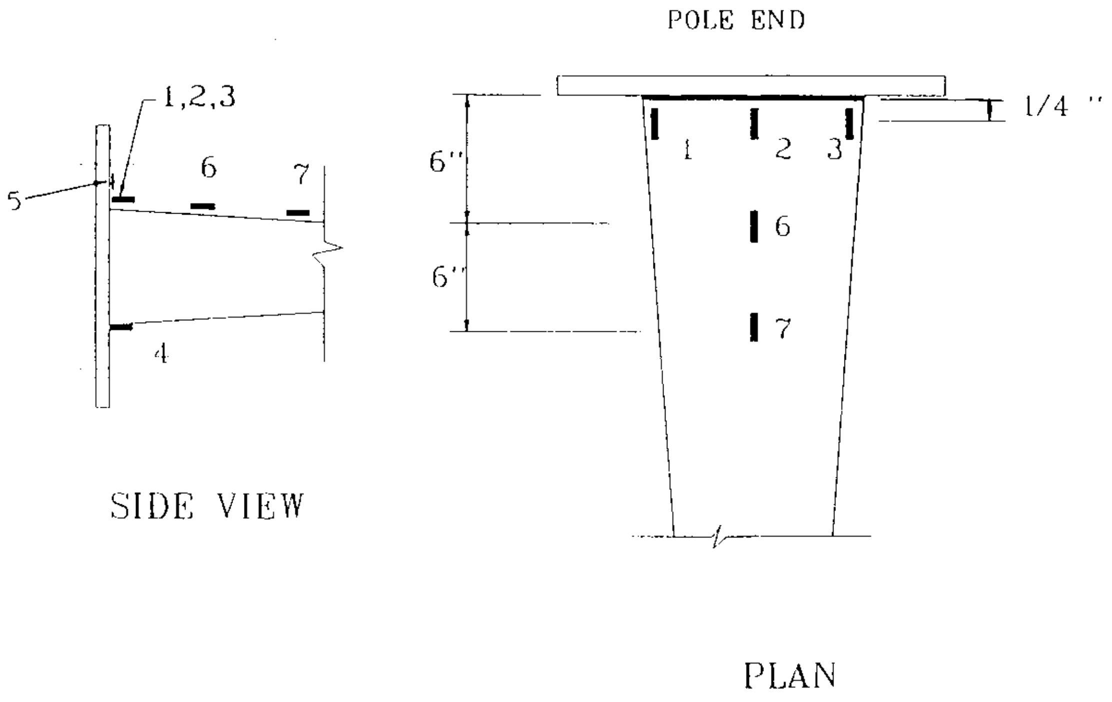


Figure 5.1. Location of strain gages

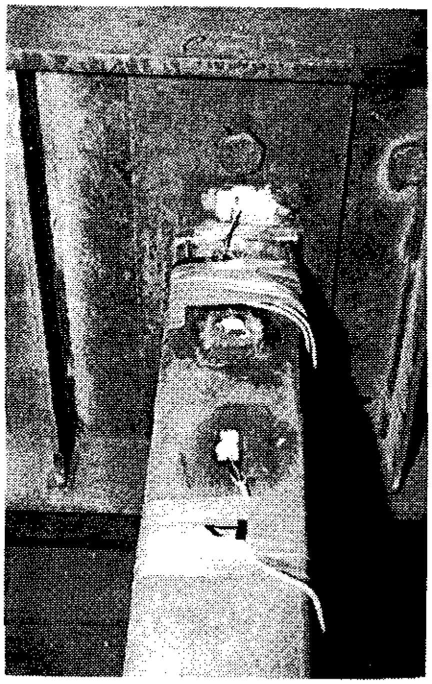


Figure 5.2. Strain gages at the connection

5.2.3 Test results

Prior to the application of the static loads, approximately 15 cycles of load with a magnitude of 1.0 kip were applied to the crossarm. The purpose of this cyclic loading was to ensure that all the connections were well seated in their positions and thereby avoid the possibility of any slip of the bolt and other components during the application of the loads.

Two cycles of static loads were then applied in steps of 0.50 kips upto 1.0 kip through the actuator at the end of the crossarm. At each load step the strains and the corresponding displacement were noted. The strain and the displacement readings have been tabulated in Table 1a and Table 1b in Appendix B.

It can be noted from these tables that an average vertical stiffness at the conductor end of approximately 1.0 kip/inch was observed. The approximate theoretical stiffness of the arm was calculated as approximately 1.5 kips/inch assuming the crossarm idealized as a fixed cantilever. The average measured stiffness was 1.0 kips/inch which is approximately 67% of the theoretical stiffness. The disparity in the stiffness could be attributed to the rotation of the support beam and to the bending of the arm base plate. This joint does not produce a total fixity because the connection is not designed as a moment connection.

It can be noted from Tables 1a and 1b of Appendix B that all of the measured strains next to the weld are less than the elastic strain of 1724 microstrains and on unloading, do not show any permanent strains. This clearly indicates the following:

1. The stresses were applied in the elastic range only.

2. Considering the peak value of the strain measured next to the weld on the top flange and the theoretical value of yield strain, one can compute the stress corresponding to the difference between these two strain values. In our case, this stress value would correspond to 367 microstrains (difference between 1357 and 1724 microstrains), which is calculated to be approximately 11 ksi. In can be concluded that the tensile residual stress, which can normally be expected to be present in the transverse direction (due to the process of welding, in the region next to the weld) can only be less than 11 ksi.

It was noted that the region next to the weld was subjected to strains much more than the theoretical strains while the strains measured at gages 6 and 7 located away from the weld showed strains near the theoretical value. The observed values of stress concentration at the different locations of the gages, for the first and the second loading cycles are tabulated respectively in Table 2a and Table 2b in Appendix B. It can be observed from these Tables that the that the stress concentration factors noted in gages 1, 2 and 3 range from 2.12 to 2.53 with an average of 2.35. The average stress concentrations noted at gages 6 and 7 are respectively 1.12 and 1.003. The presence of stress concentration in the base metal next to the fillet weld subjected to transverse stress field confirms the earlier conclusions.

This average value of 2.35 agrees well with the stress concentration value of 2.1 obtained from tests on lap plate type transverse load-carrying fillet-welded joints with a weld contact angle of 30 degrees [16].

A stress concentration factor of an average of 2.64 was noted at the bottom. It can be seen here that the stress concentration (compression) is greater at the bottom than at the top. This is due to the resistance offered by the web of the support beam to any rotation of the arm base plate, which results in straining the bottom flange in the region next to the weld. It can be observed from the tables that the strains measured at location 5 is much less than the yield strain and much less than the strains measured at other locations. As a detailed stress analysis for this location was not included in this study, the stress concentration factors were not calculated.

5.3 Fatigue Testing Procedure and Instrumentation

5.3.1 Testing Procedure

Tests were conducted with the objective of simulating galloping loads due to increasing wind speeds from 4 mph to 24 mph for a constant ice thickness of 0.30 inch. Wind speeds at an increment of 4 mph were chosen in this range. The loads corresponding to these wind speeds have been tabulated in Table 4.1. The crossarm was subjected to one hundred cycles of galloping load corresponding to each wind speed and strains were measured at the end of the cycling period. Strains at the connection were measured corresponding to zero load and the maximum load for a given wind speed. Vertical displacements at the conductor end corresponding to these loads were also measured.

The crossarm was then subjected to galloping loads corresponding to 26 mph until failure occurred. Strains at the connection and vertical displacements at the conductor end were measured at the end of 100 cycles, 2000 cycles and 4000 cycles.

5.3.2 Instrumentation

5.3.2.1 Load application It must be recalled that the pseudodynamic testing procedure was originally meant for cases where large dynamic effects are involved. In our case, the galloping loads do not produce any dynamic effect on the crossarm as discussed in the previous Chapter. Hence pseudodynamic testing was not performed using the STEX software. STEX software could not be used for the cyclic loading due to memory limitations in the computer. Hence the galloping loads were applied using the MTS testing system with the loads programmed from the analog console itself. During the tests, the function generator was programmed to produce sine waveforms of the galloping loads at the desired frequency of 0.417 Hz. This load was applied in addition to the static load of 1.02 kips at the conductor end of the crossarm.

5.3.2.2 Strain and displacement measurement

Electrical resistance strain gages mounted on the crossarm as described in Section 5.1.1 were used in this testing and the displacement measurements were made through the dcdt housed in the actuator.

5.4 Results of Fatigue Tests

5.4.1 Number of cycles to failure

As discussed earlier, fatigue loading to failure was applied on the crossarm corresponding to a wind speed of 26 mph. The crossarm started to develop a crack at the toe of the weld in the top flange at approximately 5700 cycles of load. It must be remembered that 600 cycles of load corresponding to increasing wind speeds was applied prior to this. The allowable number of cycles as per AISC code for the fatigue stress range pertaining to 26 mph, considering a stress concentration factor of 2.35 was calculated to be approximately 2400 cycles. This value cannot be strictly compared to the above observed number cycles to failure as this calculation is based on the assumption that only loads pertaining to 26 mph was applied. The allowable number of cycles was calculated based on a logarithmic regression of the allowable stress range values provided for Type C connection in AISC code [16].

5.4.2 Location of the crack

The observed crack is shown in Figure 5.3. It was observed in Section 3.5 that the weld is the most critical region under static loading conditions. However, it was observed in this test that the base metal failed (at the toe) and not the weld metal. This is in agreement with the theory based on fracture mechanics [16] which states that for fillet welds subjected to transverse axial loads, the plate is likely to fail when the nominal thickness of the fillet weld is greater than 1.2 times the plate thickness. In this test the fillet weld was 1.67 times the plate thickness.

5.4.3 Propagation of the crack

After approximately 6500 cycles substantial redistribution of stresses had taken place and the crack was

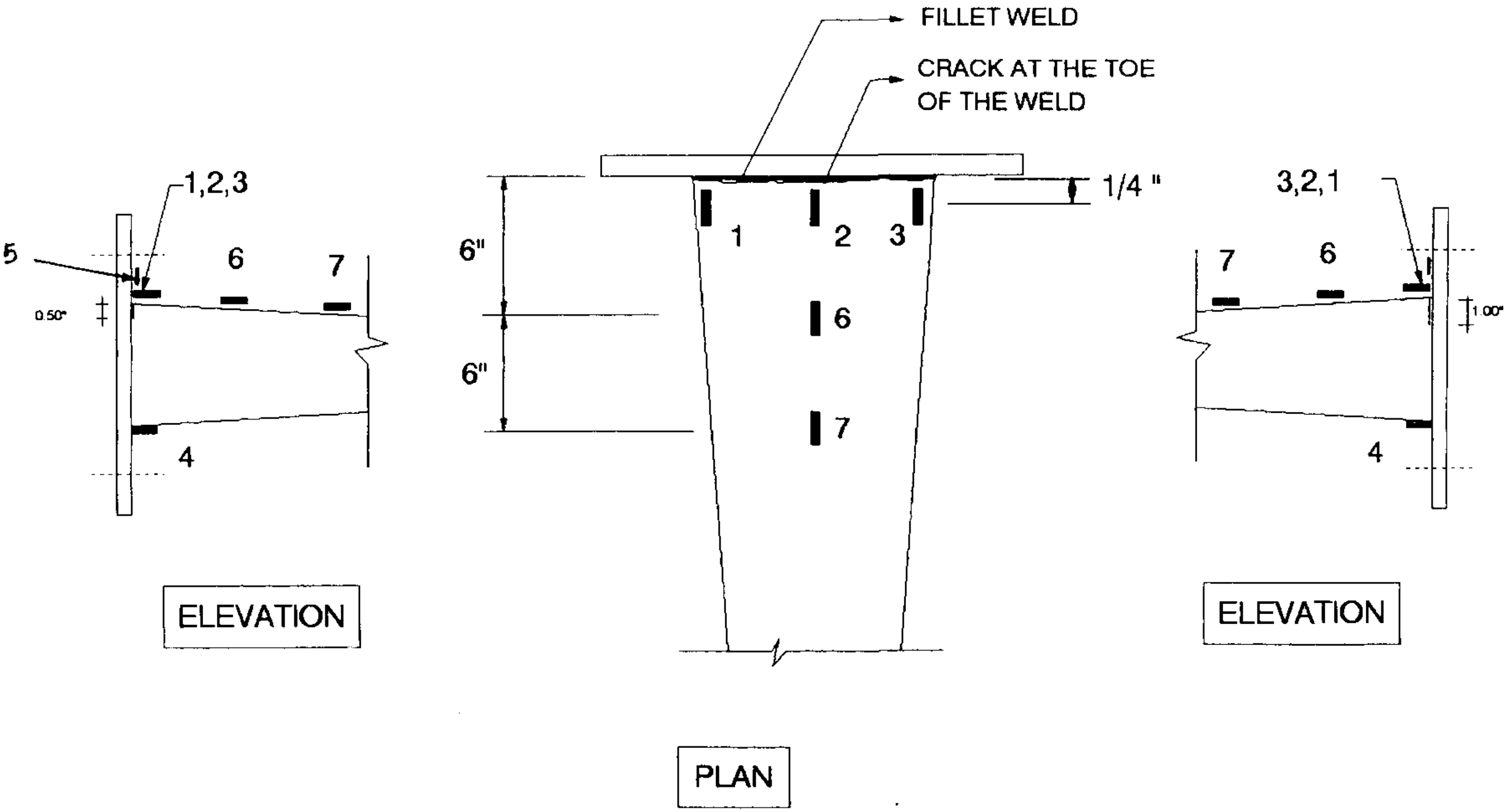


Figure 5.3. Details of the crack

seen to have extended across the entire width of the top flange and propagated well along the toe of the weld. Crack was also seen on the sides of the crossarm next to the weld. These details are shown in Figure 5.3. It was noticed that the crack had opened upto 1.0 inch below the top flange on the web adjacent to gage 3 while it had opened upto only 0.5 inch below the top flange on the web adjacent to gage 1. This is due to eccentric application of the load causing larger strains at gage 3 than at gage 1.

5.4.4 Strain observations

The strain readings measured at the end of the cyclic loadings corresponding to the maximum load and zero load are tabulated respectively in Table 3a and Table 3b in Appendix B. Although these results are not of primary interest they are presented here. Among the various observations that can be made from these strain values, the following observations are worth discussing:

1. There is a lack of symmetry in the strains at gage locations 1 and 3 for the applied loads. For example, for the load of 1.23 kips corresponding to the wind speed of 4 mph the strain at gage 3 is 1872 microstrains while it is 1530 microstrains at gage 1.

This was due to an unintentional eccentric loading of the crossarm. The actuator base was found to be set approximately

1.25 inch away from the center of the crossarm (at the connection) toward the direction of gage 3, producing an eccentric loading at an angle of approximately 1 degree and 19 minutes with negligible torsional effect. This has resulted in the discrepancy between the strains at locations 3 and 1. It must be recognized that in reality, these forces would more often be acting eccentrically producing unsymmetric bending with or without torsion.

2. An unsymmetrical bending analysis was performed to check the stress at location 1 due to the peak load corresponding to the wind speed of 4 mph. Calculations were made assuming that this location is still in the elastic range of stress. The theoretical stress corresponding to the peak load was calculated to be equal to 19.7 ksi while the stress corresponding to the measured strain of 1530 microstrains is approximately 44 ksi. This corresponds to a stress concentration of 2.23 which is close to the average value of 2.35 calculated from the preliminary static test results.

3. Table 10.3b shows strains corresponding to zero load at locations 6 and 7 at different wind speeds. These strains are created by virtue of the connection of the crossarm with the actuator. The possibility of the presence of permanent strains due to strains crossing the yield point can be ruled out because the strains corresponding to the maximum load observed at these locations are well below the yield strain

and there is no chance of any tensile residual stress occurring at this location.

It can be concluded that in the light of the objectives of this experimental study, there is not much useful information that can be derived from these strain readings. Hence, they are not discussed in detail.

6. SUMMARY AND CONCLUSIONS

6.1 Summary

This project had two major objectives. The first major objective was to validate the recently-acquired MTS Seismic and Pseudodynamic Testing System and to produce an example manual for the guidance of the future users. The second major objective involved a preliminary experimental study of the crossarm behavior to forces from galloping conductors using the MTS testing system. The research began with a literature study to understand the procedure of pseudodynamic testing method and its applications, for the purpose of validating the testing system. A literature review was also conducted to understand the phenomenon of galloping, the damage caused to the supporting structures and discover information on research involving the study of crossarm behavior to forces from galloping conductors. The review revealed that extensive damage is caused to the supporting structures during galloping. It also revealed that failures of the welded and bolted connections of the crossarm with the support pole were very common. No such study was found in the literature.

The validation process of the testing system initially involved the fabrication and assembly of the testing frame and connection of the hardware of the testing system. Secondly, it involved checking the working of STEX software and communicating with MTS Systems Corporation to correct the same. It then involved the execution of a series of uncompensated, compensated and pseudodynamic tests on simply supported steel beams using different forcing functions such as rectangular, ramp and sinesweeps. The experimental results were compared against the theoretical results which aided in understanding the limitations and capabilities of the testing system. The conclusions regarding the limitations are available in Section 6.2.1.

The experimental study of the crossarm behavior to galloping conductors was conducted on a crossarm obtained from Iowa Electric Light and Power Company, Ceder Rapids. A pole support system was defined for this crossarm and the section was checked for compliance with the strength requirements of AISC [17] for the load requirements of NESC [4]. Environmental data conducive for galloping based on observations in the past were assumed and the vertical dynamic force due to galloping at the pole end of the crossarm was calculated using an algorithm developed recently at Iowa State University [5].

The testing of the crossarm consisted of two phases. In the first phase, two cycles of static loads were applied with the objective of understanding the magnitude of stress concentrations (next to the weld) and the vertical stiffness at the conductor end. In the second phase of testing, the crossarm was subjected to forces from galloping conductors due to increasing wind speeds (considering a constant radial ice thickness) for a specified number of cycles with the forces applied using the MTS Testing System. The crossarm was then subjected to galloping forces due to a relatively high wind speed until failure occurred. These phases of tests were conducted with the objective of studying the stress concentrations next to the weld, the number of cycles to failure and the mode of failure. The conclusions are available in Section 6.2.2.

6.2 Conclusions

6.2.1 Validation of MTS testing system

The testing system was validated as per the objectives and the Example Manual was also produced.

The limitations and capability of the testing system under the various testing options are provided below:

6.2.1.1 Uncompensated and compensated testing

1. The limitations and capabilities of the testing system for a given forcing function, in a compensated or uncompensated testing, are governed by: the degree of calibration of the electronics contained in the analog and digital console, the frequency versus amplitude response of the servovalve, the capacity of the hydraulic distribution system and the system dynamics of the testing frame.

2. It was noticed that when using relatively fast rectangular pulses, the system performed better for longer duration of the pulse but it was not responding swiftly.

3. In trial tests using ramp functions, the system was not responding swiftly but was producing the maximum displacements close to the theoretical values.

4. Tests with sinesweep indicated that the system gives priority to maintaining the frequency rather than the specified amplitudes and the achieved amplitudes were dictated by the limitations discussed in item 1 of this subdivision.

5. A good calibration of the electronics generally improves the performance of the system by generating and sending servovalve signals close to the specified signals. But a swift performance of the system is dependent on the capacity of the servovalve. This performance can be improved by the use of a higher capacity servovalve.

6. The frequency versus amplitude response of the system, when using functions such as sinusoidal functions, can be improved by the process of compensation within the limitations of the servovalve.

6.2.2.2 Pseudodynamic testing Trial tests were conducted using ramp signals with varying damping coefficients and the following was observed:

The trial tests revealed a close agreement of the results with the theoretical values. The maximum response and the time of maximum response agreed well with analytical results.

6.2.2 Preliminary experimental study on crossarm behavior

It must be remembered that before making any definite conclusions on the behavior of crossarms, a large number of tests need to be conducted to validate the consistency of the results and to understand the scatter in the test results. However, the following conclusions are made from the observations:

1. The galloping load does not produce any dynamic load amplification due to the fact that there is a large difference in the magnitude of the frequency of galloping and that of the bending of the crossarm. Hence, it produces only fatigue stresses at the connection.

2. In designing the crossarm for fatigue stresses, one needs to consider the stress concentration factor due to the change in the geometry of the section. For a fillet weld with a weld contact angle of 30 degrees, the stress concentration factor was observed to be 2.35.

3. In addition to the stress concentration factor, the designer needs to consider the tensile residual stresses which are likely to be present near the weld in the longitudinal direction of the crossarm. It has been stated in reference 15 that normally the residual stresses in the neighborhood of a transverse weld will reach the yield point magnitude,

definitely in the longitudinal direction and often in the transverse direction.

4. It can be recognized that NESC overload capacity factors do not provide adequate safety against galloping. As it was illustrated, a crossarm which is designed as per NESC is likely to fail during a galloping event depending on the severity of the wind and ice loads, as the overload factor is not sufficient to define the magnitude of the vertical force due to galloping. Although fatigue stresses can also occur due to eolian vibrations, it must be recognized that these are high frequency low amplitude vibrations which do not produce stresses as high as those produced during galloping.

5. From the number of cycles (5700) withstood by the crossarm before failure, it can be said that the same crossarm, in a real situation, with a wind speed of 26 mph and a radial ice thickness of 0.3 inch, would have failed after galloping for approximately 3 hours and 45 minutes.

6.3 Recommendations

6.3.1 Validation of MTS testing system

1. The electronics of the testing system should be recalibrated.

2. Further trial tests should be conducted with a higher capacity servovalve using the same forcing functions and test specimens as used in this study to determine the increase in

the performance of the system.

6.3.2 Study of crossarm behavior to galloping forces

1. It is understood from the sensitivity study done in Section 4.3 that for a given geometry and material property of the pole support system, the radial ice thickness and the wind speed are the only two factors which influence the galloping load on the crossarm. Hence studies need to be done to arrive at suitable values of these parameters, based on probabilistic approach, for different service areas. These values can be used by the designer in quantifying the galloping loads using the recently developed algorithm.

2. Further experimental studies could be conducted on crossarms using complete penetration groove welds, which when properly welded will reduce the abrupt change in the geometry of the section and thus help in reducing the concentration of stress.

3. Further studies could be conducted to quantify the residual stress in the transverse direction of the weld which contributes to limiting the fatigue life. This study may also explore the effect of surface heat treatment procedures such as nitriding or carburizing which effectively introduce nitrogen and carbon into the surface of steel. They have an effect of introducing residual compressive stresses on the surface thus improving the fatigue behavior of the flexural

member [10].

4. In future tests, the support beam and the joints could be designed such that the bending stiffness of the test support matches with the axial stiffness of the pole and its rotational stiffness matches with the rotational stiffness of the pole being simulated.

5. As ordinary foil strain gages would not yield a high fidelity rate especially when conducting fatigue tests where large strains are involved, special strain gages such as the S-N strain gage should be used.

6. As the value of the modulus of elasticity may not be the same as the theoretical value for A588 steel, a steel coupon best representing the plate (out of which the test specimens are made) should be subjected to tensile test to determine its actual value.

BIBLIOGRAPHY

1. S. J. Fang and K. D. Simpson. "Dynamic effects ongalloping conductors." Transmission and Substation Conference, Sargent & Lundy, Chicago, Dec. 1978.
2. R. R. Gibbon, P. H. Juul, H. B. White, and W. J. Wijker. "Damage to overhead lines caused by conductor galloping." Electra, 94 (May 1984): 71-76.
3. Personal conversation of M. B. Thomas, Iowa State University with G. A. Cook, Iowa Electric Light and Power Company, Cedar Rapids, Iowa.
4. IEEE. "National electrical safety code." IEEE Inc., New York, 1987.
5. Li Li. "Dynamic loads on pole transmission line structures from galloping conductors." M.S. Thesis, Iowa State University, Ames, Iowa, 1990.
6. Personal conversation of J. Muniyandi, Iowa State University with G. A. Cook, Iowa Electric Light and Power Company, Cedar Rapids, Iowa.
7. Report of Study conducted at Iowa State University, sponsored by Iowa Power, Des Moines, Iowa, Spring 1990.
8. P. B. Shing and S. A. Mahin. "Pseudodynamic test method for seismic performance evaluation: Theory and implementation." UCB/EERC-84/01, Earthquake Engineering Research Center, University of California, Berkeley, 1984.

9. AISC. "Manual of steel construction." AISC, Inc., Chicago, 1984.

10. C. A. Keyser. "Materials science in engineering." Charles E. Merrill Publishing Company, Columbus, Ohio, 1974.

11. Sample design load sheet provided by Iowa Electric Light and Power Company, Cedar Rapids, Iowa.

12. EPRI. "Transmission line reference book." EPRI, Palo Alto, California, 1979.

13. S. G. Krishnasamy. "Wind and ice loads on overhead transmission lines." Ontario Hydro Research Review 3 (June 1981): 11-18.

14. CABLE, a software developed by M. B. Thomas, Iowa State University, to perform static analysis on a catenary.

15. Welding Handbook. American Welding Society, Miami, FL, 1987.

16. T. R. Gurney. "Fatigue of welded structures." Cambridge University Press, Cambridge, 1979.

17. AISC. "Manual of steel construction." AISC, Inc., Chicago, 1989.

18. MTS. "MTS seismic test execution software manual." MTS, Minneapolis, Minnesota, 1990.

ACKNOWLEDGMENTS

Dr. Terry J. Wipf, my major professor provided me with invaluable guidance, support and encouragement throughout the research. Dr. Mardith B. Thomas provided ample guidance in defining the problem for the experimental investigation of the crossarm. Dr. Frederick Graham helped very much in interpretation of the experimental results. Dr. Lowell F. Greimann provided good suggestions in the drafting of the interim report on this project submitted to Electric Power Research Center.

Douglas Wood helped me to get familiar with the MTS control systems and was available for troubleshooting throughout the length of the project. Gordon C. Cook of Iowa Electric and Power company helped the research by providing a prototype crossarm. His help was very timely and came in at a crucial moment.

Acknowledgements are also due to my friends who helped with the wordprocessing and deposition of my thesis. Finally, I thank my wife Shanthi who patiently waited in India for me to get back and marry her.

APPENDIX A: EXAMPLE MANUAL FOR MTS TESTING SYSTEM

INTRODUCTION

HOW DO I LEARN TO USE STEX SOFTWARE ?

1. Familiarize yourself with the system hardware components, initialization and operation of the STEX software. This information is available in the first three sections of MTS SEISMIC TESTING EXECUTION SOFTWARE manual.

2. Familiarize yourself with the eight different libraries (A library is a module where a specific function is done such as defining the system, or creation of a profile, or running a test) available in the STEX software. Information for each of the library is available in the rest of the sections of the STEX manual. This is best done by having a hands-on practice while going through this manual.

3. Now you are ready to go through this document in your hand. It is very important for the user to go through and understand Part I of this manual, which explains in detail most of the common tasks and set-ups of the hardware and the software involved in both the real time and the pseudodynamic tests.

BEFORE YOU START ON THE STEX MANUAL

1. As you go through the STEX manual, you will notice that some of the screens shown would not be the same as available in the libraries of the STEX software. This is because the manual has been set up to suit the general requirement and the STEX software at ISU differs slightly from this. Effort has been taken in this document to point out these differences as you go through.

2. There is a Glossary of the terms used in the STEX manual available in the section named GLOSSARY . This would explain the meaning of most of the key terms used in the manual. You can understand the meaning of those terms not found in the GLOSSARY when you go through the examples illustrated in this document. As the information provided in the STEX manual in completely omitted in this document to avoid any repetition, the user is urged to be familiar with STEX manual.

WHAT CAN I FIND IN THIS DOCUMENT ?

1. This document illustrates on how to use the various libraries to perform the following three major operations.
   (a) Setting up a test
   (b) Running the test and
   (c) Analyzing the post-test data.

2. Illustrations are present for Real time Dynamics and Pseudodynamic tests. The document has been divided into the following three parts.

Part I : Uncompensated Real time test.
Part II : Compensated Real time test.
Part III: Pseudodynamic test.

HOW TO SET-UP THE SYSTEM DATA

The following information should be considered while setting up the SYSTEM DATA during initialization of the database (this word refers to the sub-directory).

A **frame** can be visualized to be a block of signals on the graph whose length depends on the number of points (N) chosen. Fourier transforms are performed on such blocks of data. When random signals are created, the pattern is repetitive in each frame. Generally 1024 points per frame can be selected. **This number affects the frequency resolution as explained below.**

The **leading zeros** are the points that precede the exciting signal during excitation. These are essential when the drive signal needs to be compensated to create a new drive signal which would attempt to produce a desired signal. This would mean advancing the drive signal, into the zone of the leading zeros, to compensate for any time delay that is due to the system hydraulics, electronics of filter etc.,

$$\text{Sampling rate}(R) = \frac{1}{\text{Time resolution}(\wedge_t)}$$

$$\text{Nyquist frequency}(N_y) = \frac{1}{2*\text{Time resolution}}$$

$$\text{Frequency resolution}(\wedge_f) = \frac{N}{(N_y/2)}$$

The **time resolution** and **frequency resolution** need to be equal to or less than the smallest time and frequency that will be used in the entire database.

CAUTION: The **Nyquist frequency** has to be always greater than the cut-off frequency specified for the filter in the SD library. This caution is repeated in the SD library.

Test startup delay may normally be set at 5 seconds.

CAUTION: This is the only entry that can be edited once the database has been established. Hence considerable thought needs to be given before initializing a database depending on the requirements of the tests to be performed from that database.

PART I

REAL TIME DYNAMIC UNCOMPENSATED TEST

INTRODUCTION: This part will illustrate, with an example test, how to perform the following three major tasks for an **uncompensated** test.

(i) Test set-up (Section 1).
(ii) Hardware set-up and Test execution (Section 2).
(iii) Post-test analysis (Section 3).

SECTION 1

The following example illustrates the execution of an uncompensated test run on the premise that the drive signal will not demand any compensation. In Part II an example has been provided which illustrates the need for compensated tests, the test set up and execution procedure.

TEST SPECIMEN SET-UP: The test structure set up consisted of a simply supported beam of W 10X22 as shown in the Figure 1.1.

DYNAMIC LOAD: Consider the excitation signal as shown in Fig.1.2. It is an exponentially varying sine wave whose frequency varies from 0.2 to 10 Hz and again from 10 to 0.2 Hz over a time period of 40.0 sec. The single amplitude of the load waveform varies from 4.0 kips at the ends to 0.8 kips in the middle.

STEPS INVOLVED IN SETTING UP AN UNCOMPENSATED TEST

STEP 1. Determine the system configuration and create a System Definition. This is done in the **System Definition library.**

STEP 2. Identify the desired drive signal and create a time history for each of the selected control axis. This is done in the **Data Analysis library.**

STEP 3. Create a profile for each of the selected control axes from the time history function created in the Data Analysis library. This is done in the **Profile library.**

STEP 4. Define the test in the **Earthquake Testing library** by defining the system definition and the profile.

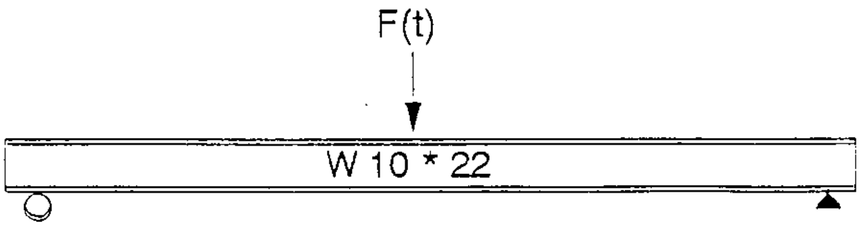


Figure 1.1 Test setup

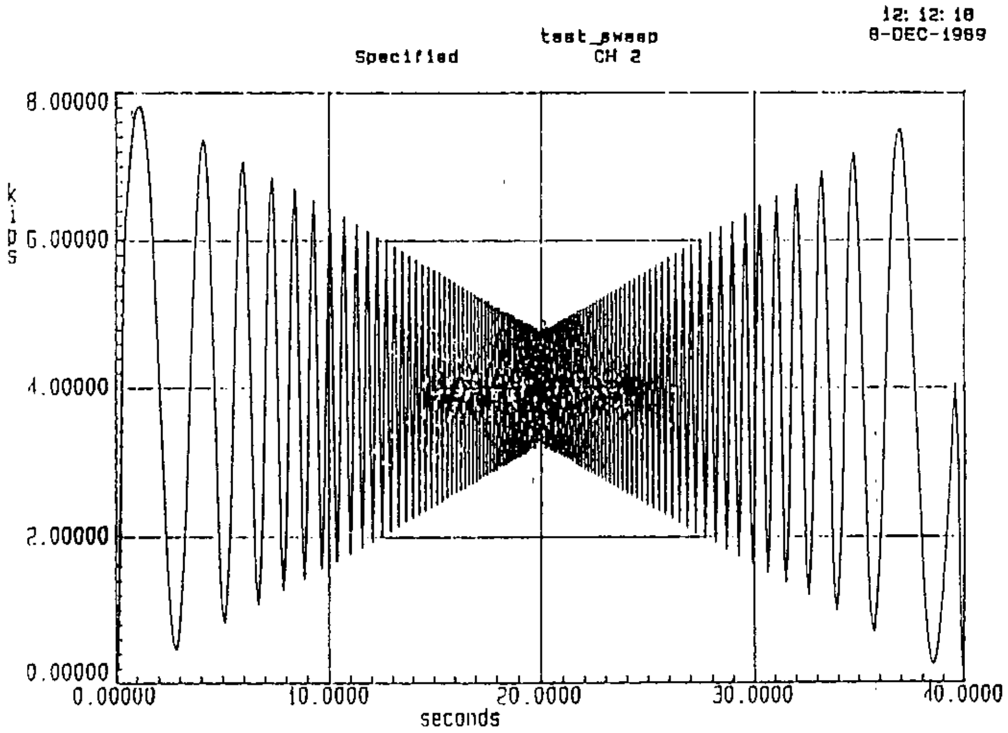


Fig. 1.2

STEP 1. CONFIGURING THE SYSTEM

This is also called defining the system.This is done in the **SYSTEM DEFINITION LIBRARY** opted from the 'Main Control Options' . It consists of the following major tasks.

A. CONTROL AXIS ENTRY: This consists of
(i) Selection of the control axes or channels.
(ii) Defining the Command, Feedback, and the Additional feedback data.

B. SPECIMEN TRANSDUCER ENTRY: This consists of defining the various external transducers set on the specimen such as strain gauge, dcdt etc.,

A.CONTROL AXIS ENTRY

The selection of the control axis is done in the dialog **D SD.2**. For this example test the channel chosen is '2'. It looks as shown in Fig. 1.3.

The dialogs **D SD.3** and **D SD.4** help us in defining the modes of the Command, Feedback and Additional feedback signals, and defining the filter parameters for each signal.

The dialogs **D SD.3** and **D SD.4** for our example are set as shown in Figures 1.4 and 1.5.

The various parameters involved in these dialogs are explained below.

Mode: This can either be LOAD or STROKE only. The appearance of the terms 'acceleration' and 'velocity' in the STEX manual can be ignored. For real time dynamic tests the driving force (command mode) may be in terms of either of the modes. The mode of the feedback data and the additional feedback data may also be of either of these.

Units: The units of the load and stroke need necessarily be in 'kips' and 'inches' respectively. Make sure there is no spelling mistake in specifying the units.

Full Scale: This is the maximum load or stroke which can be attained during the excitation. This depends on the controller that is available in the analog console, the capacity of the servovalve and the actuator. In the 443 controller the full scales available for the load are 55, 30, 10, 5 kips, and those for the stroke are 3, 1.5, and 0.6 inches.

The accuracy of the test result depends to some extent on the selection of this scale. **This should be selected such that the selected scale is just greater than the maximum load or stroke encountered in the test.**

```
                                  D SD.2
Select axis (or channel) to be edited : 2

        Axis ID - Axis

              1 - CH 1
              2 - CH 2
```

Fig. 1.3

```
                                                     D SD.3
  Edit the following data for the CH 2
  control axis as appropriate.

COMMAND DATA
     Mode        : Load
     Full Scale  : 10.0000
     Units       : kips
     Filter -
       Gain      : 1.000    (0.000, 1.000, 0.500, 0.200)
       Cutoff    : 40 Hz    (Bypass, 40, 80, 160, 240)
       Coupling  : DC (0Hz) (DC (0Hz), AC (5Hz))

FEEDBACK DATA
    Mode        : Load
   {Full Scale} : 10.0000              {  Used only if the command and   }
   {Units     } : kips                 { feedback modes are not the same }
    Filter -
      Gain      : 1.000    (0.000, 1.000, 2.000, 5.000)
      Cutoff    : 40 Hz    (Bypass, 40, 80, 160, 240)
      Coupling  : DC (0Hz) (DC (0Hz), AC (5Hz))
```

Fig. 1.4

```
                                                        D SD.4
  Specify additional feedback channels as desired.


                    Stroke

Acquire Data     :  Yes

Full Scale       :  3.00000
Units            :  inches

FILTER  Gain     :  1.0000
        Cutoff   :  40 Hz
        Coupling :  DC (0Hz)


    Gain values are selected from (0.000, 1.000, 2.000, 5.000)
    Cutoff values are selected from (Bypass, 40, 80, 160, 240)
    Coupling options are selected from (DC (0Hz), AC (5Hz))
```

Fig. 1.5

Filters: These are the electronic components housed in the digital console which filter off the unwanted signals of high frequency that accompanies the load or the stroke signal. The parameters that require selection are the gain, cutoff and the coupling values.

1. **Gain:** This can normally be set at 1.000

2. **Cutoff:** This frequency should be **greater** than the highest frequency of the signals involved in the test and **lower** than the **Nyquist frequency**.
   For a **Pseudodynamic test** (dealt in Part II) this needs to be bypassed. Then select 'bypass'.

3. **Coupling:** 'DC (0 Hz)' may be normally selected.

B. SPECIMEN TRANSDUCER ENTRY.

This consists of specifying the following items.

(i) Specimen Transducer input data channel parameters.
(ii) Conditioner gain range.
(iii) Description of the transducer and selection of the data channel.

The example test uses an axial strain gauge(named as sg_cp) and a dcdt(named as cp_dcdt). The dialogs corresponding to the definition of these two transducers are shown from Figs. 1.6 through 1.12.

The specimen transducer input data channel parameters consists of the filter parameters seen earlier. This entry is made in **D SD.5A**. For our example test this is set up as shown in Fig. 1.6. The instructions given earlier hold good in choosing the values here.

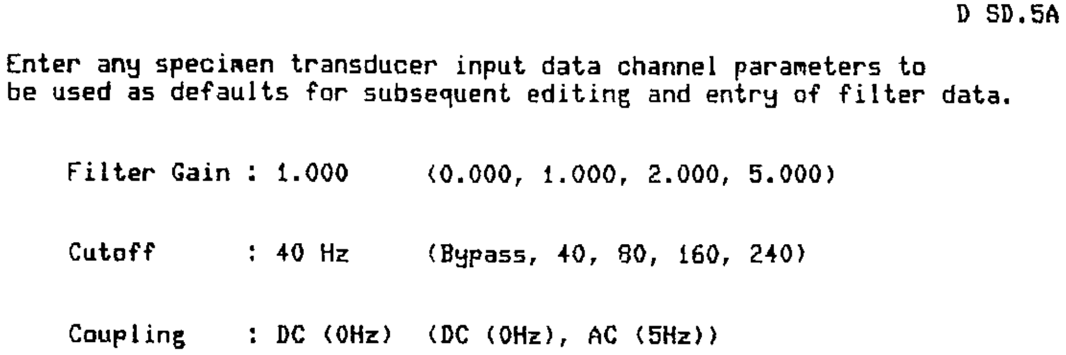
The Conditioner gain range can be normally set at '1' in **D SD.5B** as shown in Fig. 1.7.

The data from the above two dialogs are used as default values for all the transducers used for the test.

The name of the transducer and the type are entered in **D SD.6** as shown in the Figure 1.8.

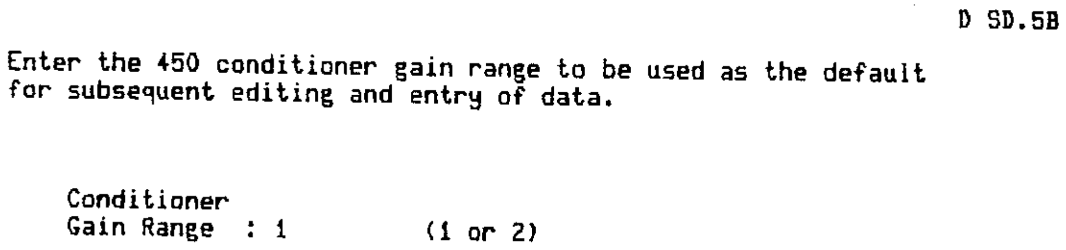
Note: The second portion of this dialog consisting of the entries of the 'descriptor' and the 'type' is displayed on the screen once the name of the transducer is entered. **'dcdt' falls in type # 6.**

At this stage the external transducers should have been calibrated



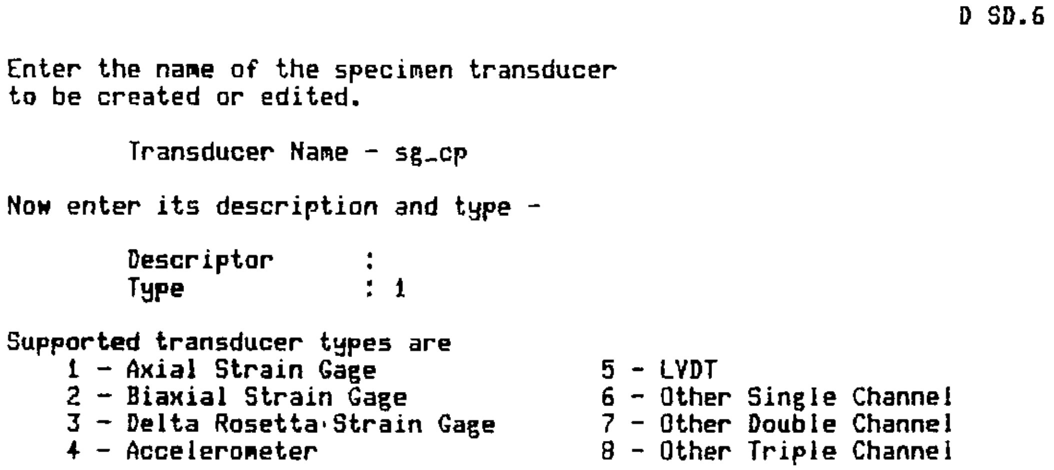
```
                                                            D SD.5A

Enter any specimen transducer input data channel parameters to
be used as defaults for subsequent editing and entry of filter data.


    Filter Gain : 1.000     (0.000, 1.000, 2.000, 5.000)


    Cutoff      : 40 Hz     (Bypass, 40, 80, 160, 240)


    Coupling    : DC (0Hz)  (DC (0Hz), AC (5Hz))
```

Fig. 1.6



```
                                                            D SD.5B

Enter the 450 conditioner gain range to be used as the default
for subsequent editing and entry of data.


    Conditioner
    Gain Range  : 1         (1 or 2)
```

Fig. 1.7



```
                                                            D SD.6

Enter the name of the specimen transducer
to be created or edited.

        Transducer Name - sg_cp

Now enter its description and type -

        Descriptor      :
        Type            : 1

Supported transducer types are
    1 - Axial Strain Gage               5 - LVDT
    2 - Biaxial Strain Gage             6 - Other Single Channel
    3 - Delta Rosetta Strain Gage       7 - Other Double Channel
    4 - Accelerometer                   8 - Other Triple Channel
```

Fig. 1.8

and the calibration results available.

The transducer parameters are to be entered in **D SD.7**. This is shown in Fig. 1.9. It contains the following parameters.

Descriptor : Any related information such as the position of the transducer etc., may be entered here.

Channel number: This refers to the number of the channel to which to the transducer is hooked to, on the 450 INTERCONNECTOR BOX. This box is in turn connected to the 450 QUAD CONDITIONER, housed in the Digital console. This conditioner is capable of handling twenty eight transducers. The first four channels serve the two actuators, two each.
For the example test the strain gauge and the dcdt are hooked to channels 9 and 10 respectively.

Full scale: The full scale of each transducer, both internal (located in the actuator) and external(which is optional), is 10 volts, in electrical units. Hence the full scale of the particular external transducer,expressed in physical units should correspond to 10 volts.

Units: This is the physical unit of the full scale of the transducer. Units such as ' inches' or ' micro strains'.
In the example test, the electrical units were used, as the transducers were not calibrated at the time of the test.

Once the entry of **D SD.7** is over, pressing ENTER enables the display of **D SD.7** with the default filter and conditioner range information together in **D SD.7E**. For our example this dialog is shown in Fig. 1.10. One additional information which is required to be given in this dialog is ' Shunt Calibration' which can be set to 0.0000.

The same procedure is repeated to define another transducer.

In the example test a dcdt named cp_dcdt was also used. The Figs. 1.11 & 1.12 correspond to this transducer.

This completes the procedure of defining the system.

CHECKING THE SYSTEM DEFINITION

The **SHOW option** available in **M** SD.2 allows you to check the contents of a definition. The dialog **D SD.10** enables listing of all the definitions or any particular one as shown in Fig 1.13.
A listing of all the definitions set for the example tests are shown in Figs. 1.14 through 1.16.

D SD'7

```
   Edit the following data for sg

Descriptor              SG_CP____________

Channel Number        : 9        (1  .. 32 )
Full Scale            : 10.0000
Units                 : volts
```

Fig. 1.9

D SD.7

```
   Edit the following data for sg

Descriptor               SG_CP

Channel Number        : 9        (1  .. 32 )
Full Scale            : 10.0000
Units                 : volts


FILTER       Gain     : 1.000
             Cutoff   : 40 Hz
             Coupling : DC (0Hz)

CONDITIONER  Range    : 1
             Shunt Cal : 0.00000

   Gain values are selected from (0.000, 1.000, 2.000, 5.000)
   Cutoff values are selected from (Bypass, 40, 80, 160, 240)
   Coupling options are selected from (DC (0Hz), AC (5Hz))
   Conditioner range values - DC ( 1 or 2 )   AC ( 1, 2, 3 or 4 )
   Conditioner shunt cal is % full scale for DC, ignored for AC
```

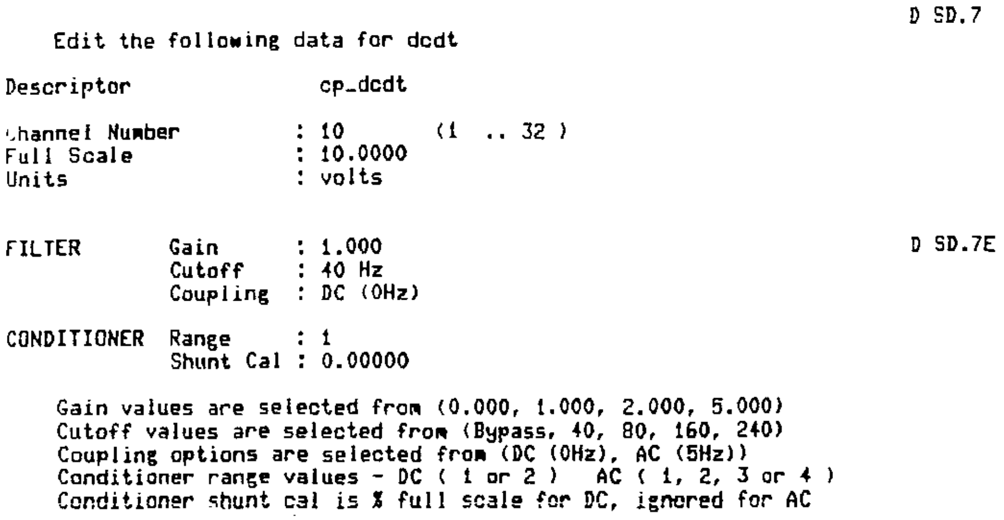
D SD.7E

Fig. 1.10

D SD.7

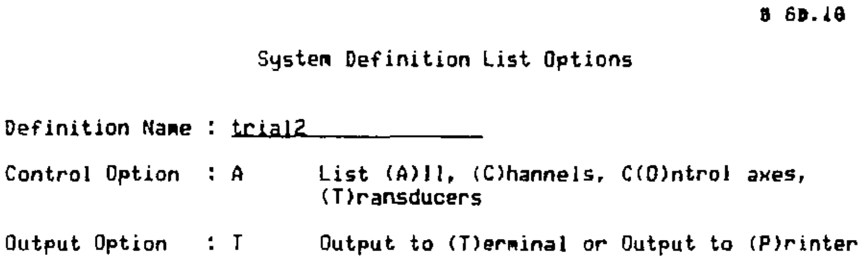
```
   Edit the following data for dcdt

Descriptor              cp_dcdt__________

Channel Number        : 10       (1  .. 32 )
Full Scale            : 10.0000
Units                 : volts
```

Fig. 1.11



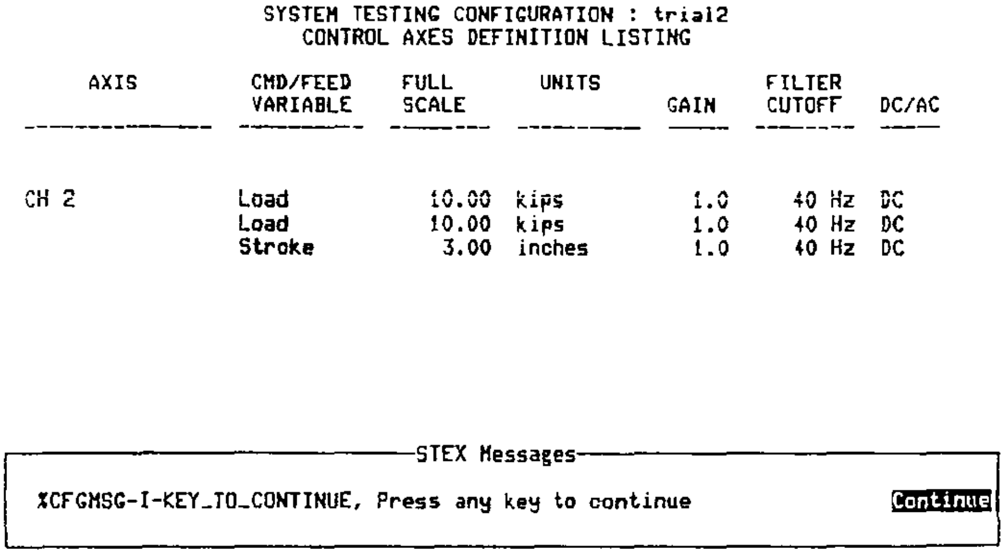
```
                                                                     D SD.7
   Edit the following data for dcdt

Descriptor               cp_dcdt

Channel Number          : 10       (1  .. 32 )
Full Scale              : 10.0000
Units                   : volts


FILTER       Gain       : 1.000                                      D SD.7E
             Cutoff     : 40 Hz
             Coupling   : DC (0Hz)

CONDITIONER  Range      : 1
             Shunt Cal  : 0.00000

    Gain values are selected from (0.000, 1.000, 2.000, 5.000)
    Cutoff values are selected from (Bypass, 40, 80, 160, 240)
    Coupling options are selected from (DC (0Hz), AC (5Hz))
    Conditioner range values - DC ( 1 or 2 )   AC ( 1, 2, 3 or 4 )
    Conditioner shunt cal is % full scale for DC, ignored for AC
```

Fig. 1.12



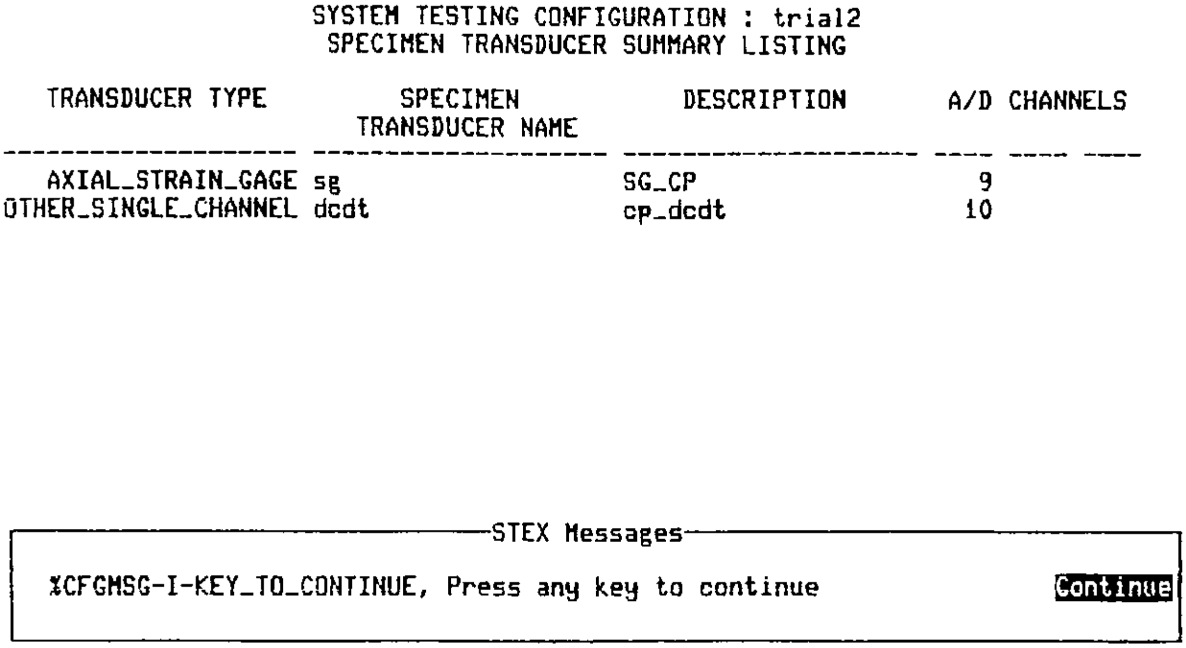
```
                                                            D SD.10

                     System Definition List Options


    Definition Name : trial2

    Control Option  : A      List (A)ll, (C)hannels, C(O)ntrol axes,
                             (T)ransducers

    Output Option   : T      Output to (T)erminal or Output to (P)rinter
```

Fig. 1.13



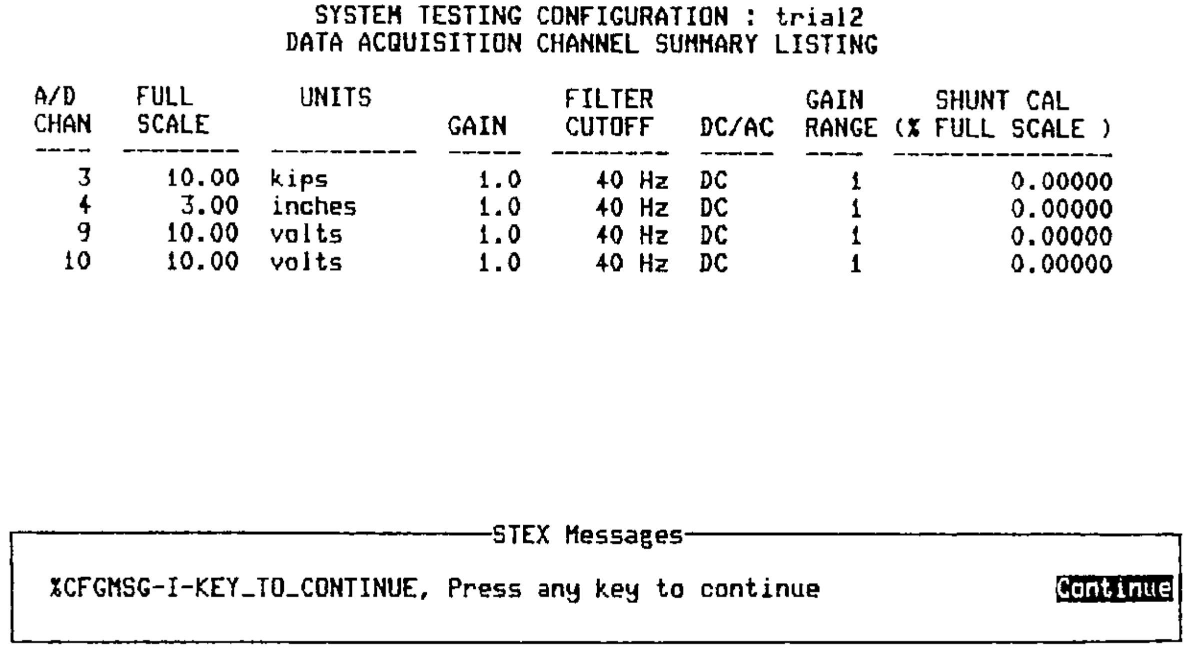
```
                   SYSTEM TESTING CONFIGURATION : trial2
                      CONTROL AXES DEFINITION LISTING

        AXIS          CMD/FEED    FULL       UNITS               FILTER
                      VARIABLE    SCALE                   GAIN   CUTOFF    DC/AC
  --------------     ----------  --------  ----------    -----  --------  -----


  CH 2               Load          10.00   kips           1.0    40 Hz    DC
                     Load          10.00   kips           1.0    40 Hz    DC
                     Stroke         3.00   inches         1.0    40 Hz    DC




--------------------------------STEX Messages-----------------------------------

 %CFGMSG-I-KEY_TO_CONTINUE, Press any key to continue                  Continue

--------------------------------------------------------------------------------
```

Fig. 1.14



```
                    SYSTEM TESTING CONFIGURATION : trial2
                     SPECIMEN TRANSDUCER SUMMARY LISTING

   TRANSDUCER TYPE          SPECIMEN          DESCRIPTION       A/D CHANNELS
                         TRANSDUCER NAME
-------------------- ------------------- ------------------- ---- ---- ----
   AXIAL_STRAIN_GAGE sg                  SG_CP                  9
OTHER_SINGLE_CHANNEL dcdt                cp_dcdt               10



 ----------------------------------STEX Messages-----------------------------------
|                                                                                  |
| %CFGMSG-I-KEY_TO_CONTINUE, Press any key to continue                     Continue|
|                                                                                  |
 ----------------------------------------------------------------------------------
```

Fig. 1.15



```
                    SYSTEM TESTING CONFIGURATION : trial2
                  DATA ACQUISITION CHANNEL SUMMARY LISTING

 A/D   FULL      UNITS              FILTER          GAIN    SHUNT CAL
 CHAN  SCALE                 GAIN   CUTOFF   DC/AC  RANGE (% FULL SCALE )
 ----  -------  ---------    -----  -------  -----  ----  ---------------
   3    10.00  kips           1.0    40 Hz   DC       1          0.00000
   4     3.00  inches         1.0    40 Hz   DC       1          0.00000
   9    10.00  volts          1.0    40 Hz   DC       1          0.00000
  10    10.00  volts          1.0    40 Hz   DC       1          0.00000



 ----------------------------------STEX Messages-----------------------------------
|                                                                                  |
| %CFGMSG-I-KEY_TO_CONTINUE, Press any key to continue                     Continue|
|                                                                                  |
 ----------------------------------------------------------------------------------
```

Fig. 1.16

STEP 2. CREATION OF THE TIME HISTORY

The time history of the excitation signal is created in the **DATA ANALYSIS** library.
The important operations that can be performed in this library are listed below.

1. Analyzing data.
2. Creating functions
3. Plotting analyzed data and creating functions.
4. Accesing other data or functions.
5. Listing other STEX libraries.

Each of the above functions has been explained in the STEX manual in the section **DA** .

The commands which are available to perform the above functions can be broadly classified into the following categories.

1. Data Analysis commands.
2. General commands.
3. Function Creation commands.
4. Assignment or Access commands.
5. Listing commands.

The summary of the above commands are available in the dialogs **D DA.3**, **D DA.4** and **D DA.5** and are reproduced on Figs. 1.17a through 1.17c.

The operation and the dialog entry information for each of the above commands is explained in the STEX manual in the section **DA.**

Examples of creating some basic forcing functions are given below.

Figures 1.18a and 1.18b illustrate the definition of a rectangular time history function using **CTH** (Create Time History) command.

Figures 1.19a and 1.19b illustrate the definition of a ramp function using the same command. Note that since the duration of the ramp is long, the function looks almost like a rectangular one.

Figures 1.19c and 1.19d illustrate the definition of a sine wave using the **SINE** command.

Forcing function for the example test: This consists of an exponentially varying sine wave whose frequency varies from 0.2 to 10 Hz and again from 10 to 0.2 Hz over a time period of 40.0 sec. The single amplitude of the load function varies from 4.0 kips at the beginning and the end to 0.8 kips in the middle.

The creation of this function requires the creation of many other functions. All these functions are listed in Fig. 1.20 (a) & (b).

```
Data Analysis Commands :              General Commands :                D DA.3

ASD  - auto spectral density          PLT  - plot a single function or result
COH  - coherence                      PLTO - plot overlayed functions or results
CSD  - cross spectral density         PLTP - plot a parameteric of two functions
DIF  - differentiation
EXTR - extreme values                 EDIT - edit a function
FT   - fourier transform              DEL  - delete a function or result
IFT  - inverse fourier transform
INT  - integration                    UP   - move ledger window
IRSP - inverse response spectrum      DOWN - move ledger window
MEAN - mean                           LEDG - go back to the command summary
RMS  - rms integral value             REPT - repeat the next command
RSP  - response spectrum
STD  - standard deviation             EXIT - terminate session
TERG - total energy
TRF  - transfer function              HELC - additional help - listing of
                                             the function creation commands
                                      HELA - additional help - listing of
ADD, SUB, MUL, DIV -                         the function access commands
       generic operations

ENTER THE DESIRED COMMAND : HELC   ( LEDG to return to the command summary )
```

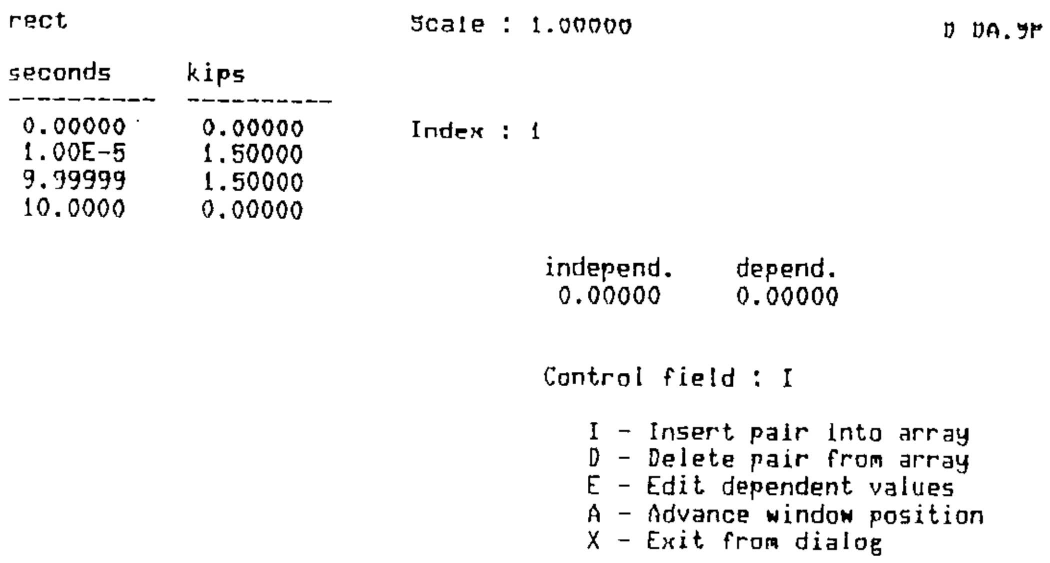
Fig. 1.17a

```
Function Creation Commands :                                            D DA.4

  Create a time history function :
      SINE - sine wave
      LSWP - sine sweep with linearly varying frequency
      ESWP - sine sweep with a exponentially varying frequency
      CTH  - time history ( by editing an even-tabulated or paired function )

  Create a frequency function by editing a paired function :
      CASD - auto spectral density
      CSS  - shock spectrum
      CPHA - create phase data

  Create a function from another :
      INTP - even-tabulated function by interpolating a paired function
      SCAL - scale an existing function by some constant and power
      CONC - concatenate sections of one or two existing functions
      LINC - linear combination, scale and combine two existing functions
      EXP  - new function with exponential values of an existing function
      LN   - new function with natural log values of an existing function
      ABS  - new function with absolute values of an existing function
      PHAS - phase data extraction from an existing complex function

ENTER THE DESIRED COMMAND : HELA   ( LEDG to return to the command summary )
```

Fig. 1.17b

```
Function Access Commands :                                              D DA.5

  Assign a name in the ledger to an external function :
      TIN  - get a function from an external text file
      XIN  - get a function from an external binary file

  Assign a name in the ledger to a function outside this session :
      AANL - an Analysis function           AMOD - a Model function
      APRO - a Profile function             ARAN - a Random function
      ATST - an Earthquake test function
      APSE - a Pseudodynamic test function

  List the contents of a library :
      LANL - the Analysis library directory  LMOD - the Model library
      LSES - a specific Analysis session     LPRO - the Profile library
      LTST - the Earthquake test library     LRAN - the Random library
      LPSE - the Pseudodynamic test library

ENTER THE DESIRED COMMAND : LEDG   ( LEDG to return to the command summary )
```

Fig. 1.17c



```
rect                          Scale : 1.00000                    D DA.9P

seconds      kips
----------   ----------
 0.00000      0.00000         Index : 1
 1.00E-5      1.50000
 9.99999      1.50000
 10.0000      0.00000

                                        independ.     depend.
                                         0.00000      0.00000

                                        Control field : I

                                           I - Insert pair into array
                                           D - Delete pair from array
                                           E - Edit dependent values
                                           A - Advance window position
                                           X - Exit from dialog
```

Fig. 1.18a

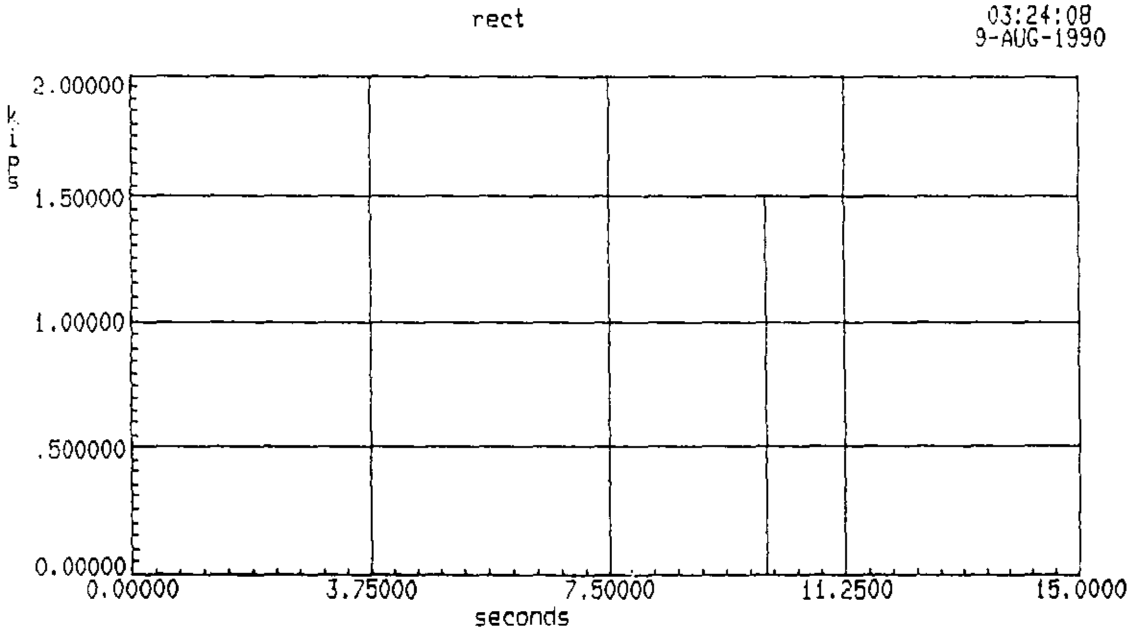
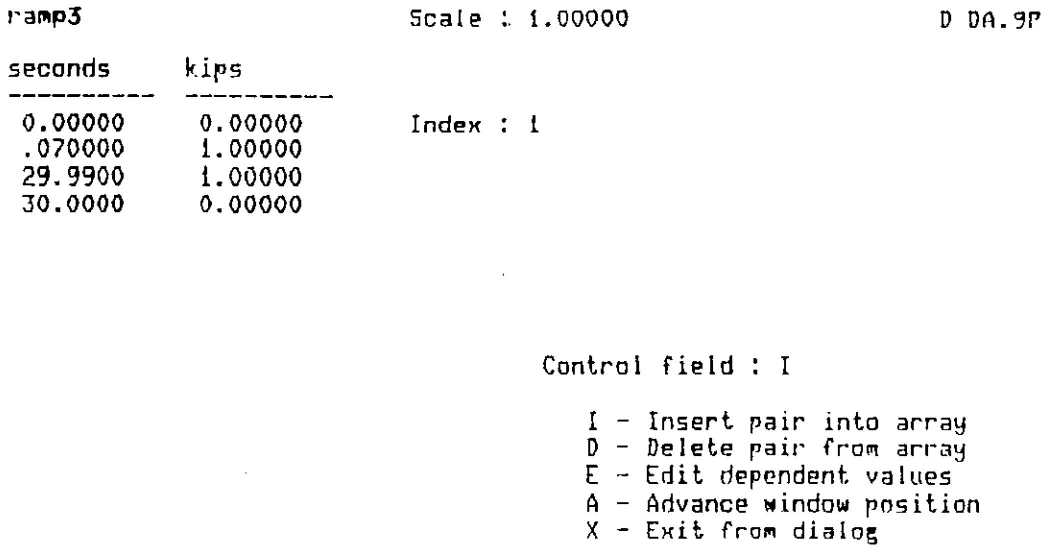


Fig. 1.18b



```
ramp3                              Scale : 1.00000                        D DA.9P

seconds       kips
----------    ----------
 0.00000       0.00000              Index : 1
 .070000       1.00000
 29.9900       1.00000
 30.0000       0.00000



                                           Control field : I

                                              I - Insert pair into array
                                              D - Delete pair from array
                                              E - Edit dependent values
                                              A - Advance window position
                                              X - Exit from dialog
```

Fig. 1.19a

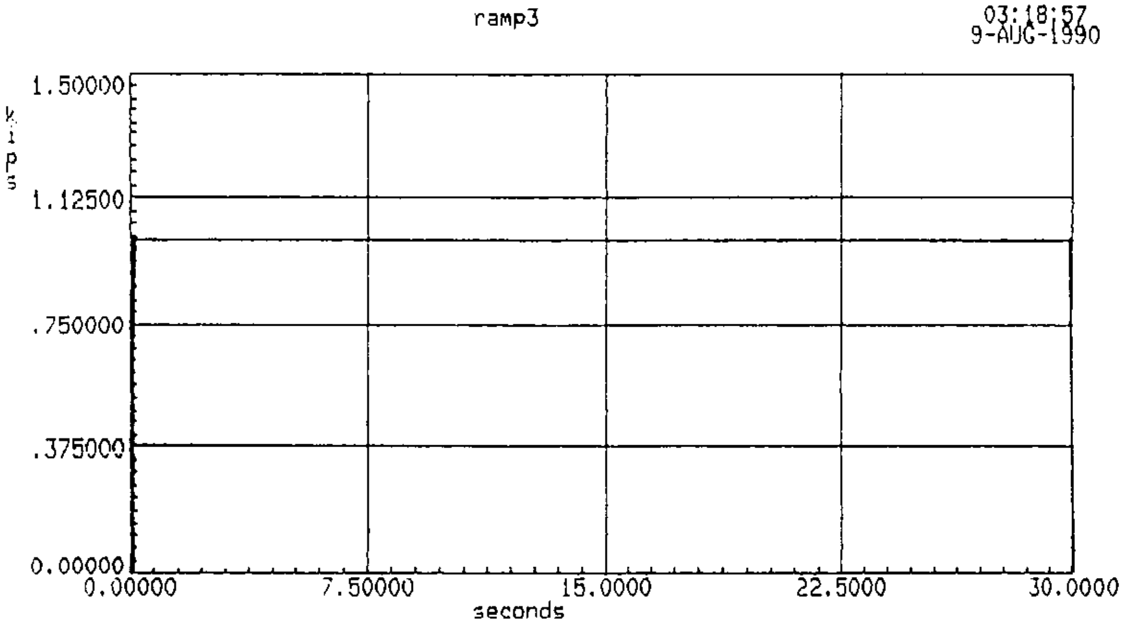


Fig. 1.19b

```
demo_1                   Analysis Results Ledger    D DA.2
Total Results Generated : 11

Top Result Index : 4
 ifin_0.2              = INTP (fin_0.20)
 stoke_fb              = ATST (demo_2,Feedback [Axis, Mode,CH 2,Stroke,,1.000,Yes)
 RAMP_1.5_0.01         = CTH  (P,5.000,KIPS,1.000)
 IRAMP_1.5_0.01        = INTP (RAMP_1.5_0.01)
 LOAD_FB               = ATST (DEMO_3,Feedback [Axis, Mode,CH 2,Load,,1.000,Yes)
 ACH_FB                = ATST (DEMO_3,Achieved [Axis],CH 2,Load,,1.000,Yes)
 S_FB                  = ATST (DEMO_3,Feedback [Axis, Mode,CH 2,Stroke,,1.000,Yes)
 SIN_1.0               = SINE (0.000,5.000,0.000,1.000,KIPS,1.000,0.000)

      Result Function = Sine (arguments listed)              D DA.5A

        Result Name             :
        Initial f=0 Time Span : 0.00000 seconds
        Approximate Duration  : 5.00000 seconds
        Final f=0 Time Span   : 0.00000 seconds
        Amplitude (and Units) : 1.00000 kips
        Frequency             : 1.00000 Hz   ( minimum frequency is 1E-4 )
        Phase Offset          : 0.00000 degrees
```

Fig. 1.19c

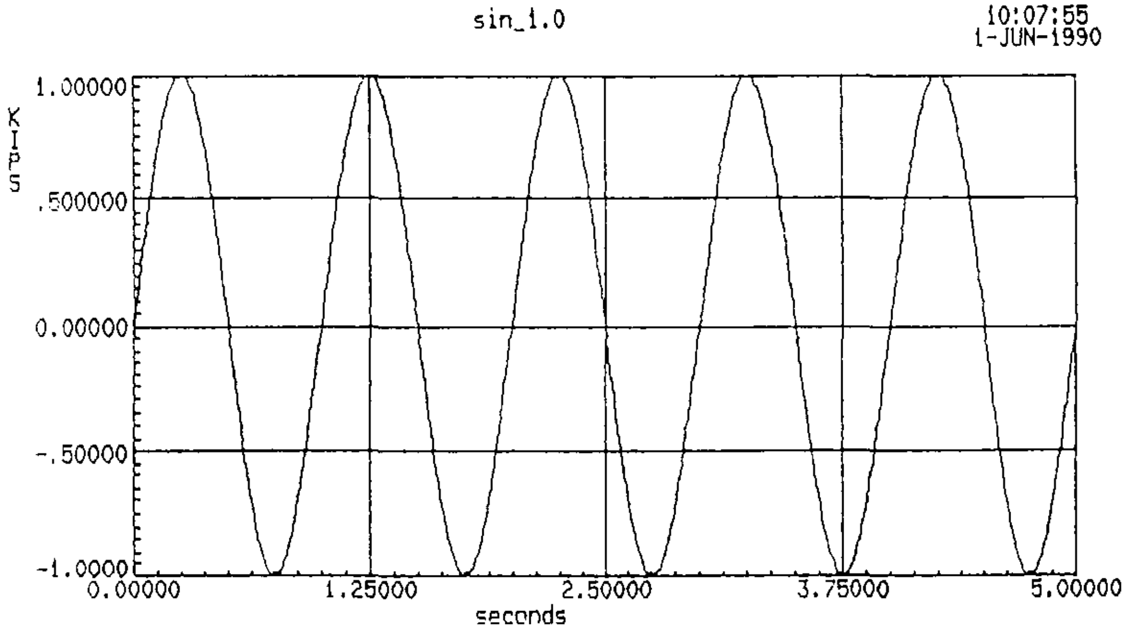
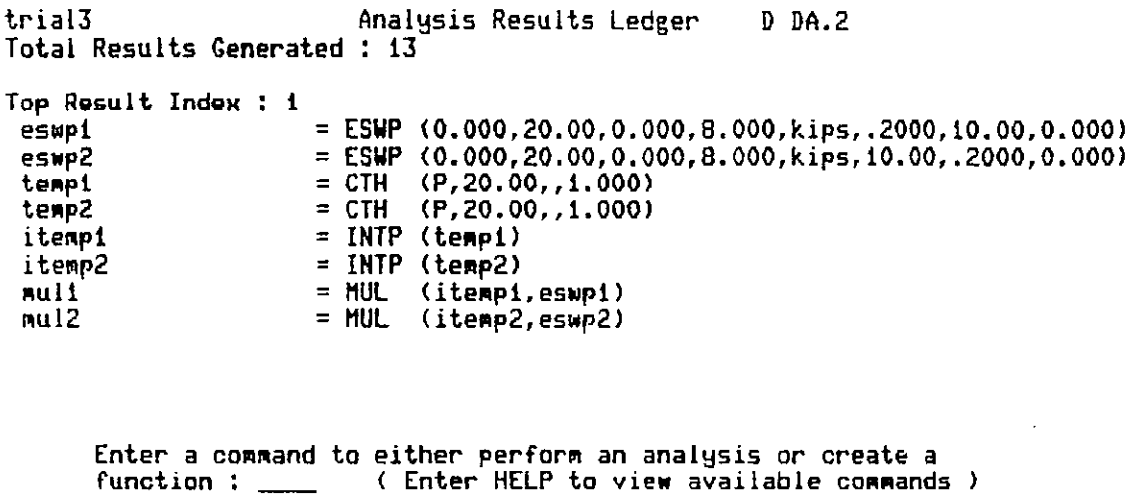
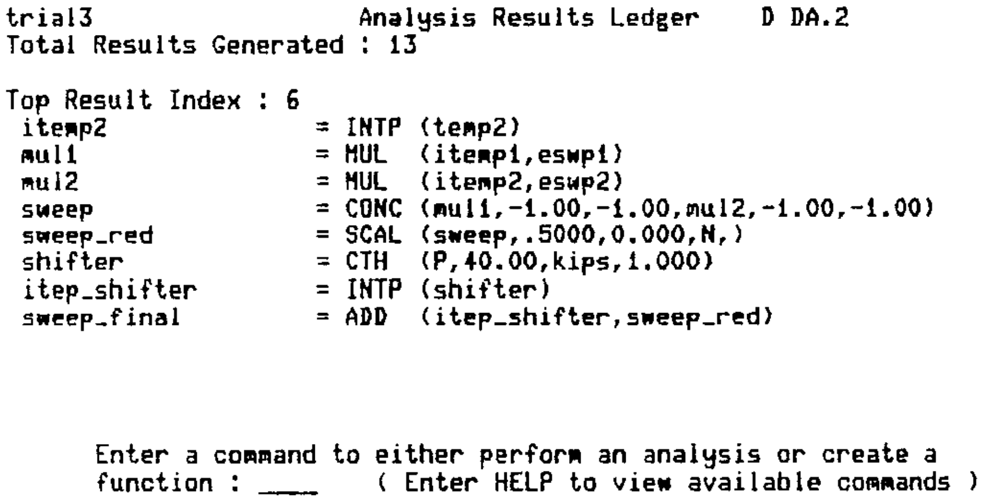


Fig. 1.19d



```
trial3                   Analysis Results Ledger    D DA.2
Total Results Generated : 13

Top Result Index : 1
 eswp1                 = ESWP (0.000,20.00,0.000,8.000,kips,.2000,10.00,0.000)
 eswp2                 = ESWP (0.000,20.00,0.000,8.000,kips,10.00,.2000,0.000)
 temp1                 = CTH  (P,20.00,,1.000)
 temp2                 = CTH  (P,20.00,,1.000)
 itemp1                = INTP (temp1)
 itemp2                = INTP (temp2)
 mul1                  = MUL  (itemp1,eswp1)
 mul2                  = MUL  (itemp2,eswp2)



      Enter a command to either perform an analysis or create a
      function : ____    ( Enter HELP to view available commands )
```

Fig. 1.20a



```
trial3                   Analysis Results Ledger    D DA.2
Total Results Generated : 13

Top Result Index : 6
 itemp2                = INTP (temp2)
 mul1                  = MUL  (itemp1,eswp1)
 mul2                  = MUL  (itemp2,eswp2)
 sweep                 = CONC (mul1,-1.00,-1.00,mul2,-1.00,-1.00)
 sweep_red             = SCAL (sweep,.5000,0.000,N,)
 shifter               = CTH  (P,40.00,kips,1.000)
 itep_shifter          = INTP (shifter)
 sweep_final           = ADD  (itep_shifter,sweep_red)



      Enter a command to either perform an analysis or create a
      function : ____    ( Enter HELP to view available commands )
```

Fig. 1.20b

The procedure of creating the forcing function for the example test is outlined below. The names of the functions are emphasised in dark letters below. These created functions are shown in Figs. 1.21(a) **through** 1.21(j). Please refer to the STEX manual for the set-up screens of each of the function.

(i) Using the ESWP command **eswp1** and **eswp2** are created for the varying frequencies. These functions correspond to each half of the total period. These are shown in Figures 1.21 (a) and (b).

NOTE: The amplitude used at the start of this creation varied from 8.0 kips to 5.8 kips. Later during the creation this has been however scaled down by a factor of 0.5 in **sweep_red.** sweep_red is shown in Figure 1.21 (h).

(ii) The gradual reduction, of the amplitude from the ends towards the middle, is done in a couple of steps.The linearly varying functions **temp1** and **temp2** are created using the command CTH. These functions are interpolated (**itemp1** and **itemp2**) and correspondingly multiplied with **eswp1** and **eswp2** to be called as **mul1** and **mul2**. These functions are shown in Figures 1.21 (c) through 1.21 (f).

NOTE: Functions which are created using the CTH command are interpolated before multiplying with another function.

(iii) These two functions mul1 and mul2 are joined, at t=20 secs by using CONC command, into the function called **sweep**. This function is shown in Figure 1.21 (g).

(iii) In order to define the entire load as acting downward on the beam, the function **itep_shifter** which is an interpolated function with a constant downward (positive) load of 4.0 kips is added to the reduced **sweep** (called **sweep_red**). These functions are shown in Figures 1.21 (h) and (i).

The resulting function **sweep_fin** is the desired function. This is used in the Profile library to set up a profile before setting up a test. This is shown in Figure 1.21 (g).

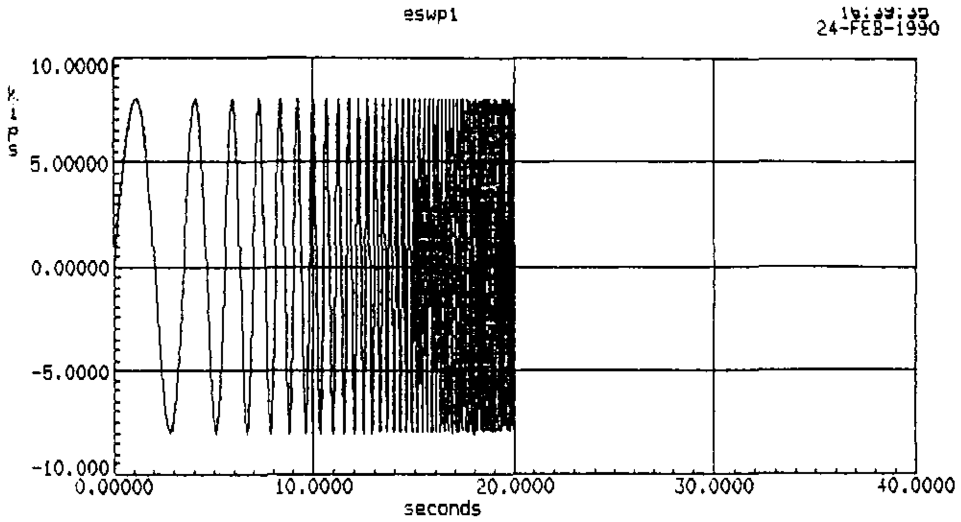


Fig. 1.21a

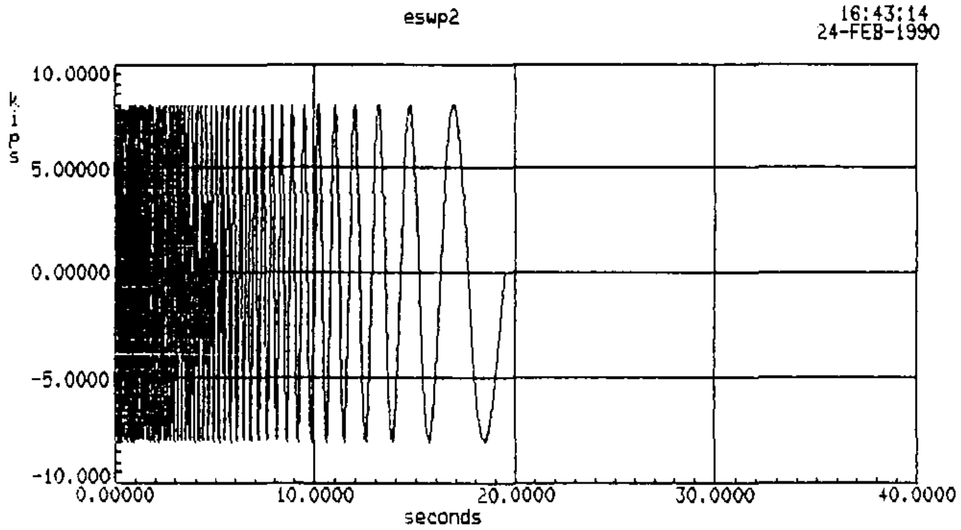


Fig. 1.21b

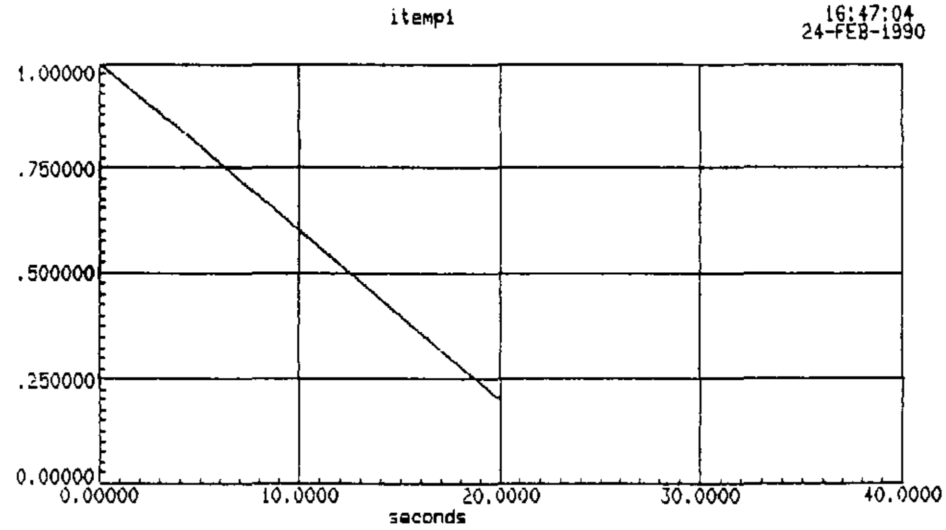


Fig. 1.21c

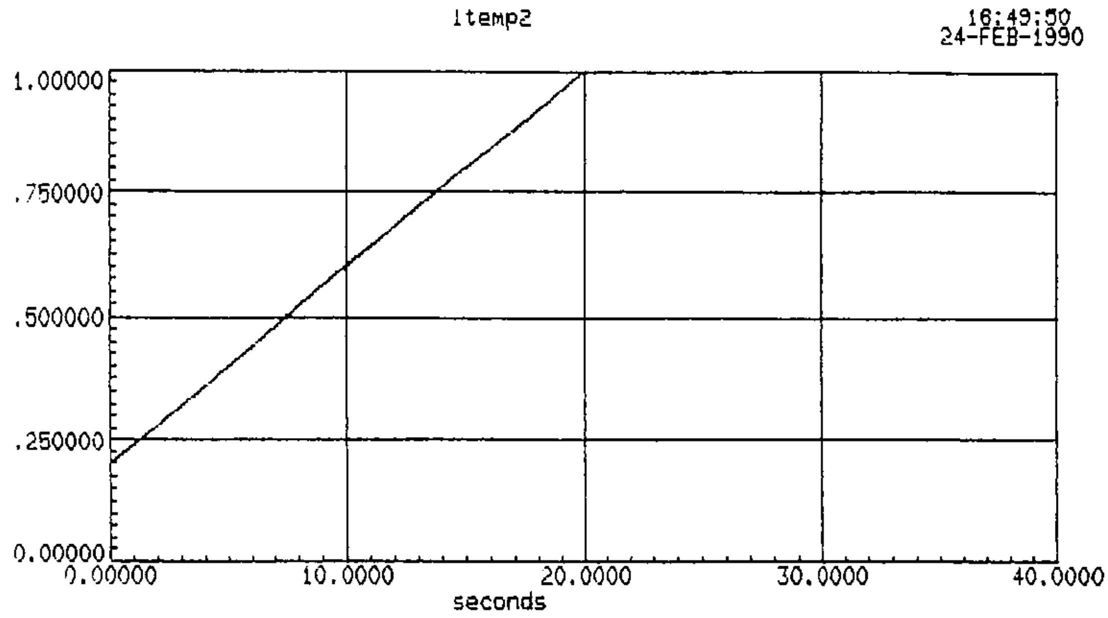


Fig. 1.21d

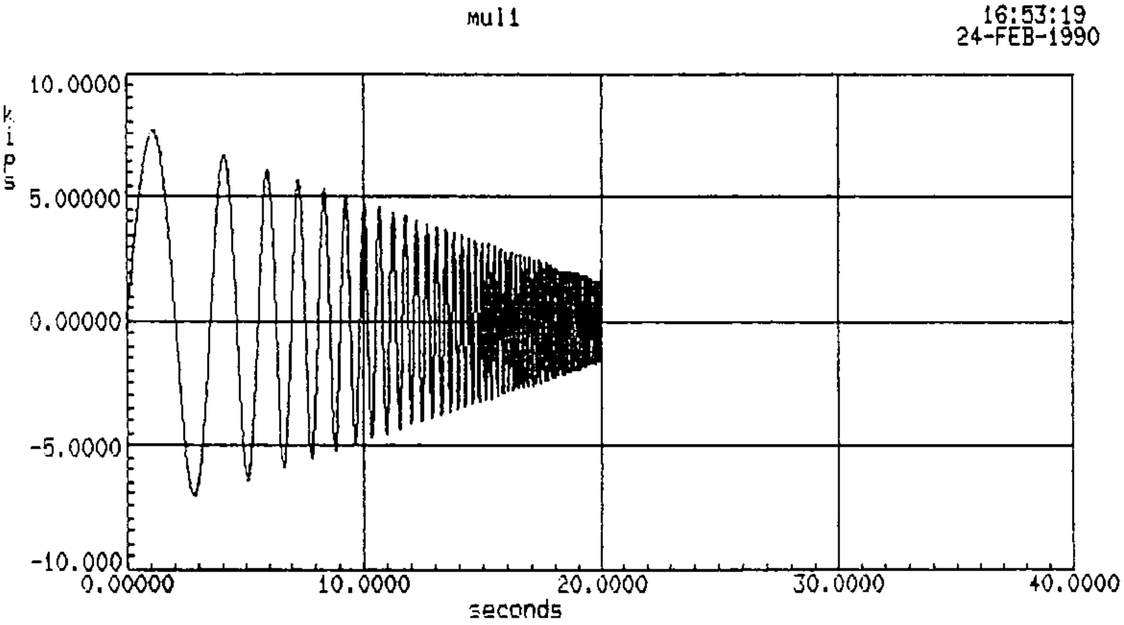


Fig. 1.21e

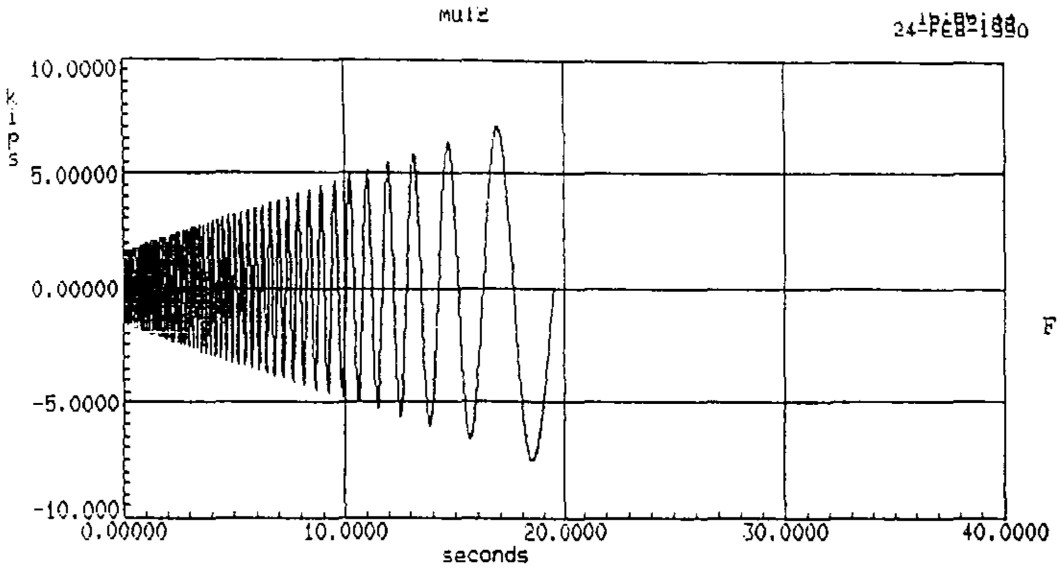


Fig. 1.21f

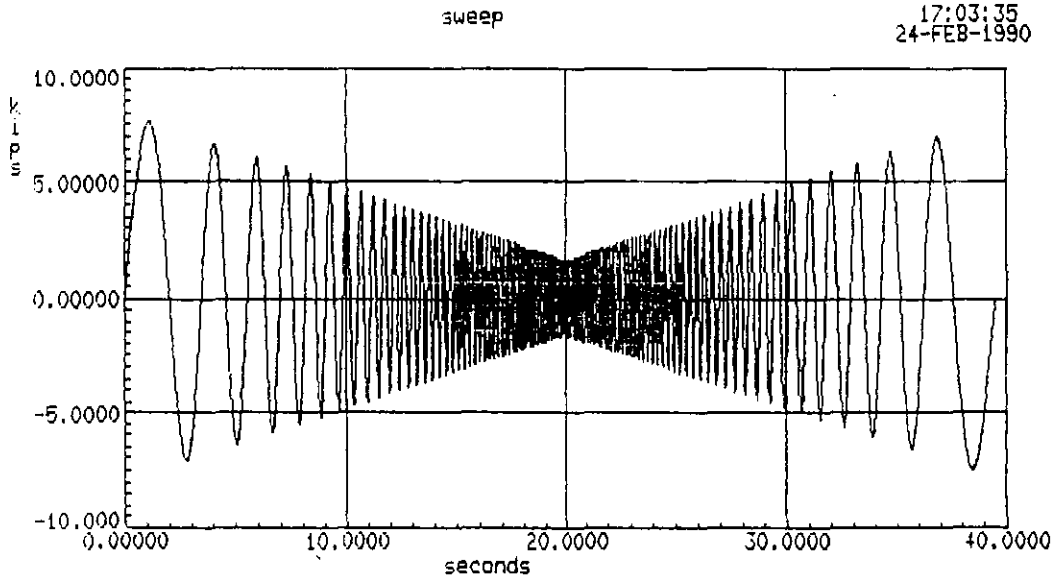


Fig. 1.21g

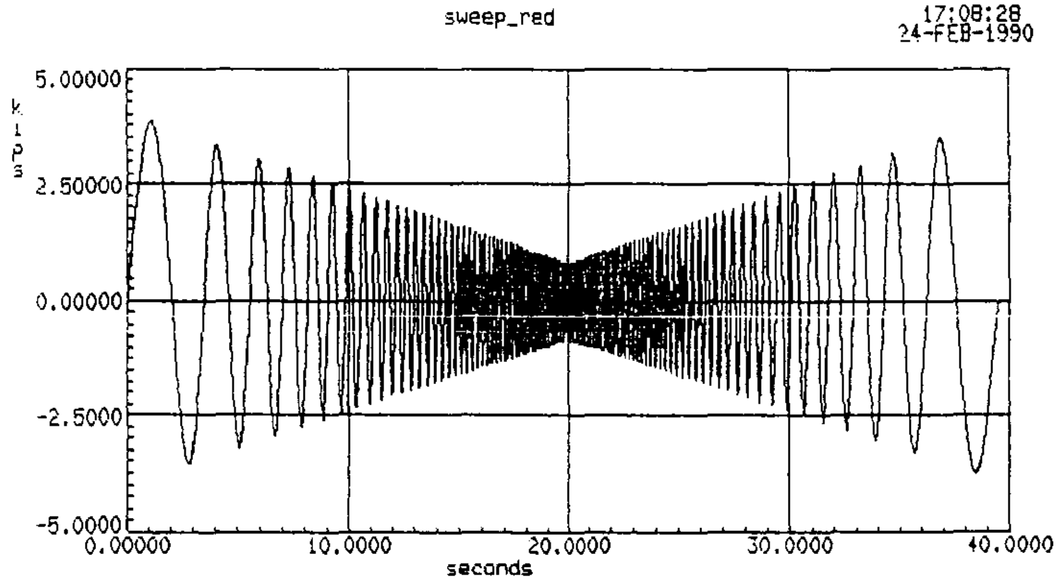


Fig. 1.21h

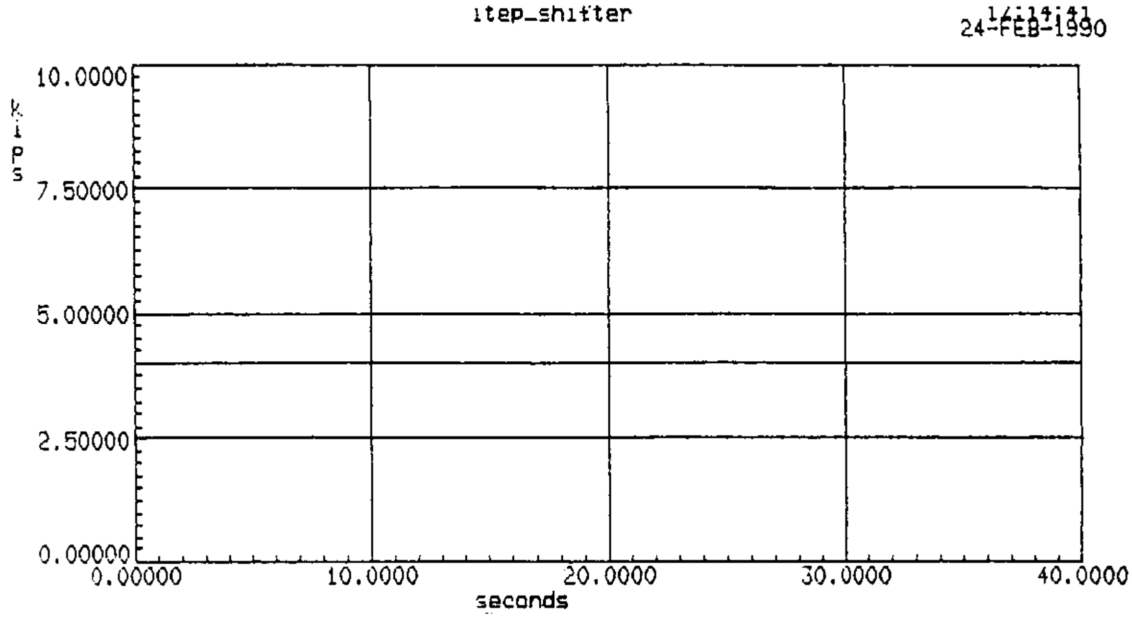


Fig. 1.21i

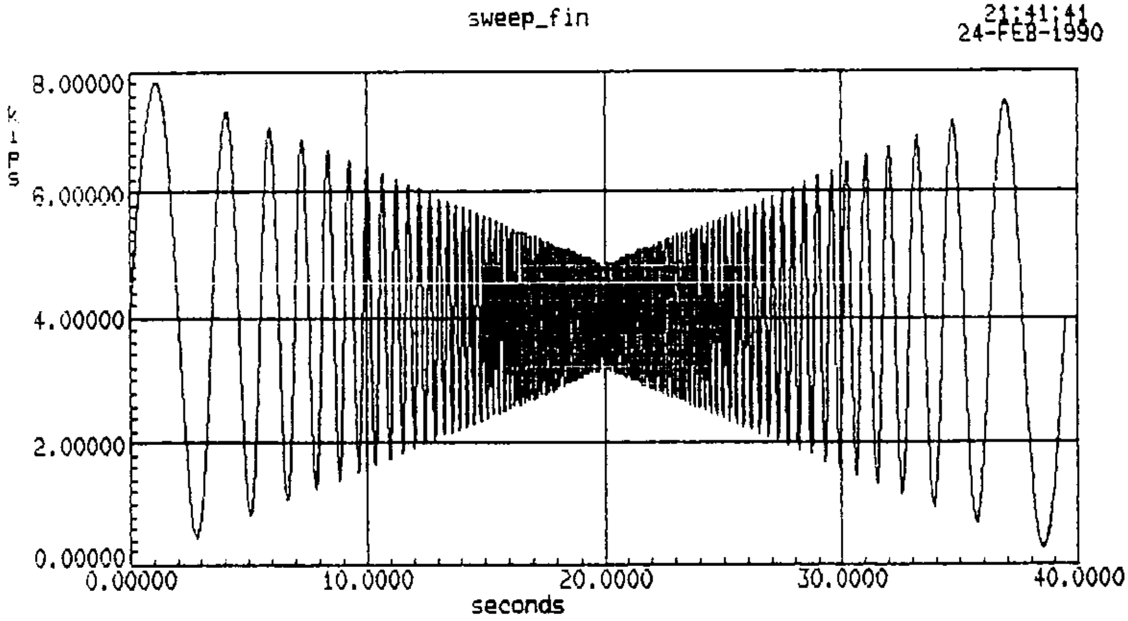


Fig. 1.21j

STEP 3. CREATION OF THE PROFILE

The profile of the time history function (already created in the **Data Analysis** library) is created in the **PROFILE LIBRARY.** The primary purpose of this library is to configure the time history function into the profile format required for testing. The required profile format is shown in Fig. **PL-1** of the STEX manual which has been reproduced in Fig. 1.22.

This creation is done in D PL.1.

For the example test this dialog is as shown in Fig. 1.23.

Note:1. As explained earlier in **'Setting up the system data'**, the leading zeros are required for compensation of the excitation signal. Compensation is a procedure in which a pseudo desired signal is set up depending on the system dynamics to overcome the limitations of the servovalve. If a profile is to be used in any compensated test or in an uncompensated test which will be used to calculate a system model (required in the compensation procedure), the number of leading zeros must be at least equal to one-half of one frame length.

2. The words 'minimum' and 'maximum' used in D PL.1 when defining the taper refers to the time domain. 'minimum' refers to the starting time (0.0000 secs) and 'maximum' refers to the ending time (e.g: 40 secs for the example test) of the function.

For the example test, the drive signal was not expected to be compensated or to be used to create a model. Hence there was no leading zeros provided.

The created profile is shown in Fig. 1.24.

This completes the creation of the profile.

STEP 4. DEFINING A NEW UNCOMPENSATED PROFILE EARTHQUAKE TEST

This is **accomplished** in the **EARTHQUAKE TESTING LIBRARY** . This involves **the** definition of the following in D **EQ** 1P.

(i) **Name of the test**
(ii) Name of the system configuration set up in the System Definition library
(iii) Name of the profile set up in the Profile Library.
This has to be defined for the appropriate axis in D **EQ** 1P.

For the example test, this dialog appears as shown in Fig. 1.25.

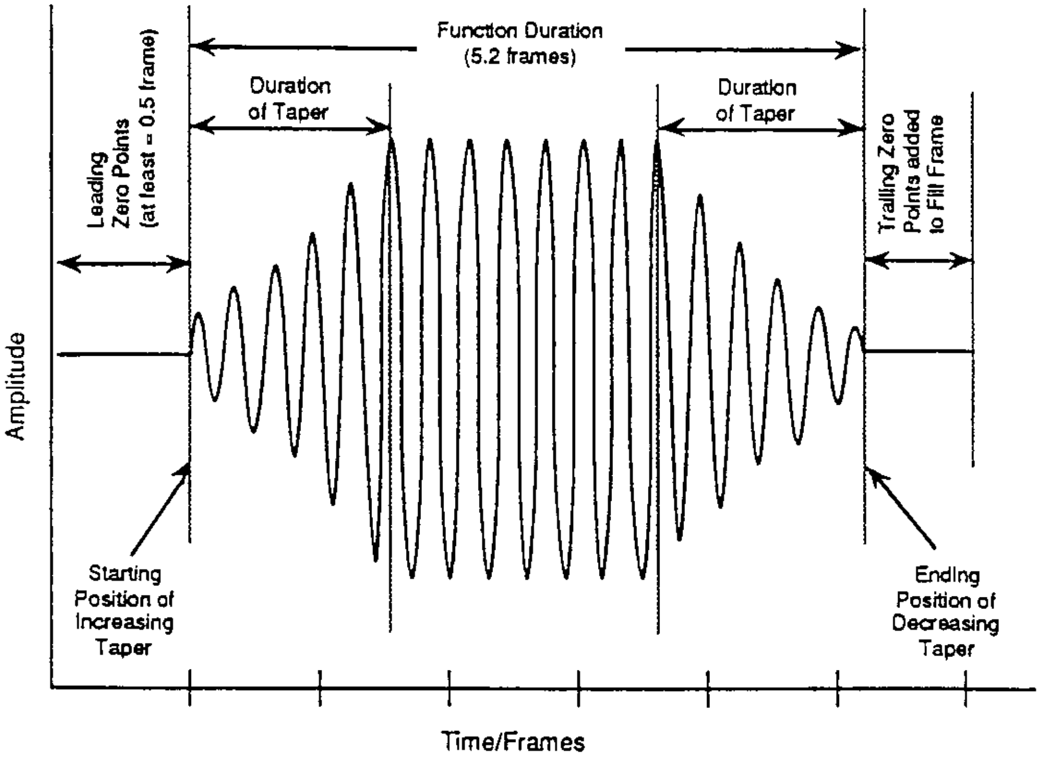
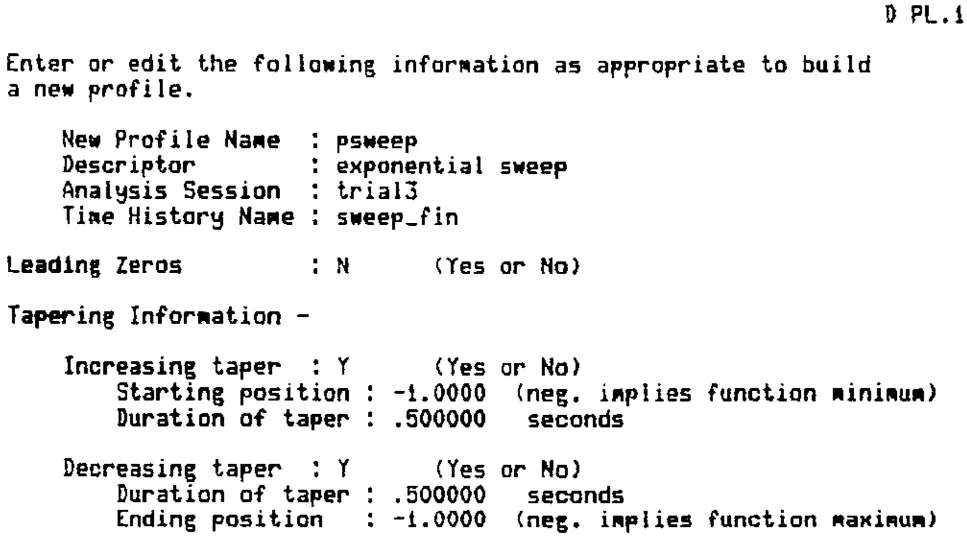


Figure PL-1. Profile Format Description

Fig. 1.22



```
                                                          D PL.1

Enter or edit the following information as appropriate to build
a new profile.

    New Profile Name  : psweep
    Descriptor        : exponential sweep
    Analysis Session  : trial3
    Time History Name : sweep_fin

Leading Zeros         : N      (Yes or No)

Tapering Information -

    Increasing taper  : Y      (Yes or No)
        Starting position : -1.0000  (neg. implies function minimum)
        Duration of taper : .500000   seconds

    Decreasing taper  : Y      (Yes or No)
        Duration of taper : .500000   seconds
        Ending position   : -1.0000  (neg. implies function maximum)
```

Fig. 1.23

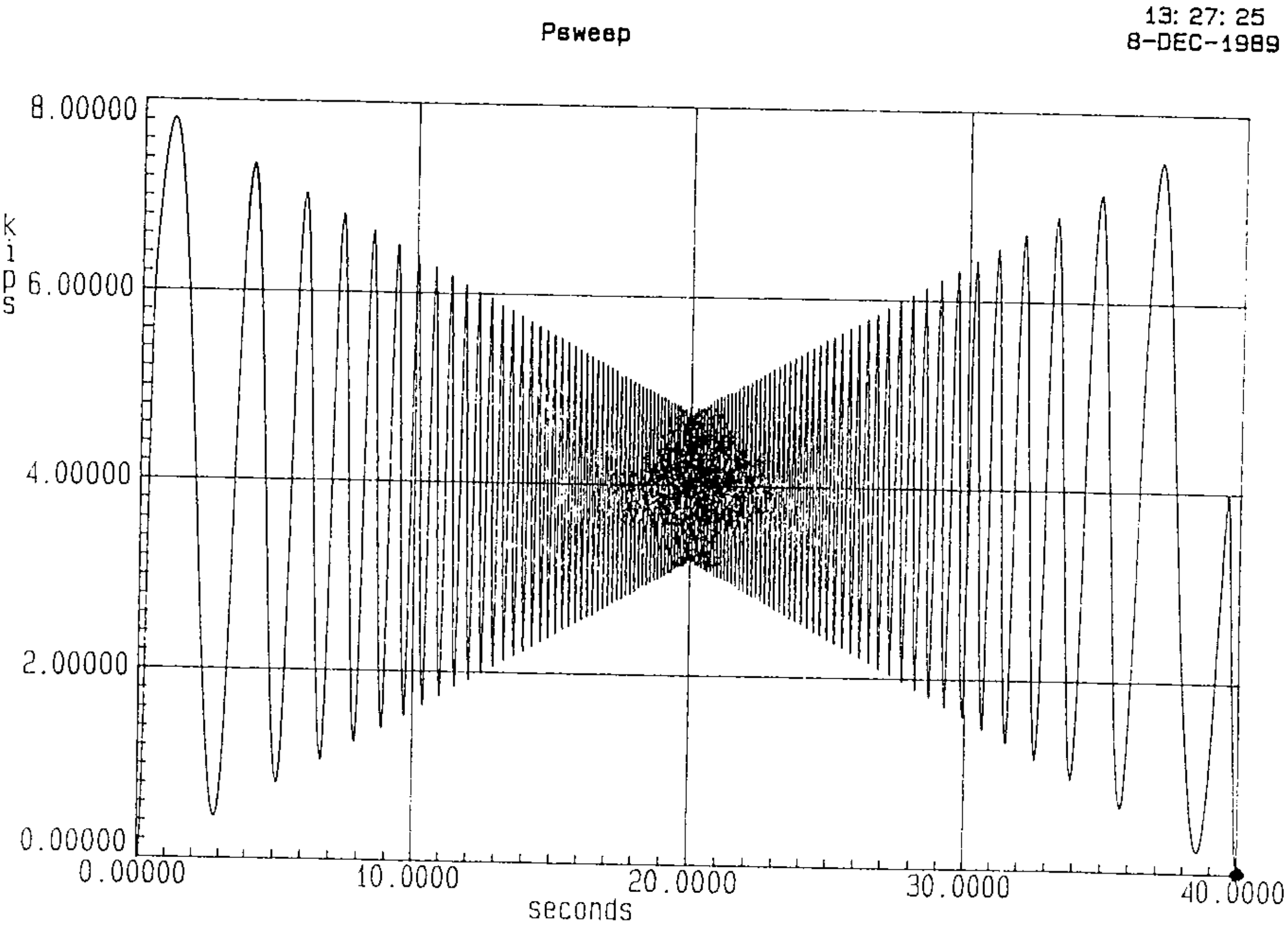
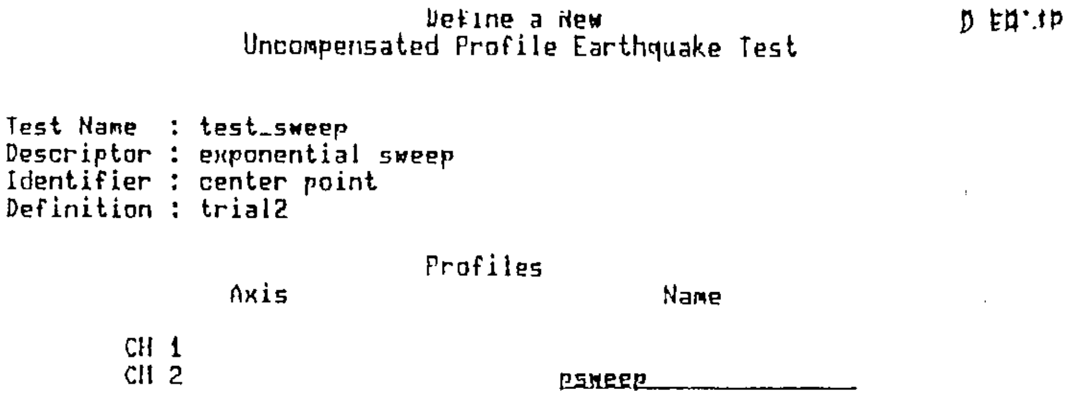
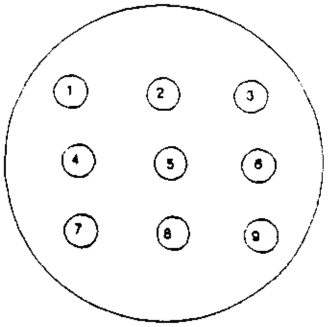

Psweep
13: 27: 25
8-DEC-1989
kips
8.00000
6.00000
4.00000
2.00000
0.00000
0.00000
10.0000
20.0000
30.0000
40.0000
seconds

Fig. 1.24



```
                    Define a New                          [illegible]
             Uncompensated Profile Earthquake Test


Test Name  : test_sweep
Descriptor : exponential sweep
Identifier : center point
Definition : trial2

                          Profiles
           Axis                            Name

      CH 1
      CH 2                          psweep__________
```

Fig. 1.25



For Strain Gauge:
2. White
3. Black
6. Red

For DCDT:
2. White and Black.
3. Green
6. Red

Fig 1.26 Details of connection at 450 Interconnector box

Fig. 1.26

SECTION 2. HARDWARE SET UP AND TEST EXECUTION

A. HARDWARE SET-UP.

The setting up of the hardware involves the following procedure.

1. Setting up of the Digital console.
2. Setting up of the Hydraulic system.
3. Setting up of the Analog console.
4. Setting up of and checking the specimen involved.

1. Setting up of the Digital Console

This involves the following two adjustments.

A. Setting up of the 450 INTERCONNECTOR BOX.

The electrical cords from the external transducers set up on the specimen should be connected to the appropriate data acquisition channels of the interconnector box. These channels should be the same as defined in the system configuration.

The connection details for a strain gauge and dcdt are shown in Fig. 1.26.

B. Selection of the channels in the Digital console.

The pertaining data channels should be selected in the MTS Meter Mux Module. The 450 QUAD CONDITIONER housed in this console will probably require some calibration for the specific channels being used i.e., strain, dcdt etc. Help in these settings may be obtained from the Lab Supervisor.

2. Setting up of the Hydraulic system.

The following items have to be ensured before using the hydraulics.

A. Water supply line, to the hydraulic distribution system must be kept open. This is located below the watch tower by the side of the hydraulic distribution system enclosure.

B. The valve of the hose carrying oil from the system to the servovalve should be kept open. This is achieved by bringing the lever of the valve parallel to the hose. Also make sure the other outlet valves are closed. Close other valve if actuator on that line is not being used.

3. Setting up of the Analog console

The following settings are made on the 443 CONTROLLER and the 436 CONTROL UNIT housed in the MTS STRUCTURAL TEST SYSTEM.

NOTE: These adjustments are the same for the uncompensated and the compensated real time dynamic tests.

This comprises the following items.

A. Adjustments to be made in the 443 controller:

The following steps need to be followed in accomplishing the setup of the 443 controller.

(i) With the METER selected to check the DC ERROR, use the SET POINT knob to nullify the meter (bring the needle in the meter to zero). Now, the SET POINT will be in the neighborhood of 5.0 (main scale reading).

(ii) Make sure that the SPAN is set at zero. The number at which this is set gives the percentage of the signal that would be sent to the SERVO CONTROLLER. This is to prevent sending any signal accidentally to the servovalve which may damage the actuator and/or the specimen. This should be turned to 100% before the test is run.

(iii) Selection of the ranges (**full scale**) of the stroke and the load: The RANGE knobs in the A.C CONDITIONER (for **stroke**) and the D.C CONDITIONER (for **load**) are used to select the full scales. These full scales should correspond to the full scales defined for each of the modes in the **system definition** used for the particular test.

(iv) The voltages from these conditioners should be +0.00 or -0.00. Otherwise, it would mean that an initial stroke or load of the + or - sense of magnitude corresponding to the voltage is present.

This can be checked by feeding in the voltage from the conditioners into the 430 DIGITAL INDICATORS. Seek help from the lab supervisor in this regard.

(v) **Make sure that the** PROGRAM SELECTOR knob selects **'random'** for real **time** dynamic tests. For pseudo tests this should be set at "R". "R" stands for 'Remote'.

(vi) The PROGRAM CONDITIONER should be set at displacement. Check if the displacement button is lit.

(vii) The FEEDBACK SELECTOR knob should be set at the same mode as the command. Check if the corresponding command mode button is lit on the front panel.

(viii) The LIMIT DETECTORS may be used for controlling load and stroke magnitudes. This enables you to set the maximum and the minimum limits of the modes. This can be set either to indicate on the front panel (when the signal crosses the limit) or to produce a hydraulic interlock which in turn stops the system.

(ix) If there is any hydraulic interlock present as displayed by the HYD INTLK button present in 436 CONTROL UNIT, press the RESET switch (red coloured) in the controller. The system cannot run in the presence of this interlock.

B. Set up required in 436 CONTROL UNIT:

This unit has the control over the **hydraulic distribution system** and the **program activation.**

WARNING: Before applying LOW hydraulic pressure , make sure that the DC ERROR needle has been **nullified**. This would otherwise cause the actuator to move when the low pressure is applied and may result in damaging the specimen and/or the actuator.

(i) To set the hydraulic pressure at LOW, press the LOW button twice. The pressure should be increased to **HIGH** only after a few minutes. If you desire to shut down the hydraulic system, you should first reduce the pressure to **LOW** before pressing the button **HYD OFF**. However, the **EMERGENCY STOP** knob can be used in the case of an emergency.

(ii) The use of program activation switches will be discussed later.

(iii) The STOP (program) button should be lit now.

4. Setting up of and checking the specimen

The set up of the specimen may vary from one test to another. The following general checks may however be performed for all the tests.

(i) **Check** if the supports such as the rollers or pins are sturdy.

(ii) **Check** if the external transducers are hooked up at the right locations. The vibrations during the test may sometime disturb the location of the transducer depending on where it rests.

(iii) Check the whole length of the hydraulic hose to make sure there is no leak anywhere. The junctions at the ACCUMULATOR should also be checked. **If you detect any leak turn the pump off immediately and contact the lab supervisor.**

B. EXECUTION OF THE TEST

This is performed in the EARTHQUAKE TESTING library.

If the test is already available in this library the test can be conducted by using the SELECT option. Otherwise, the test may be continued from the definition stage (Step 4) or the modification stage.

In each of the cases the confirmation on the correctness of the data provided in **D EQ 1P** is prompted. Pressing ENTER here would set up the system to perform the following tasks.

(i) Retrieve the configuration and the specified motions from the SYSTEM DEFINITION and the PROFILE library respectively,
(ii) Create the multiplexed files,
(iii) Determine the drive signal and
(iv) Perform the limit checks.

When the system performs these processes, messages flash on the screen.

Successful definition of the test using one of the select, modify or define options available in the Earthquake testing options menu would prompt the **Earthquake Testing Control Options Menu** which is **M EQ 2U**. This looks as shown in Fig. 1.27.

This allows you to perform the following before executing the test.

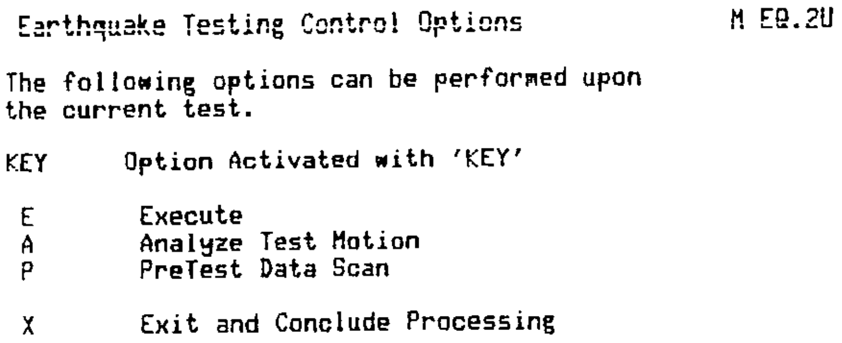
(i) **Analyze test motions:** This gives you the final chance to check the Drive signal.

(ii) **Pretest data scan:** This in turn allows you to perform the following via **M EQ.9**.

(a) Channel data scan: Provides information on the DC voltages corresponding to each of the channels (both control and transducer data acquisition channels).

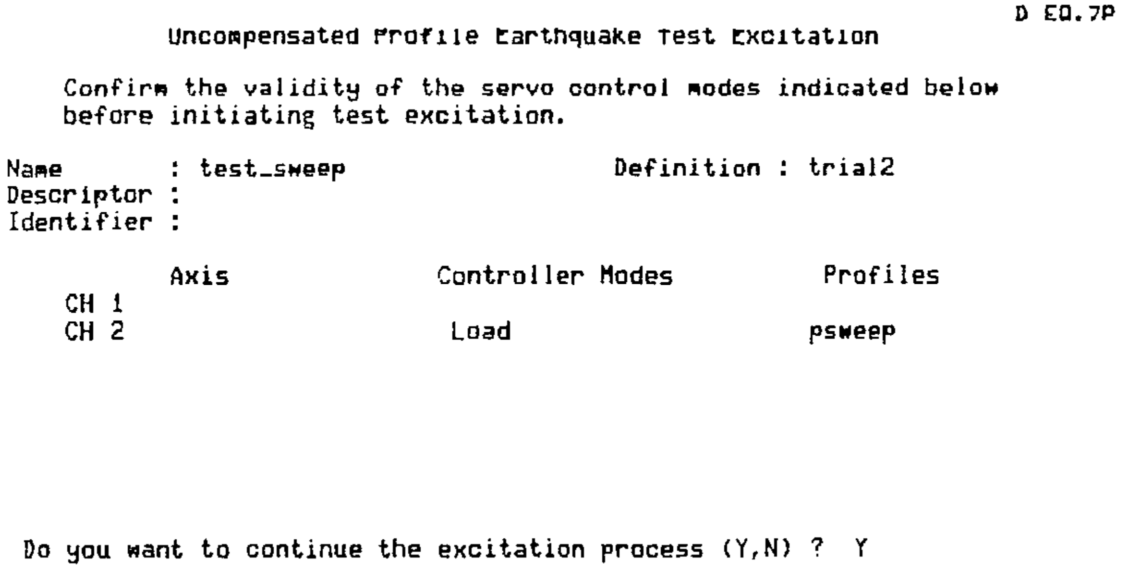
(b) Auto-zeroing of A/D channels: Please refer to the glossary of STEX manual.

(c) **Shunt** calibration of A/D channels: This is a check on the transducer data access channel electronics.



```
Earthquake Testing Control Options            M EQ.2U

The following options can be performed upon
the current test.

KEY     Option Activated with 'KEY'

 E       Execute
 A       Analyze Test Motion
 P       PreTest Data Scan

 X       Exit and Conclude Processing
```

Fig. 1.27



```
                                                          D EQ.7P
         Uncompensated Profile Earthquake Test Excitation

    Confirm the validity of the servo control modes indicated below
    before initiating test excitation.

 Name       : test_sweep                  Definition : trial2
 Descriptor :
 Identifier :

          Axis               Controller Modes          Profiles
    CH 1
    CH 2                      Load                    psweep




 Do you want to continue the excitation process (Y,N) ?  Y
```

Fig. 1.28

The choice to execute the test in **M** EQ 2U would prompt the following questions.

(i) **Do you want to scale or limit check the drive (Y,N) ?**

If you are sure that the drive signal is within the full scale limits you may skip this. Refer STEX manual for further explanation about this, in the section EXECUTE.

(ii) **Do you need to Multiplex the drive data (Y,N) ?**

The drive data should be definitely multiplexed before the test is conducted. **Multiplexing** is a process of arranging the command signal data point at each time step is a fashion suitable for the hardware to recognize and create the servo signals. The reverse of this process is called **demultiplexing**, which is an arrangement of the achieved signal in a particular order for the computer to recognize. Hence the achieved data should be definitely demultiplexed in order to plot the data and analyze after the test is over.

Answering 'Y' to this question will display **D EQ 7P** for you to confirm the validity of the data for the final time. This also gives an option to cancel the test at this stage to enable correction if anything is wrong.

For the example test, called **test_sweep**, this dialog is shown in Fig. 1.28.

Answering 'Y' to continue with the excitation, the system displays the STATUS CHECK PANEL as shown in Figs. 1.29(a) through 1.29(j). Respond to these checks by using the letters 'O', 'A' or 'I' to signify OK, ABORT or IGNORE respectively. These messages are provided only as a reminder to the user. The software **does not** check the console setups to ensure correct settings.

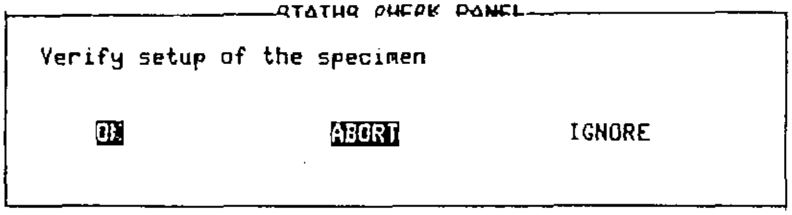
While most of these checks are self-explanatory, the following deserve some explanation.

(i) **Set servo gains to correct settings**
This is done on the analog console.

(ii) **Set program source to computer.**
This is done by setting the PROGRAM SELECTOR to **'random'**.

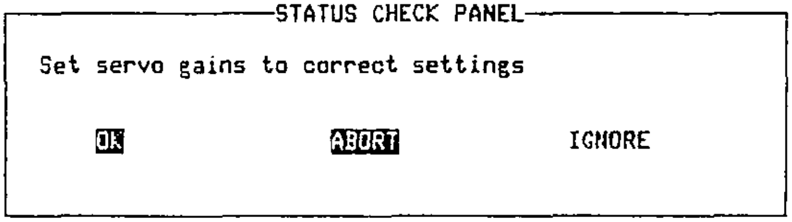
(iii) **Verify hydraulic pressure and temperature.**
The hydraulic pressure can be checked by using the pressure gauge fitted on the **accumulator**. The temperature can be checked at the **413 MASTER CONTROL PANEL** housed in the **MTS 810 MATERIAL TEST SYSTEM.**

(iv) **Set the controller spans to 100%**
Check if the SPAN knob on the 443 CONTROLLER is set at 100%.



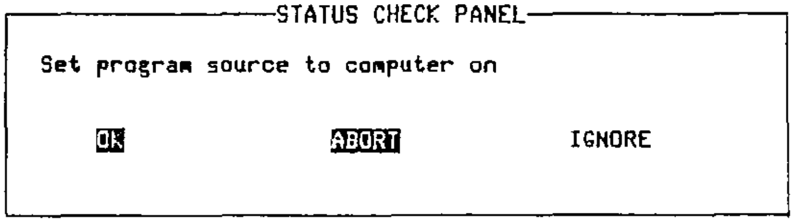
Verify setup of the specimen

Fig. 1.29a



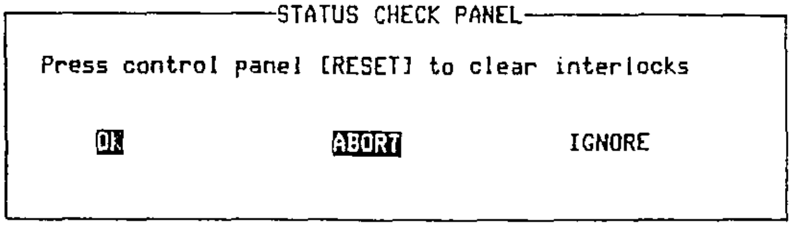
Set servo gains to correct settings

Fig. 1.29b



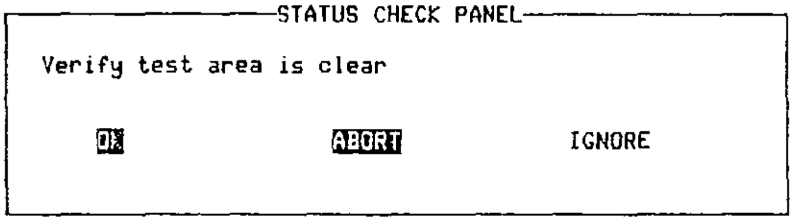
Set program source to computer on

Fig. 1.29c



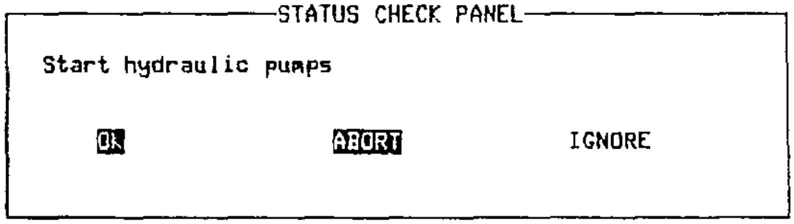
Press control panel [RESET] to clear interlocks

Fig. 1.29d



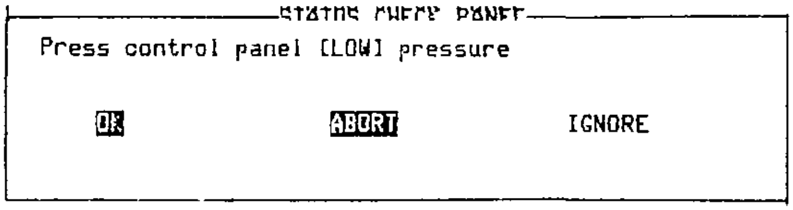
Verify test area is clear

Fig. 1.29e



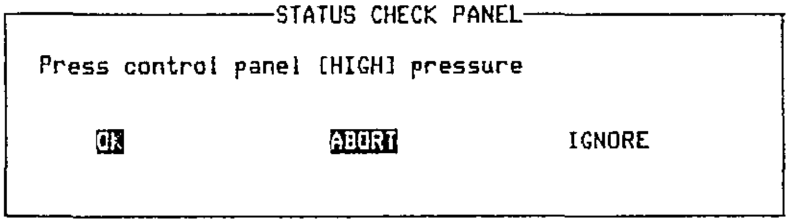
Start hydraulic pumps

Fig. 1.29f


STATUS CHECK PANEL

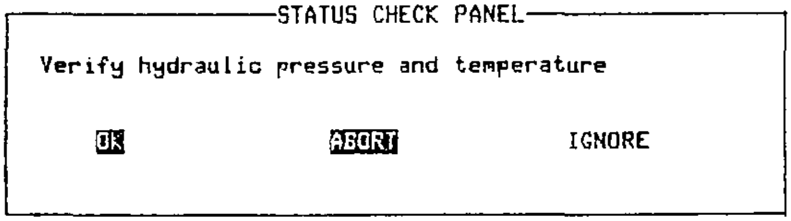
Press control panel [LOW] pressure

Fig. 1.29g


STATUS CHECK PANEL

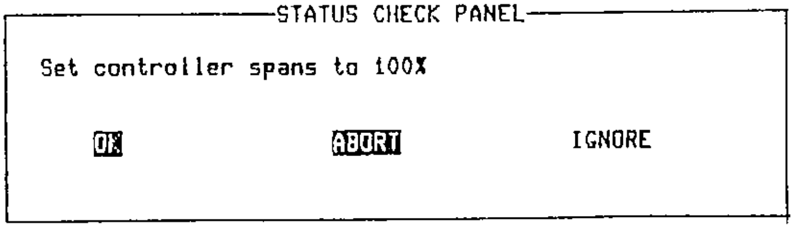
Press control panel [HIGH] pressure

Fig. 1.29h


STATUS CHECK PANEL

Verify hydraulic pressure and temperature

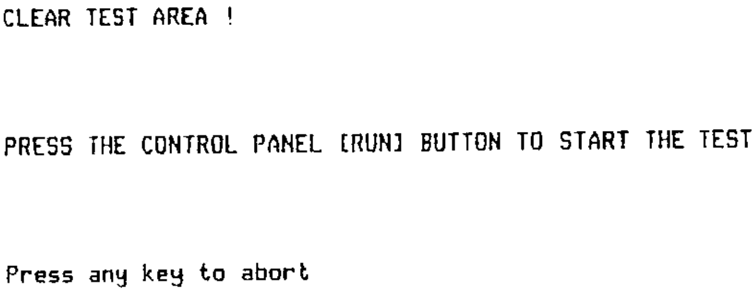
Fig. 1.29i



STATUS CHECK PANEL

Set controller spans to 100%

Fig. 1.29j

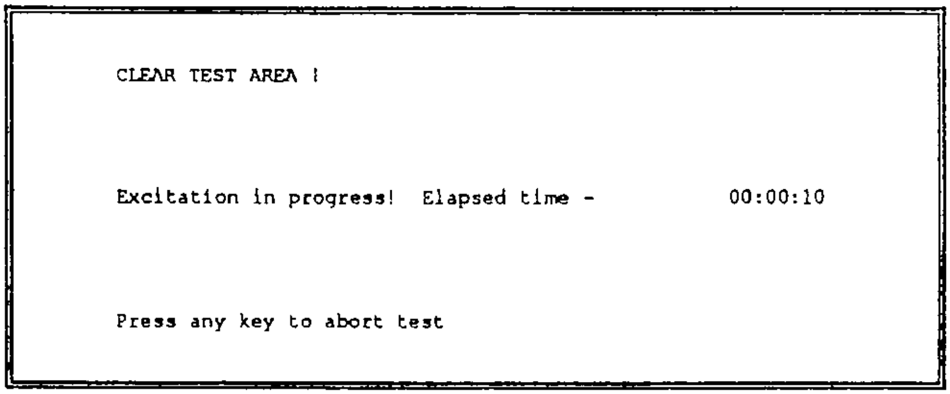


CLEAR TEST AREA !

PRESS THE CONTROL PANEL [RUN] BUTTON TO START THE TEST

Press any key to abort

Fig. 1.30a



CLEAR TEST AREA !

Excitation in progress! Elapsed time - 00:00:10

Press any key to abort test

Fig. 1.30b

NOTE: STEX software does not check the analog console to ensure the neccessary settings. The list has been provided only to serve as a check list.

At the end of the check list, the message to start the test using the **RUN** switch on the 436 CONTROL UNIT, as shown in Fig. 1.30(a) appears.

To continue with the test press RUN switch at which the test is started and the screen changes to inform that the excitation is in progress and also displays the elapsed time. This screen is shown in Fig. 1.30(b).

Once the test is completed, the message shown on Fig. 1.30b appears confirming the completion and the system automatically activates the program STOP switch on.

The system then prompts with the question **'Do you wish to demultiplex the achieved data (Y,N) ?'** As mentioned earlier the achieved data should be demultipexed to plot and do the neccessary post-test analysis.

CAUTION: Responding 'N' to this question does not save the test.

SECTION 3. POST-TEST ANALYSIS

The post-test analysis for an uncompensated test is best done by accessing the results from the DATA ANALYSIS library.
However, the achieved signal and the error may be obtained immediately after the test. **Error** is defined as the differnce between the desired and the achieved signal. This is done by opting to **analyze test motion** in **M EQ.2U**, shown in Fig. 1.27, which prompts **D EQ 14**. This dialog is shown in Fig. 1.31. The result may also be viewed by opting to DISPLAY the test from Earthquake library's main menu.

In the data analysis library the test data from the Earthquake Test library is obtained by using the Assignment command ATST. This command displays D DA.15J as shown in Fig. 1.32.

For the example test, the **Specified, Drive, Achieved, and Feedback (stroke) signals** are shown respectively in Figs. 1.33 through 1.36.

The following remarks are evident from a comparison of the first three signals.

(i) The specified signal is the same as the drive signal. This is because no compensation has been done to the drive signal.

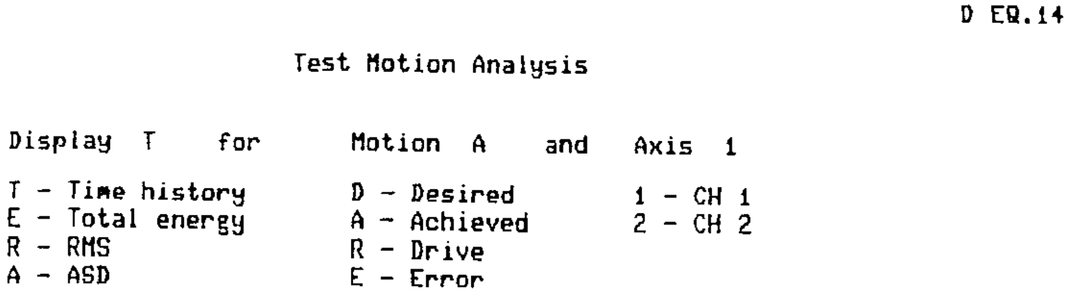
(ii) The Achieved signal is slightly off the 0.0000 position of the X-axis. It looks slightly shifted in the + Y direction. This reflects the existence of some positive initial voltage present in the control channel before the test was conducted. This can be avoided by zeroing the channel of the corresponding mode in the anolog console.

(iii) It can also be observed in the same signal that the specified frequency has been well maintained. The amplitude varies from 4.0 kips at the beginning and the end but it reduces to 0.5 kips in the center. This is because the capacity of the servovalve is such that while trying to maintain the specified frequency i.e. 10.0 Hz. it is unable to maintain the amplitude. This limitation of the servovalve may be partially overcome by compensating the desired signal.

The frequency-amplitude performance of a servovalve depends on what amount of oil it can pump to move the actuator piston at a given frequency. The characteristic curves giving this relationship for different servovalves of MTS is available in MTS service manual. As it can be seen from these curves, generally the capacity to pump oil decreases with the increase in frequency. When the signal is compensated, at the higher frequencies the servovalve would be forced to pump more oil to improve the amplitude.

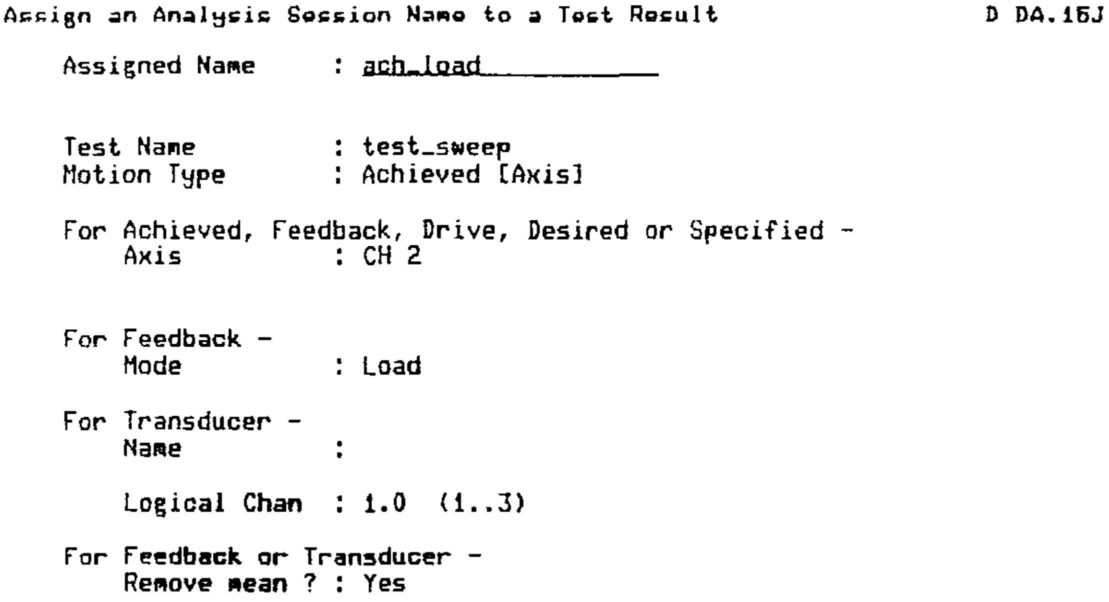
NOTE: It should be remembered that compensation of the signals may not be the solution to obtain the desired signals.

The **Stroke feedback signal** shows a maximum stroke of 0.7675 inches.



```
                                                            D EQ.14
                     Test Motion Analysis

   Display  T    for       Motion  A    and    Axis  1

   T - Time history        D - Desired         1 - CH 1
   E - Total energy        A - Achieved        2 - CH 2
   R - RMS                 R - Drive
   A - ASD                 E - Error
```

Fig. 1.31



```
Assign an Analysis Session Name to a Test Result             D DA.15J

   Assigned Name      : ach_load


   Test Name          : test_sweep
   Motion Type        : Achieved [Axis]

   For Achieved, Feedback, Drive, Desired or Specified -
       Axis           : CH 2


   For Feedback -
       Mode           : Load

   For Transducer -
       Name           :

       Logical Chan   : 1.0  (1..3)

   For Feedback or Transducer -
       Remove mean ? : Yes
```

Fig. 1.32

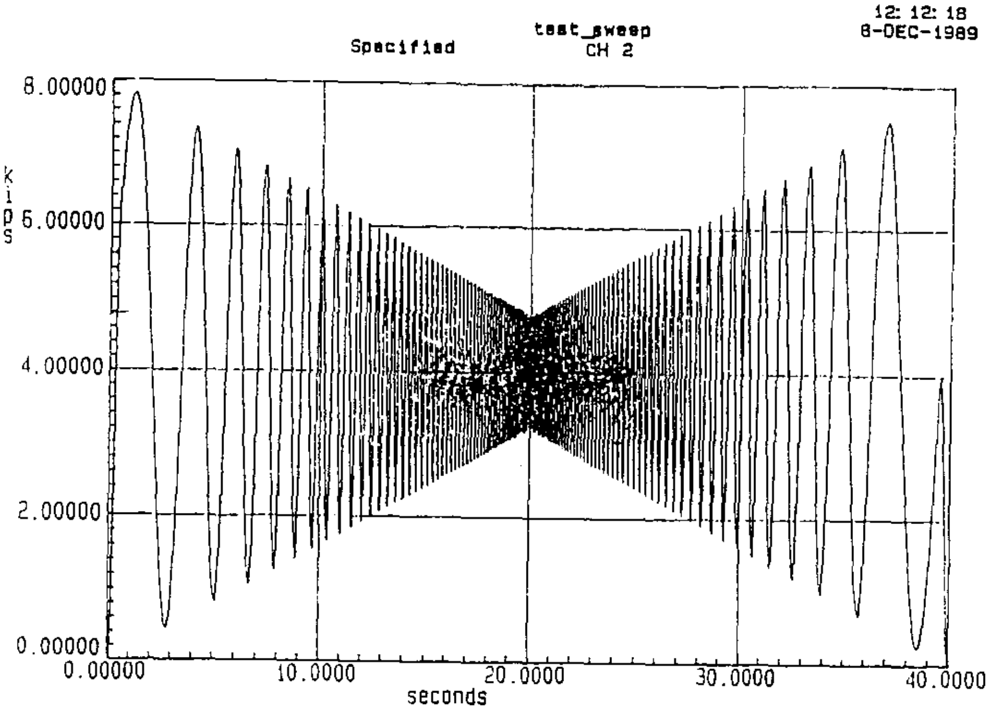


Fig. 1.33

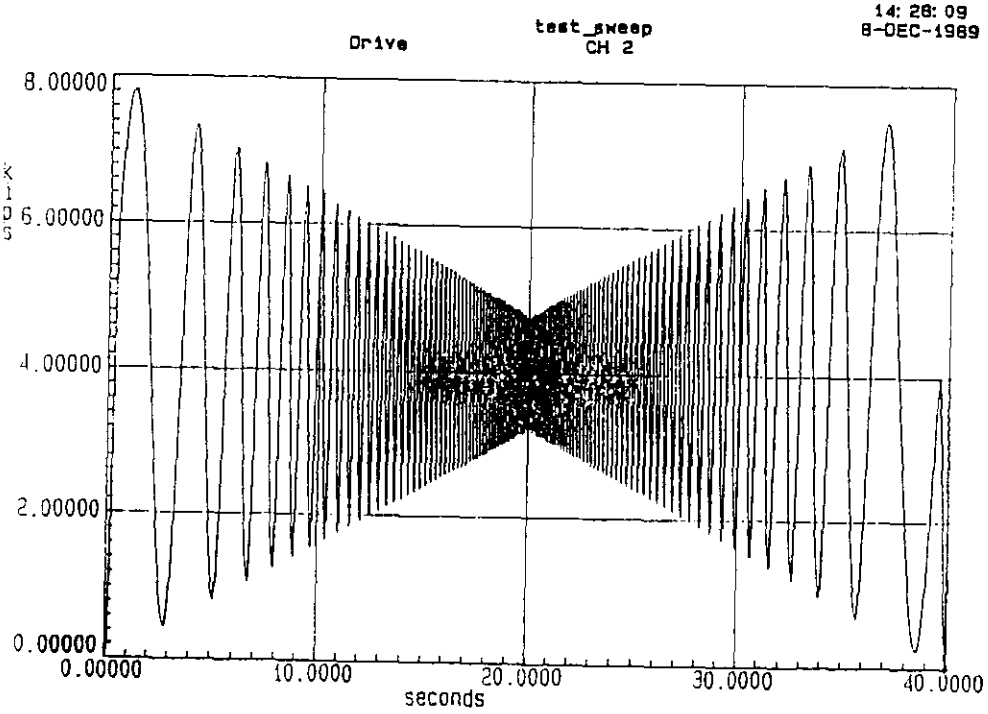


Fig. 1.34

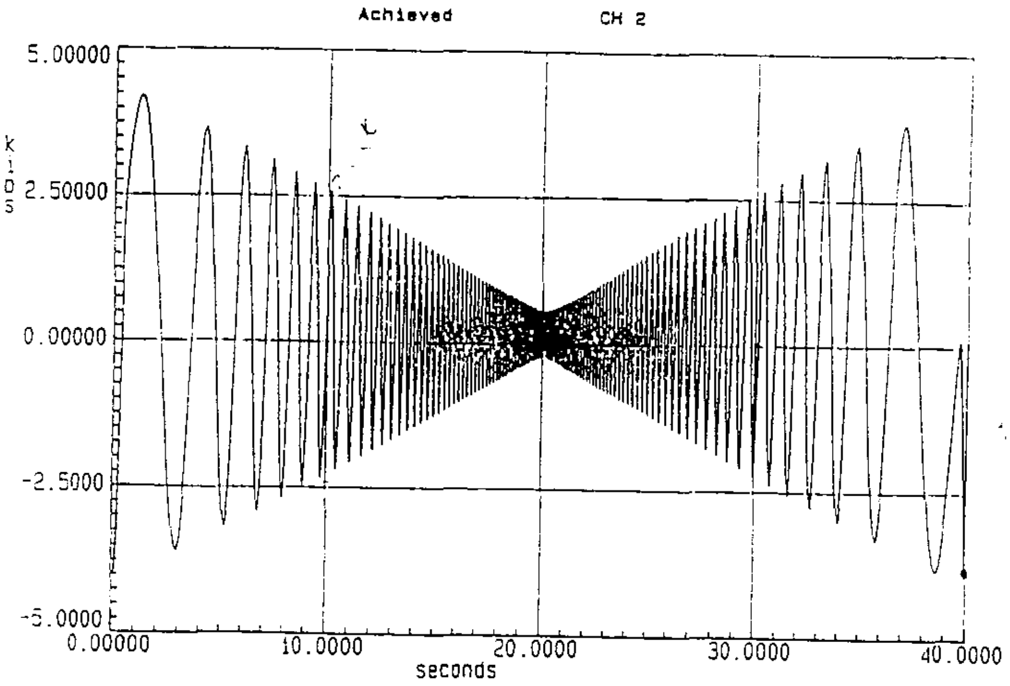


Fig. 1.35

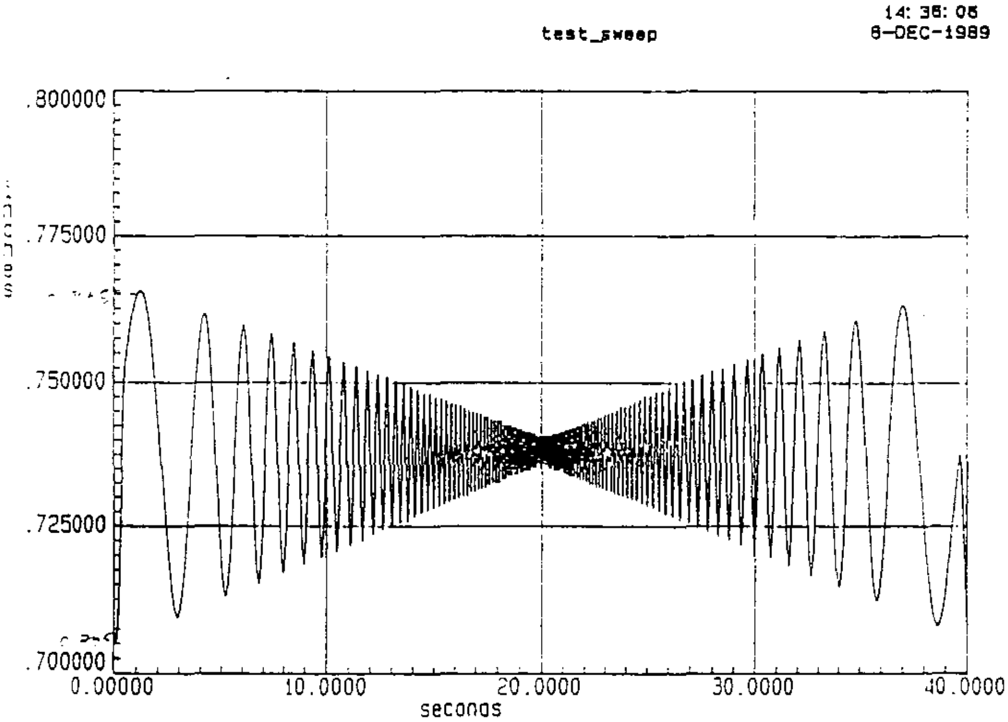


Fig. 1.36

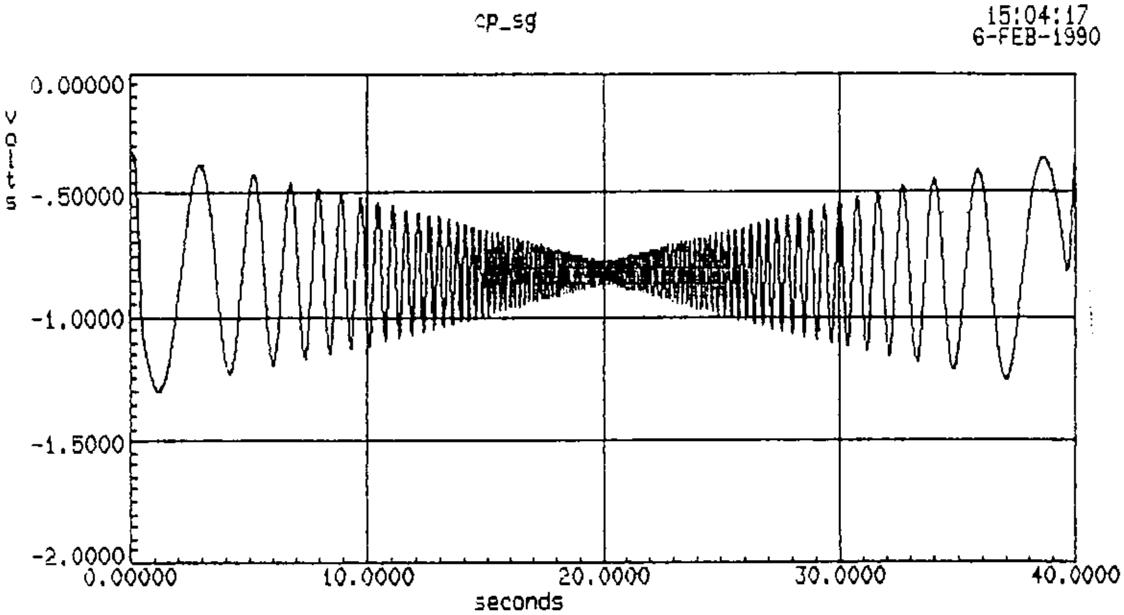


Fig. 1.37

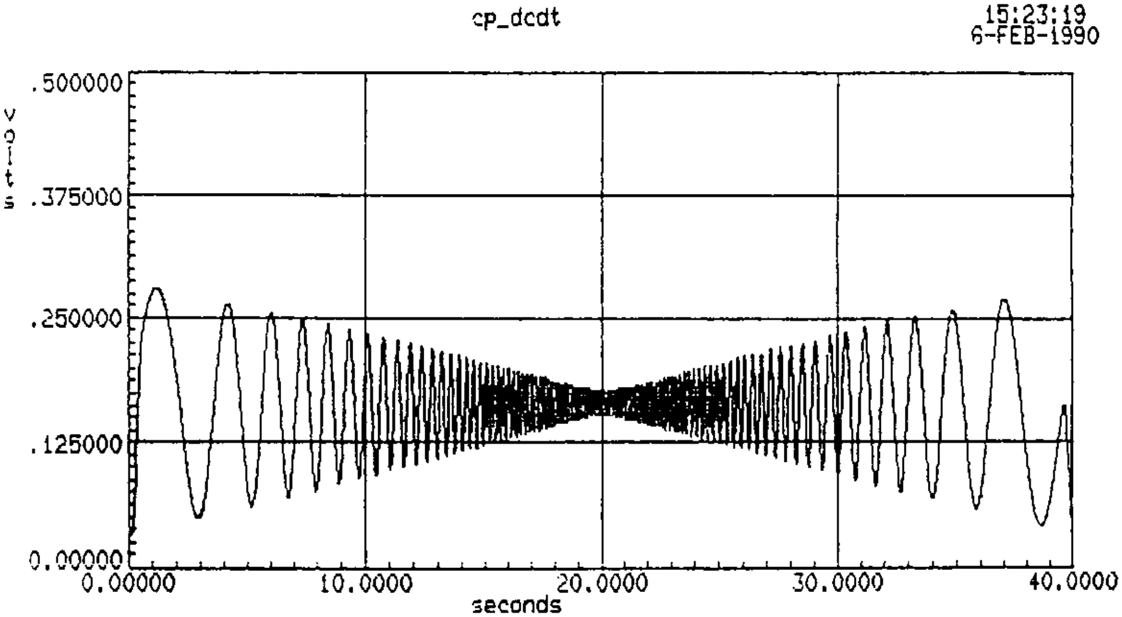


Fig. 1.38

This is because of an offset of approximately 0.73 inches in the displacement channel which was not zeroed out fully. The maximum displacement value corresponding to the first peak is 0.0275 inches and the calculated value corresponding to the first peak is also 0.026 inches.

The transducer feedback (strain gauge) and Transducer feedback (dcdt) are shown in Figs. 1.37 and 1.38. It can be noted that the units of these responses are shown in volts. This is because at the time of the test these transducers were not calibrated and the full scale value of 10.0 volts was given for both the strain gauge and the dcdt. It can be appreciated that the response of the strain gauge and the dcdt have followed the pattern of the forcing function.

PART II

COMPENSATED TESTING

Introduction

Compensated testing is done when the drive signals are required to be adjusted for the system dynamics and the electronics of the testing system. The limitations of the hardware depends on the capacity of the servovalve, the hydraulic pump and the calibration of the system electronics. The servovalve receives the electronic signals from the analog console and sets up the signals which command the hydraulic pump. The hydraulic distribution system pumps the necessary oil at a given time to produce the necessary displacement.

Familiarity of the user to the following topics is assumed in this part.

(i) MTS STEX manual with emphasis on sections DA, RL, ML and EQ.

(ii) Knowledge of Fourier analysis and Random vibrations (Recommended reading: Structural Dynamics by Mario Paz).

(iii) Part I of this manual.

Steps involved in running a compensated test

These steps generally follow the flow chart provided in Chapter 2 of the thesis, but with greater detail.

STEP 1. Define the system configuration in the SYSTEM CONFIGURATION library.

STEP 2. Create the forcing function in the DATA ANALYSIS library.

STEP 3. Create the profile in the PROFILE library.

STEP 4. Define an UNCOMPENSATED PROFILE EARTHQUAKE TEST and execute the same in the EARTHQUAKE TESTING library.

Steps 1 through 4 is the procedure for running an uncompensated test which has been explained in Part I of this manual. The user is advised to refer to Part I for guidance in these steps. The following steps for compensated testing are to be used if on analyzing the results at Step 4, the need for compensation is felt.

STEP 5. Define an Auto spectral density (ASD) function in DATA ANALYSIS library.

STEP 6. Create a random vector in the RANDOM library using the ASD function created in the previous step.

STEP 7. Execute an UNCOMPENSATED RANDOM EARTHQUAKE TEST in the EARTHQUAKE TESTING library.

STEP 8. Create a SYSTEM MODEL using the results of the uncompensated random test in the MODEL library.

STEP 9. Define a COMPENSATED EARTHQUAKE TEST by specifying the system definition, system model and the profile of the desired signal and execute the same in EARTHQUAKE TESTING library.

STEP 10. Tune the signal by comparing the achieved with the desired motion signal and correct the signal if necessary in the EARTHQUAKE TESTING library.

STEP 11. Execute another test using the corrected drive signal.

STEP 12. Repeat steps 10 and 11 as desired.

EXAMPLE TEST

The forcing function is shown in Figure 2.1. It consists of a sine wave with an exponential variation of the frequency from 0.1 Hz to 5.0 Hz over a duration of 30.0 secs. The amplitude of the wave varies from 1.0 inch at 0.1Hz to 0.4 inch at 5.0 Hz. This function is created in a similar manner as the example function used in Part I. Hence the user is advised to refer to Part I for guidance in the creation of such a function.

DISCUSSION OF THE RESULT OF THE UNCOMPENSATED TEST.

For the example test, the achieved signal of the stroke revealed that it followed the drive signal very closely upto approximately 22 seconds, after which it could not produce the amplitudes corresponding to the higher frequencies. An overlay plot of the drive and the achieved signal in the region between 20 and 35 seconds in shown in Figure 2.1 a reveals the same.

This could have been due to (i) the system dynamics of the test setup (the setup is the same as used the tests in Part I), (ii) the limitations of the servovalve and the hydraulic distribution system. Hence, this necessitates the compensation of the drive signal to adjust for the system dynamics and to a some extent overcome the limitations of the hardware.

STEP 5. DEFINITION OF AUTO SPECTRAL DENSITY FUNCTION.

The auto spectral density function is created using the creation command **CASD** in the DATA ANALYSIS library. This function specifies the frequency content of the random function to be created in the next step. The creation dialog **D DA.9P** for the example is shown in Figure 2.2. The created function is shown in Figure 2.3.

NOTE: The units need not be specified here. This is later defined at the stage of creation of the random function.

Factors need to be considered when defining this function:

(i) The frequency content of the forcing function.
(ii) The amplitudes involved in the forcing function.
(iii) The frequency amplitude performance of the servovalve must not be exceeded.

Note that in the example, as the forcing function contains frequency from 0.1 Hz to 5.0 Hz, the ASD function has been defined such that the random function is created with full amplitudes at frequencies below 1 Hz and the amplitude decreases to 10% of the full amplitude at 10 Hz. The amplitude then decreases gradually to 1% at 50 Hz.

STEP 6. CREATION OF RANDOM VECTOR.

Random function is created in the RANDOM library.

The name of the random vector to be created, the name of the analysis session containing the ASD function and the approximate time span are defined in **D RL.1**. For the example, this dialog is shown in Figure 2.4. On entering here, the system prompts for the

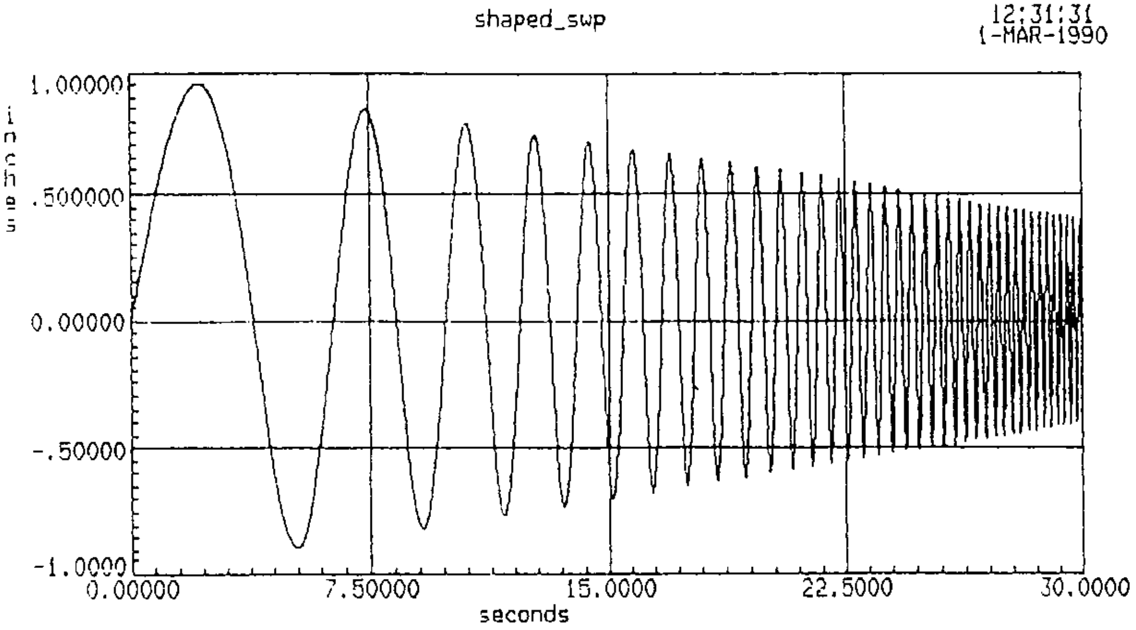


Fig. 2.1

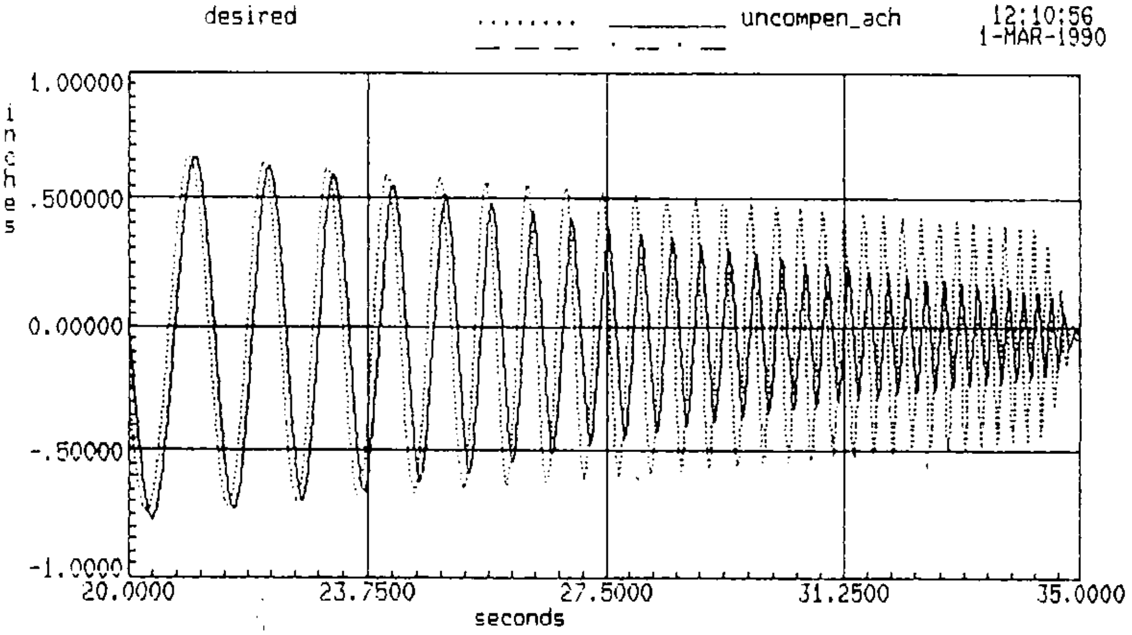
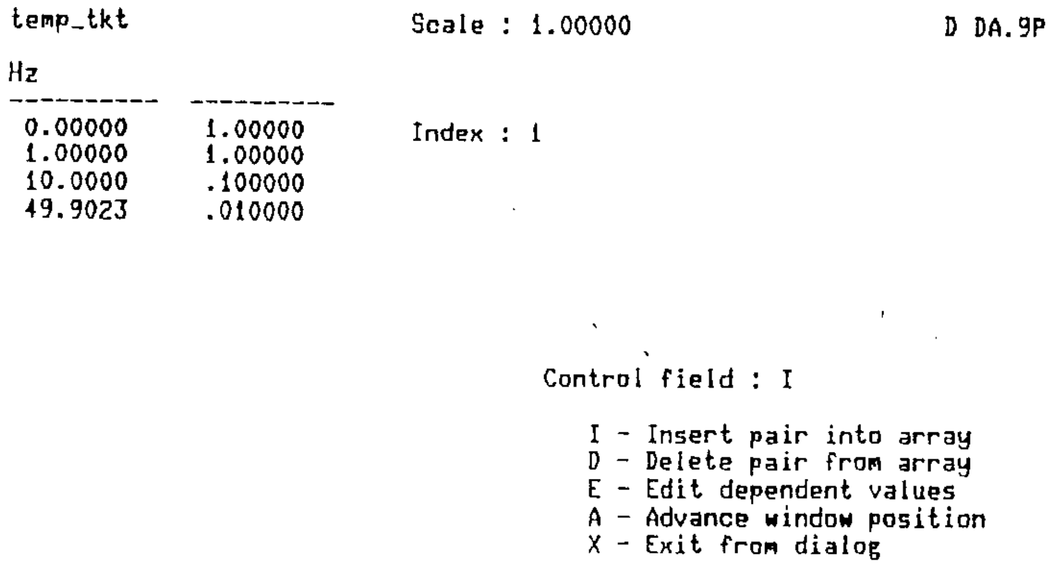


Fig. 2.1a



```
temp_tkt                          Scale : 1.00000                         D DA.9P
Hz
----------  ----------
 0.00000     1.00000              Index : 1
 1.00000     1.00000
 10.0000     .100000
 49.9023     .010000


                                        Control field : I

                                           I - Insert pair into array
                                           D - Delete pair from array
                                           E - Edit dependent values
                                           A - Advance window position
                                           X - Exit from dialog
```

Fig. 2.2

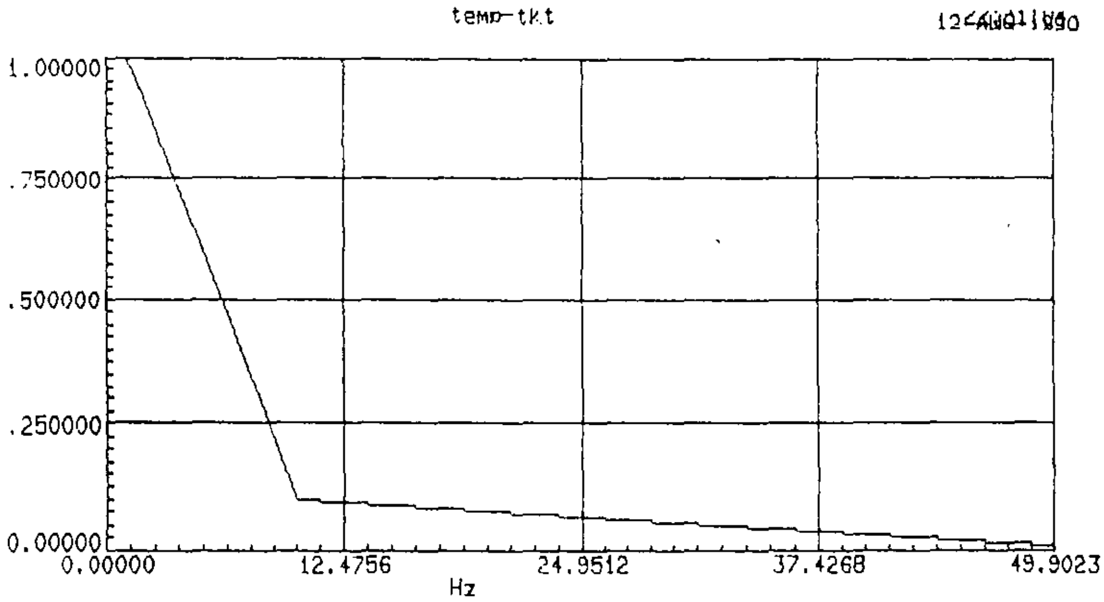
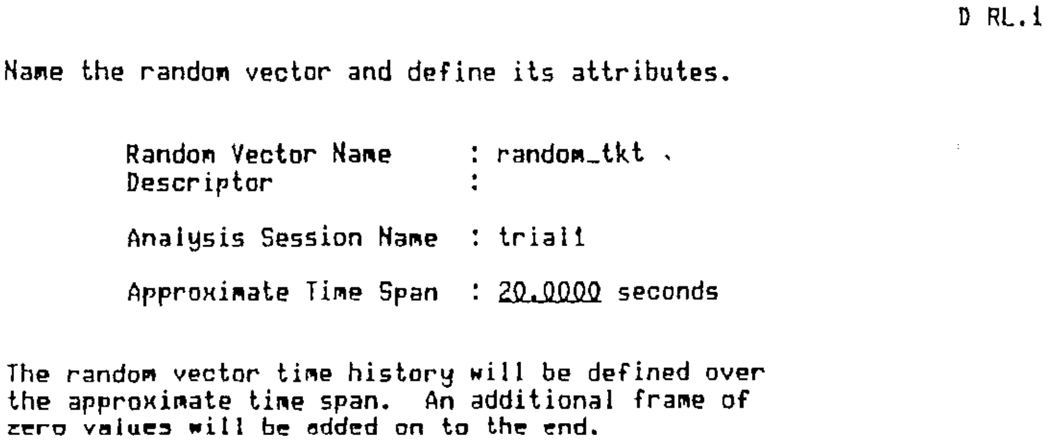


Fig. 2.3



D RL.1

Name the random vector and define its attributes.

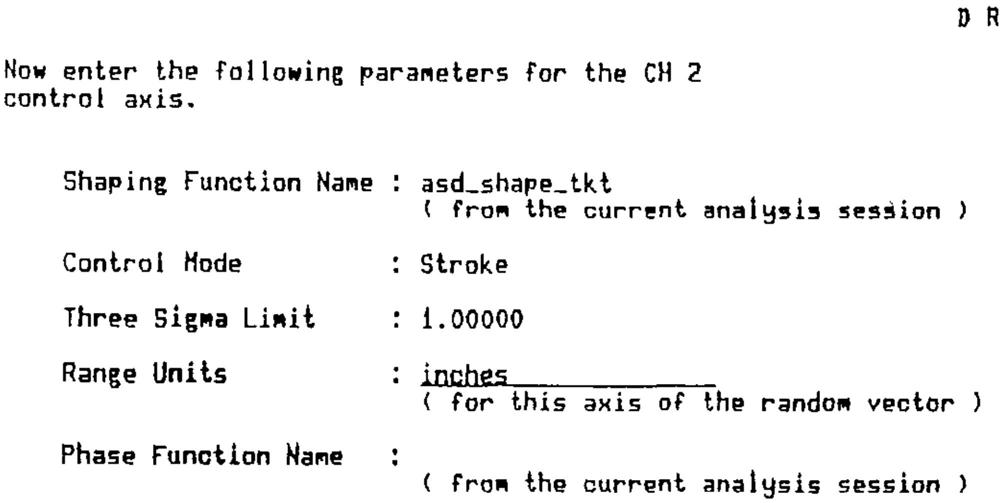
Random Vector Name : random_tkt
Descriptor :

Analysis Session Name : trial1

Approximate Time Span : 20.0000 seconds

The random vector time history will be defined over the approximate time span. An additional frame of zero values will be added on to the end.

Fig. 2.4



D RL.2

Now enter the following parameters for the CH 2 control axis.

Shaping Function Name : asd_shape_tkt
(from the current analysis session)

Control Mode : Stroke

Three Sigma Limit : 1.00000

Range Units : inches
(for this axis of the random vector)

Phase Function Name :
(from the current analysis session)

Fig. 2.5

name of the ASD function to be used for each of the axis being used. Pressing ENTER on the blank dialog would enable bypassing any unused axis. The example uses CH2 and the pertaining dialog is shown in Figure 2.5.

NOTES: 1. The Phase function is optional and is not used in the example. This option may be required when working with a seismic record where the random may be desired to have a phase close to the seismic record.

2. A Random function generated with a random phase function would collect better data from the specimen for the creation of a better model for a function such as the one used in this example.

3. It is suggested that between 5 and 10 frames of random signal be run to generate a good system model.

On pressing ENTER, the system calculates the minimum time span required based on the number of control channels being used. The user is referred to **Section RL** for the algorithm used to calculate the minimum span. This is displayed in **D RL.3** shown in Figure 2.6. The user is allowed to edit this time if a greater time span needs to be set.

On accepting the time span, the system starts to create the random vector. During the creation, it displays the following messages on the screen.

"Creating random vector"
"Working on white noise vector"
"Working on random noise vector"

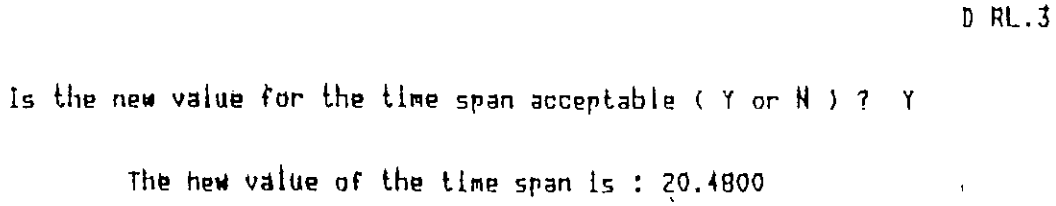
" Random vector NAME was successfully saved"

This random vector can be used directly to run an uncompensated random earthquake test without setting a profile. The random vector created is shown in Figure 2.6 a.

STEP 7. EXECUTION OF UNCOMPENSATED RANDOM EARTHQUAKE TEST.

The choice R in the EARTHQUAKE TESTING library menu prompts the user to define the name of the random test, the system definition name, and the name of the random function in the RANDOM library in **D EQ.1R** which has been shown for the example test in Figure 2.7. The rest of the procedure involved in the setting of the hardware and the execution of the test is similar to the Uncompensated Profile Earthquake Test as explained in Section 2 of Part I. A post test analysis is not required, while it is possible to do so as described in Section 3 of Part I.

STEP 8. CREATION OF SYSTEM MODEL.



```
                                                              D RL.3

Is the new value for the time span acceptable ( Y or N ) ?  Y

       The new value of the time span is : 20.4800
```

Fig. 2.6

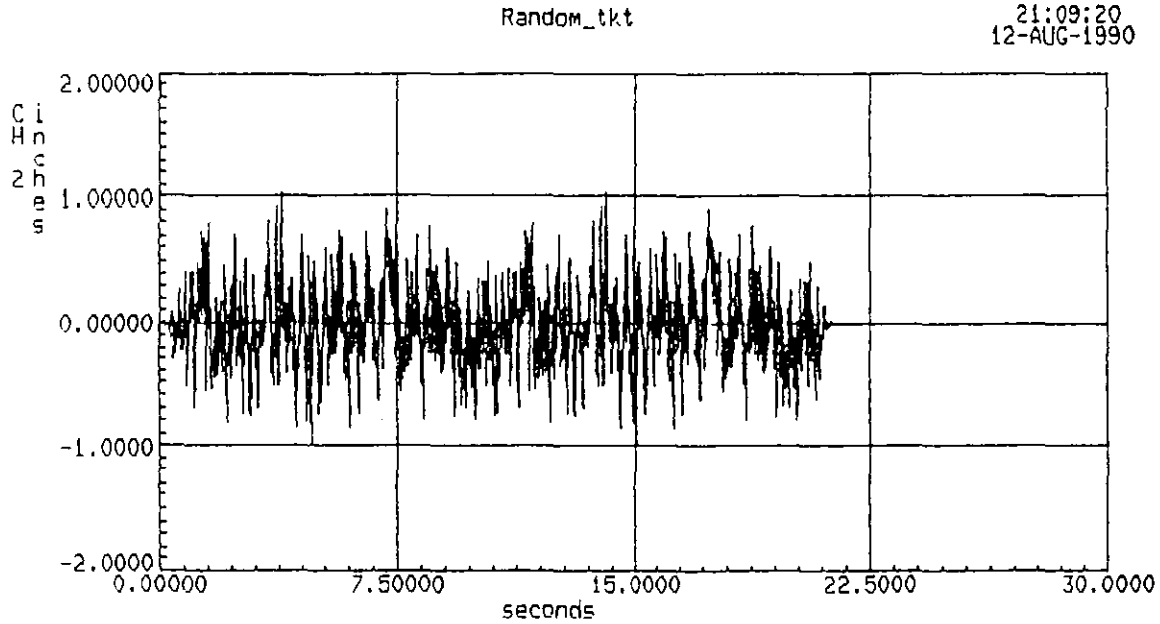
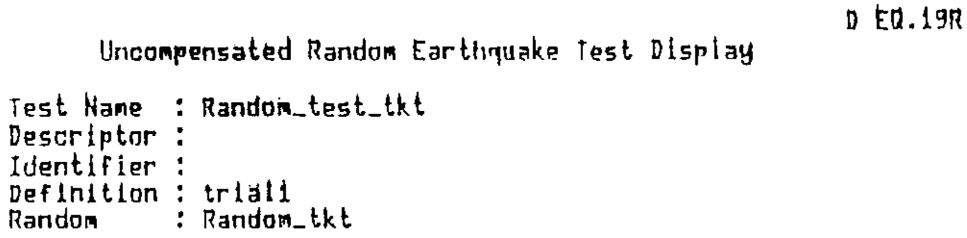


Fig. 2.6a



```
                                                        D EQ.19R
      Uncompensated Random Earthquake Test Display

  Test Name  : Random_test_tkt
  Descriptor :
  Identifier :
  Definition : triali
  Random     : Random_tkt
```

Fig. 2.7

The procedure for creating a good system model involves the following steps.

A. Creation of the system model by defining the name of the random function.

B. Evaluation of the system model created.

C. Creation of the Expanded Inverse.

D. Modification of the Expanded Inverse function as required.

A. Creation of the System Model

The system model is created in the MODEL library using the results of the uncompensated random test made in the previous step. Option **N** in **M ML**.1 is chosen to create a model. M ML.1 is shown in Figure 2.8. The system then prompts with D ML.2, shown in Figure 2.8a for defining the name of the test to be used. On opting to create the system model from this dialog, the system works on creating the various matrices, vectors and functions associated with the system model. It displays messages during the creation of the same. These functions are displayed on Figure 2.9 on the dialog D ML.4.

B. Evaluation of the System Model

At the completion of the creation of the various functions, the system displays the Model Evaluation Options menu **M ML**.3 which is shown in Figure 2.10. This menu provides the options to evaluate the System Model and to create the Expanded Inverse.

A typical evaluation sequence is outlined on page ML-7 in Section ML of STEX manual. The purpose of the process of evaluation is to refine the expanded inverse function which alone modifies the drive data during the compensated test. The other functions and matrices are provided to enable a better understanding of the response of the Uncompensated Random Test. These are the tools of the Spectral Analysis of a random function and its response. Knowledge of Fourier Analysis and Random Vibrations is required to understand the various functions listed in Figure 2.9.

The choice to plot the system model from M ML.3 prompts the user with the dialog D ML.4. Any item in D ML.4 can be plotted by specifying the appropriate number. The system displays the plotting options menu D P5 shown in Figure 2.10 a before plotting. The plots of the various Matrices, Vectors and Functions for the example test are shown from Figures 2.11 through 2.20. Each of this item is discussed below.

1. **System Frequency Response:** This function is obtained by

```
        Model Library Utility Options                          M ML.1


      KEY      Option Activated with 'KEY'

       N        Create or Edit a Model
       D        Delete a Model from the Library
       P        Display a Model
       L        List the Model Library Directory

       X        Exit from Model Options
```

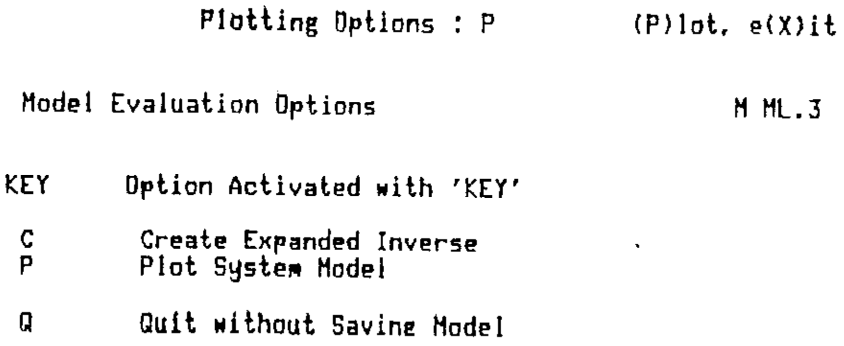
Fig. 2.8

```
                                                                  D ML.2

Enter the name of the test upon which the model derivation
is to be based.

        Test Name - random_tkt
```

Fig. 2.8a

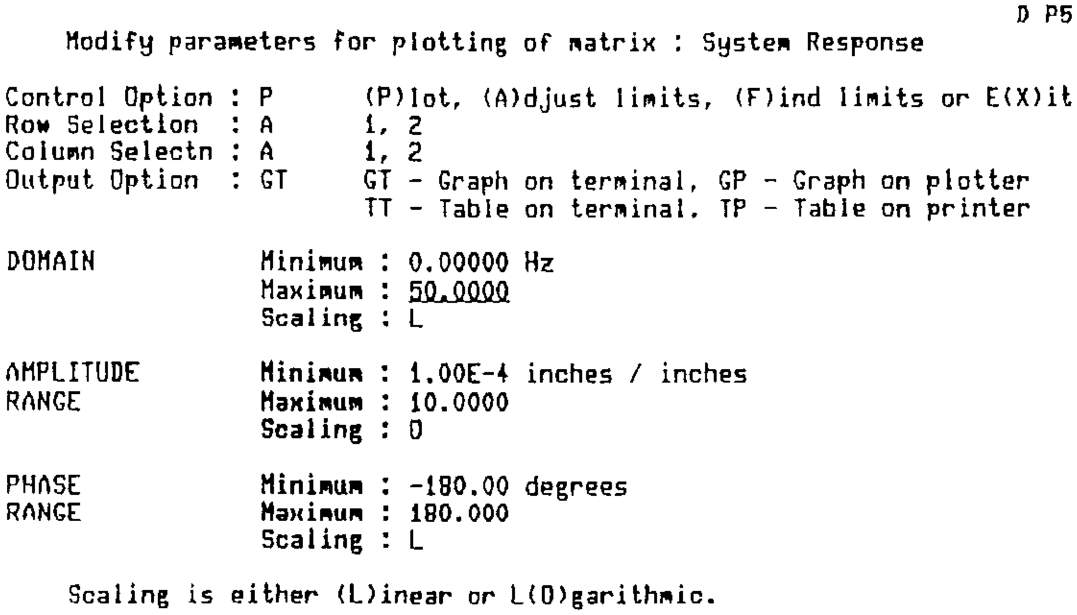
```
                                                                D ML.4

Enter index for display of a matrix, vector, or function from
model Model_tkt

        Index : 1

        Index       Matrix / Vector / Function
          1  -  System Frequency Response
          2  -  Inverse System Frequency Response
          3  -  Drive Auto Spectral Density
          4  -  Response Auto Spectral Density
          5  -  Drive/Response Cross Spectral Density
          6  -  Drive/Response Ordinary Coherence
          7  -  Expanded Inverse Matrix
          8  -  Drive Motion Vector
          9  -  Response Motion Vector
          0  -  Determinant
```

Fig. 2.9



```
            Plotting Options : P          (P)lot, e(X)it

   Model Evaluation Options                             M ML.3

  KEY      Option Activated with 'KEY'

   C         Create Expanded Inverse
   P         Plot System Model

   Q         Quit without Savine Model
```

Fig. 2.10



```
                                                              D P5
    Modify parameters for plotting of matrix : System Response

Control Option : P      (P)lot, (A)djust limits, (F)ind limits or E(X)it
Row Selection  : A      1, 2
Column Selectn : A      1, 2
Output Option  : GT     GT - Graph on terminal, GP - Graph on plotter
                        TT - Table on terminal, TP - Table on printer

DOMAIN           Minimum : 0.00000 Hz
                 Maximum : 50.0000
                 Scaling : L

AMPLITUDE        Minimum : 1.00E-4 inches / inches
RANGE            Maximum : 10.0000
                 Scaling : O

PHASE            Minimum : -180.00 degrees
RANGE            Maximum : 180.000
                 Scaling : L

    Scaling is either (L)inear or L(O)garithmic.
```

Fig. 2.10a

performing a Fourier Transform on the Achieved signal of the Uncompensated Random Test. The Fourier Transform technique transforms the time history function to a frequency function. This provides the information on the response of the system for the various frequencies.

For the example test, this function is shown in Figure 2.11. As the beam used had a natural frequency of 294 Hz, this response does not show any sharp spike. It can be seen that the response decreases from 1.0 inch / inch at 0 Hz and reduces to approximately 0.2 inch / inch at 10 Hz; it reduces gradually further with greater variations upto 50 Hz.

The Phase function provided at the bottom of the function gives the phase difference corresponding to the frequency. An ideal phase function with no distortion will be linear. Hence, a non-linear region would represent a greater distortion.

NOTE: This function as a whole is a part of a matrix of the order N, where N is the number of Degree of Freedoms (DOF) used. In the example test only one DOF at CH2 (Channel 2) was used.

2. **Inverse System Frequency Response:** This function is just the inverse of the System Frequency Response. It can seen as the mirror image of the previous function. For the example test, this function is shown in Figure 2.12.

3. **Drive ASD:** This is an auto spectral density function of the drive signal. The ASD function can be defined as the Fourier Transform of the mean square of the random vector, when it is done on a single record of random vector. This function can be considered to be the energy represented by the various frequencies in the random vector. Hence, this function helps is identifying the predominant frequencies present in the given vector.

For the example test, this function is shown in Figure 2.13. It can be noted that a predominant response is noted between 0 Hz and 10 Hz which corresponds to the ASD function defined in the Data Analysis library used for the creation of the Random function. In fact, this function is the same ASD function plotted in the log scale.

Note that there is zero phase change, indicating that there is no frequency distortion. This makes sense as no phase function was defined during the creation of the Random function.

4. **Response ASD:** This is ASD function of the Achieved signal of the random test. For the example test, this function is given in Figure 2.14. In comparison to the Response function, it can be inferred that this function follows the pattern of the Response function but over a wider variation of the ordinate. In general, the ordinate values are small because the Spectral Density function is the mean square of the ordinates of the Achieved signal represented in the frequency range.

5. **Drive/Response Cross Spectral Density:** This can be defined as the ASD analysis done on two different records. For the example

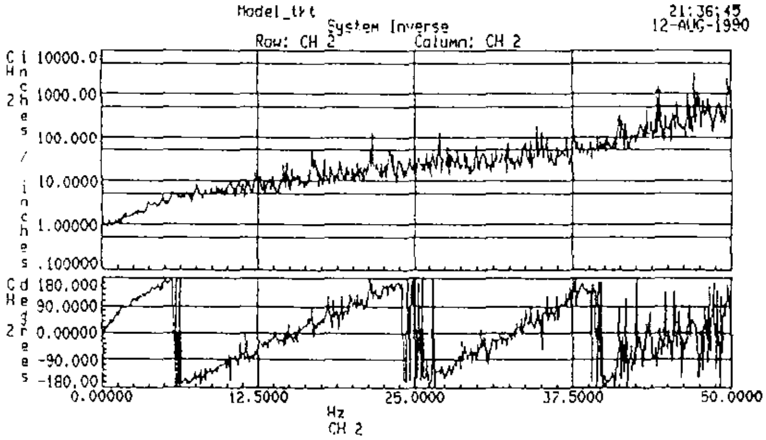


Fig. 2.11

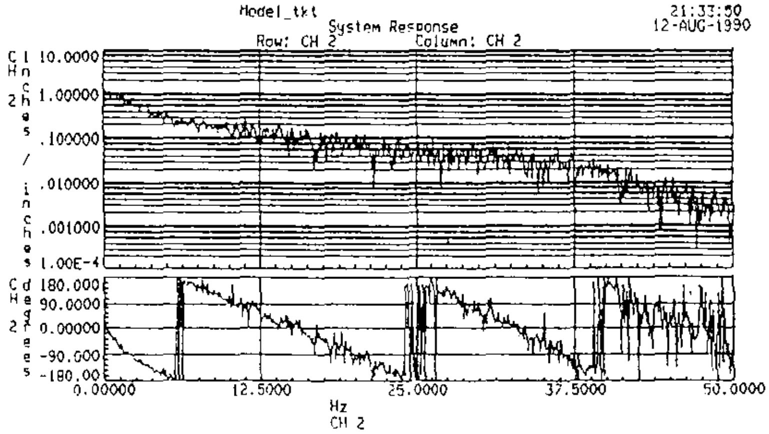


Fig. 2.12

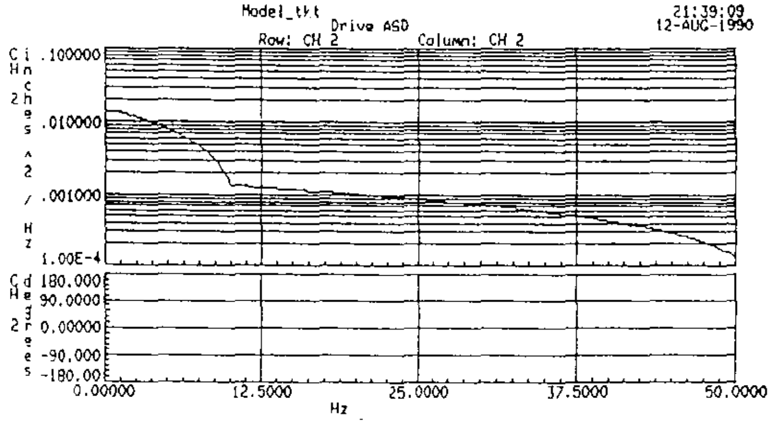


Fig. 2.13

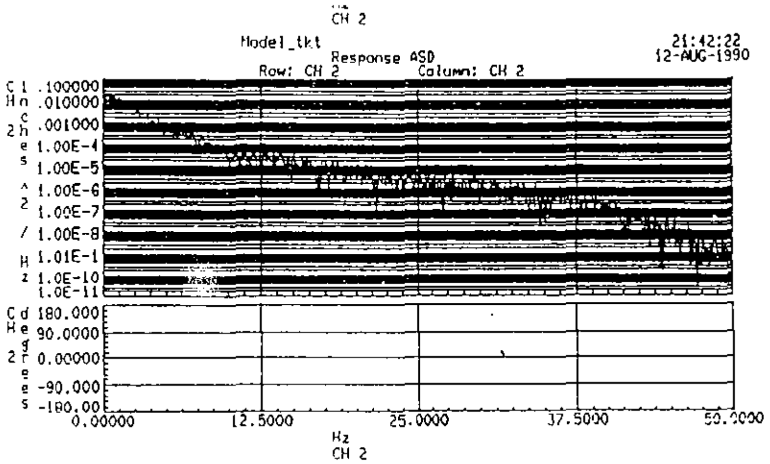


Fig. 2.14

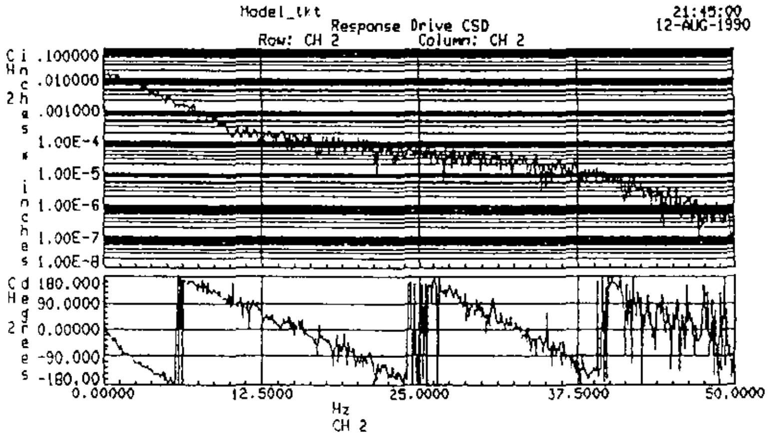


Fig. 2.15

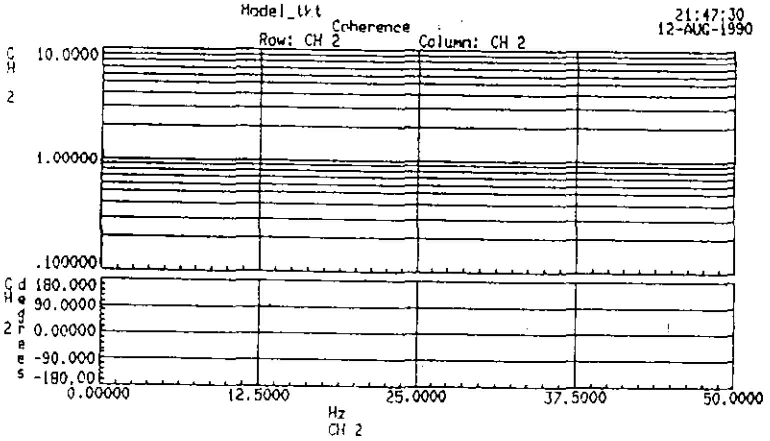


Fig. 2.16

test, this function is shown in Figure 2.15. It can be seen that the predominant response is over the range from 0 Hz. to 10 Hz.

6. **Drive/Response Ordinary Coherence:** This can be defined as the Fourier Transform of the Correlation function. It is a measure of the coherence of the frequency of the response of the specimen with that of the excitation signal. It can be seen that a Coherence of unity was obtained for the example test, shown in Figure 2.16, which means that the specimen beam vibrated at the same frequencies as the drive signal, however producing less displacements. Phase lag is zero throughout which demonstrates that the system tries to maintain the frequency rather than the amplitude.

7. **Expanded Inverse Matrix:** This matrix contains the Expanded Inverse functions corresponding to the DOFs involved. This function is developed from the Inverse Response function by the operations of Zeroing and Clipping. This function is shown in Figure 2.17 for the example test. The function shown here has been using the option C of M ML.3.

8. **Drive Motion Vector:** This is the same drive signal created in the Random library. For the example test this is shown in Figure 2.18.

9. **Response Motion Vector:** This is the same as the Achieved signal obtained in the Random Uncompensated Test. This is shown in Figure 2.19 for the example test.

0. **Determinant:** This is the determinant of the elements present in the response function matrix.

C. Creation of Expanded Inverse Function

The Expanded Inverse is created by opting C of M ML.3. Then the system displays the default Clipping Factor and prompts the user to modify the same if required. The Clipping factor decides the Clipping Level that will be used by the system in smoothening the Inverse function in the desired range of frequencies. These dialogs corresponding to the example test are shown in Figures 2.21 and 2.22. The default clipping factor is used in this example test.

Then the system prompts with D ML.10 and D ML.9 which is shown in Figure 2.23. As it can be seen in the Figure, D ML.10 displays the matrix of DOFs and the default frequency regions which will be zeroed. D ML.9 prompts to define the zeroed-region to be edited. In the example this is A. On defining A and entering, the system displays the editing menu D ML.8 in the place of D ML.9 which is shown in Figure 2.24. For the example test, the portion beyond 10 Hz. was zeroed. After defining the regions to be zeroed, choose C to create the new Expanded Inverse function. Then the system displays the Model Evaluation menu.

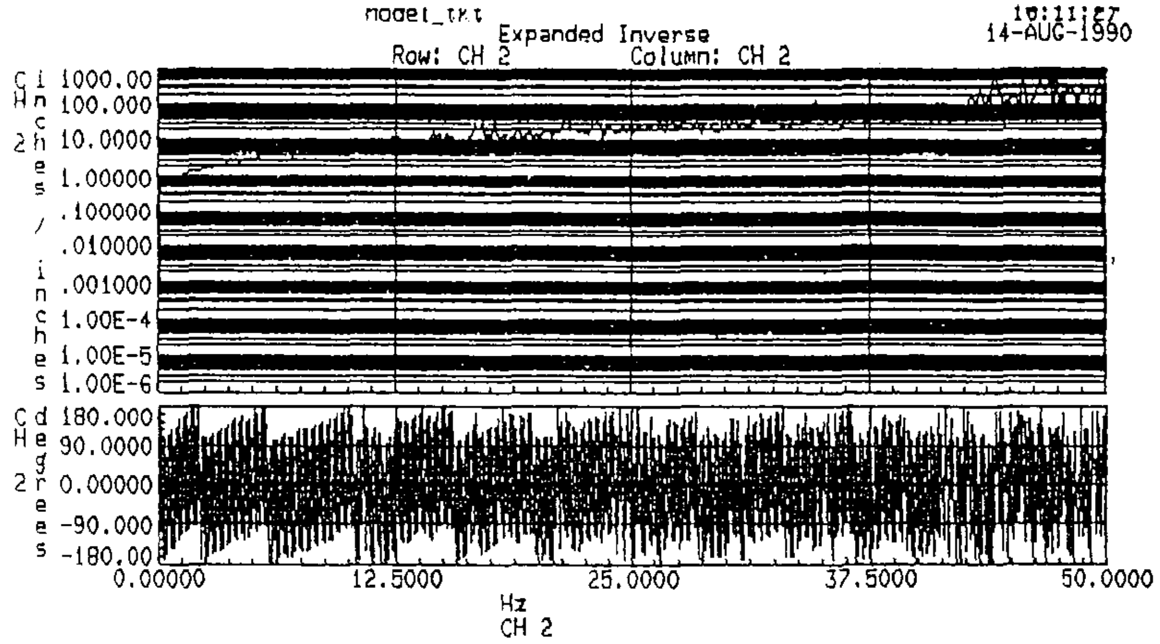


Fig. 2.17

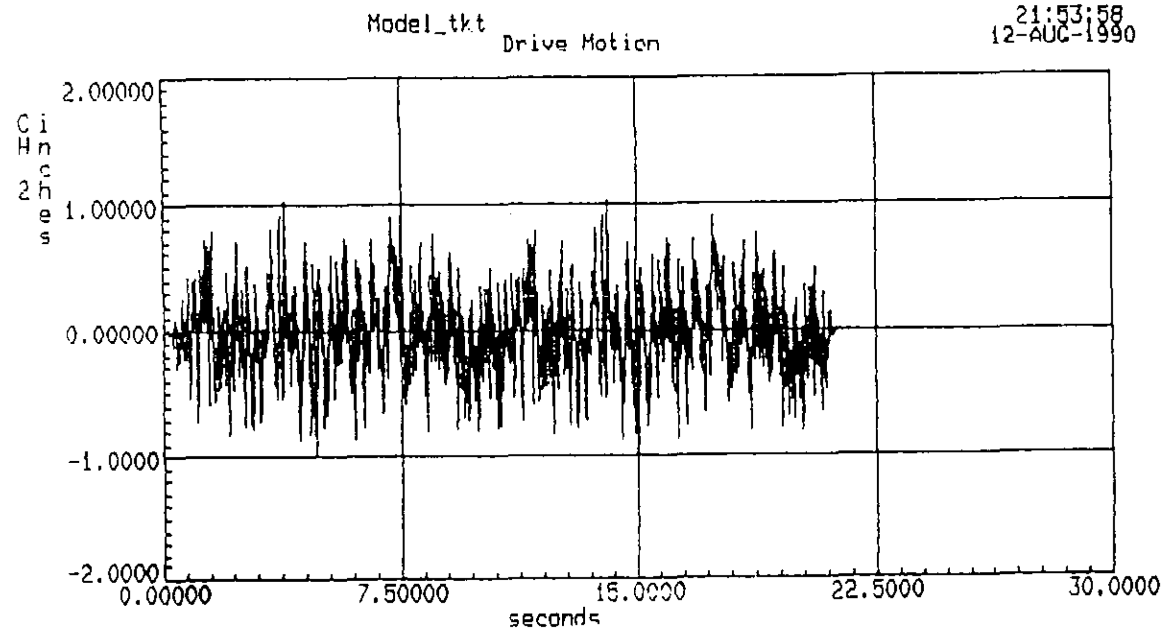


Fig. 2.18

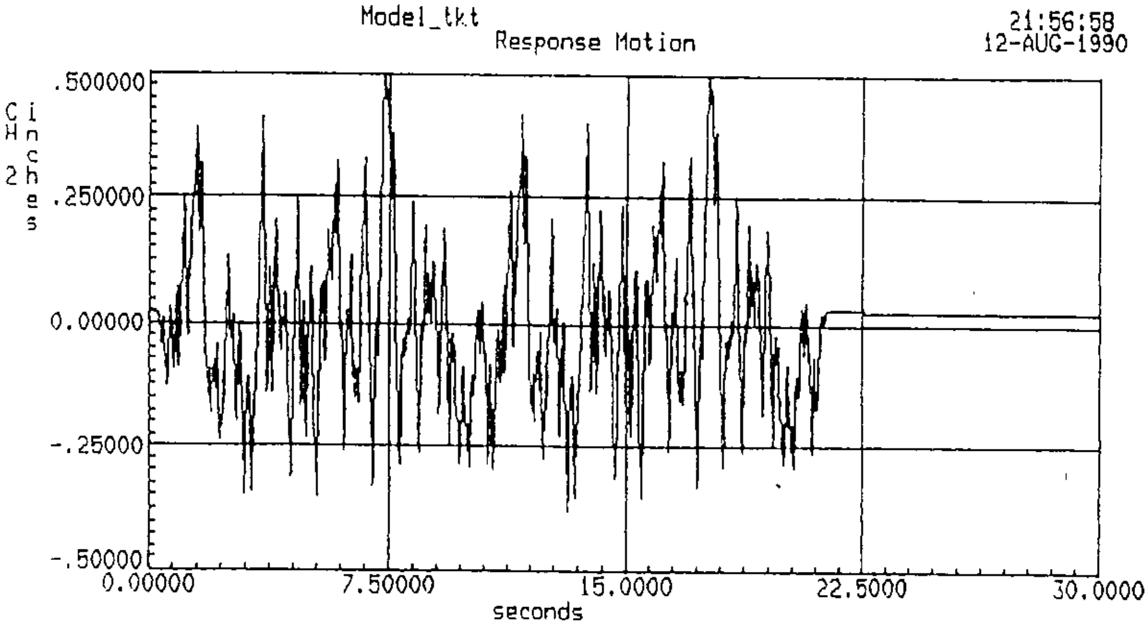


Fig. 2.19

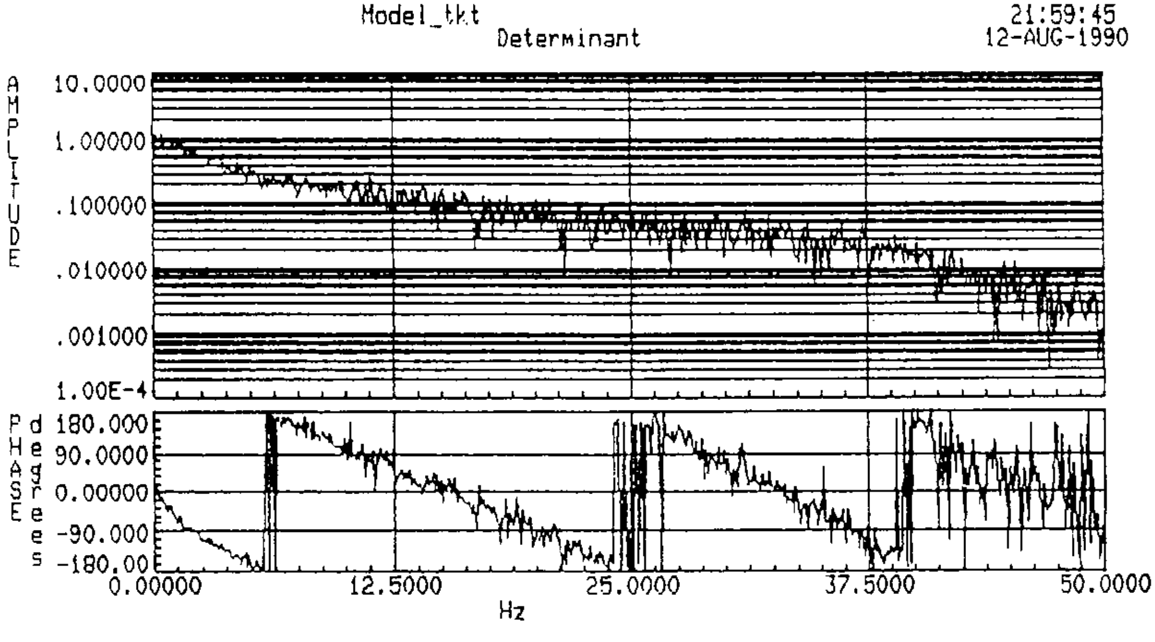


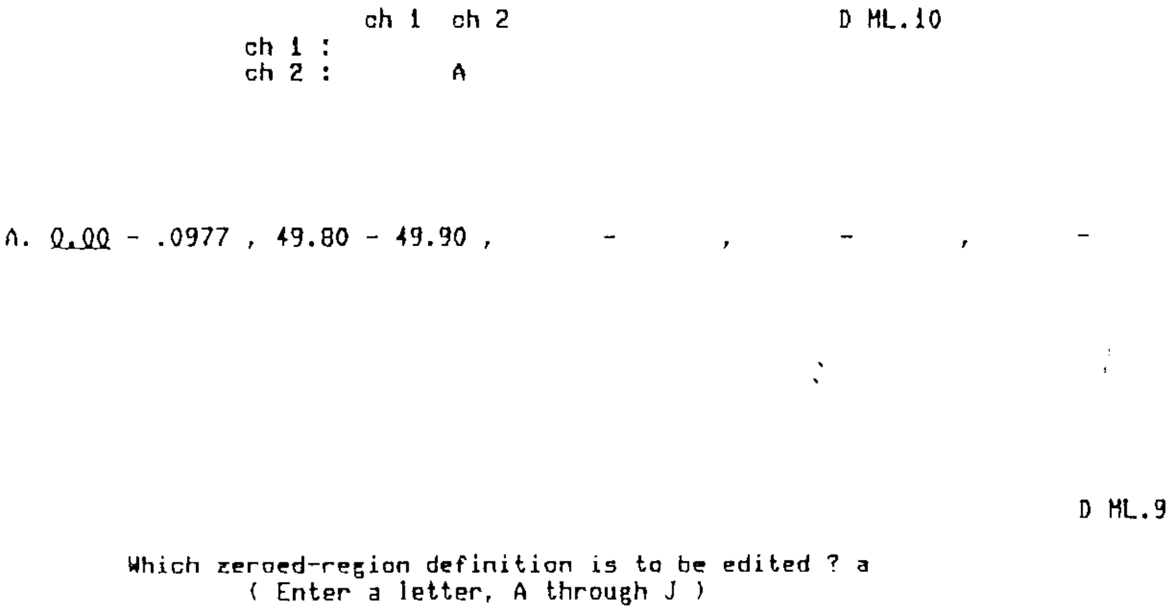
Fig. 2.20

```
                                                    D ML.6

The clipping factor default value is : 1000.00


Do any of the clipping factors need to be individually
edited (Y or N) ? N
```

Fig. 2.21

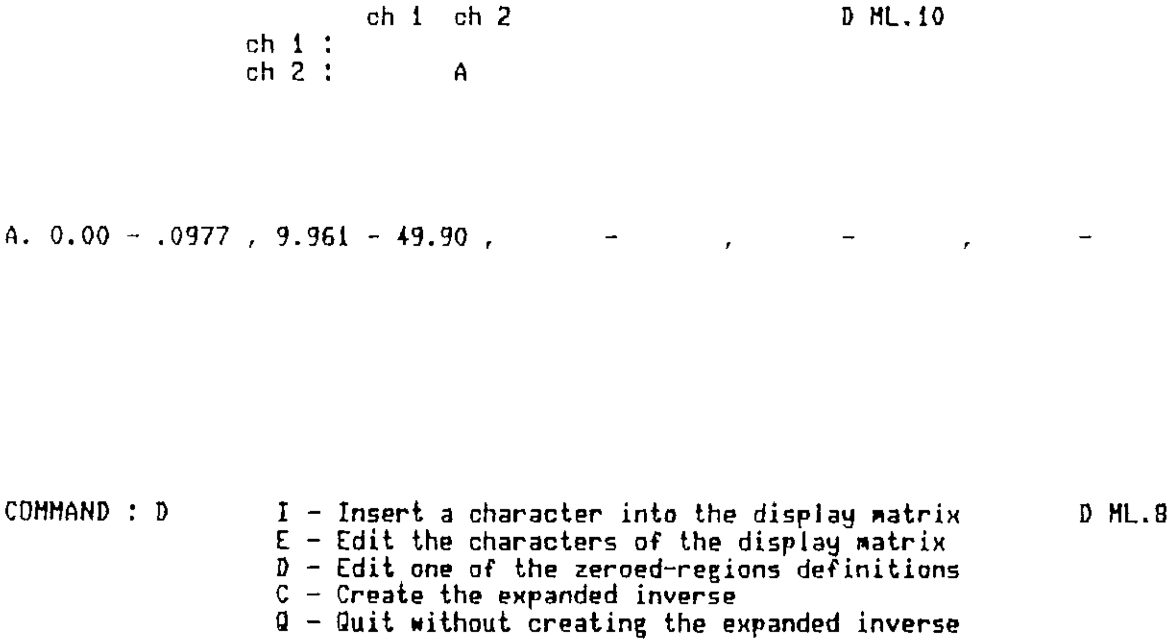
```
                                                    D ML.7
                    Clipping Factors

                   ch 1        ch 2


          ch 1 :


          ch 2 :              1000.00
```

Fig. 2.22



```
                ch 1  ch 2                          D ML.10
          ch 1 :
          ch 2 :       A



A. 0.00 - .0977 , 49.80 - 49.90 ,         -         ,         -         ,         -




                                                                                D ML.9

      Which zeroed-region definition is to be edited ? a
              ( Enter a letter, A through J )
```

Fig. 2.23



```
                ch 1  ch 2                          D ML.10
          ch 1 :
          ch 2 :       A



A. 0.00 - .0977 , 9.961 - 49.90 ,         -         ,         -         ,         -




COMMAND : D          I - Insert a character into the display matrix          D ML.8
                     E - Edit the characters of the display matrix
                     D - Edit one of the zeroed-regions definitions
                     C - Create the expanded inverse
                     Q - Quit without creating the expanded inverse
```

Fig. 2.24

The Expanded Inverse function can once again be evaluated by plotting the same. The modified Expanded Inverse function is the one in Figure 2.17 for the example test.

D. Modification of the Expanded Inverse function

The process explained in the above steps C and D may be repeated to refine the Inverse function.

NOTE: The Expanded Inverse function is also called the Transfer function.

STEP 9. EXECUTION OF COMPENSATED TEST.

A compensated test is defined in the EARTHQUAKE library by choosing the option C. This option prompts the user with **D EQ.19C** to define the following:

1. Name of the test
2. Name of the system definition
3. Name of the system model and
4. Name of the profile of the desired signal.

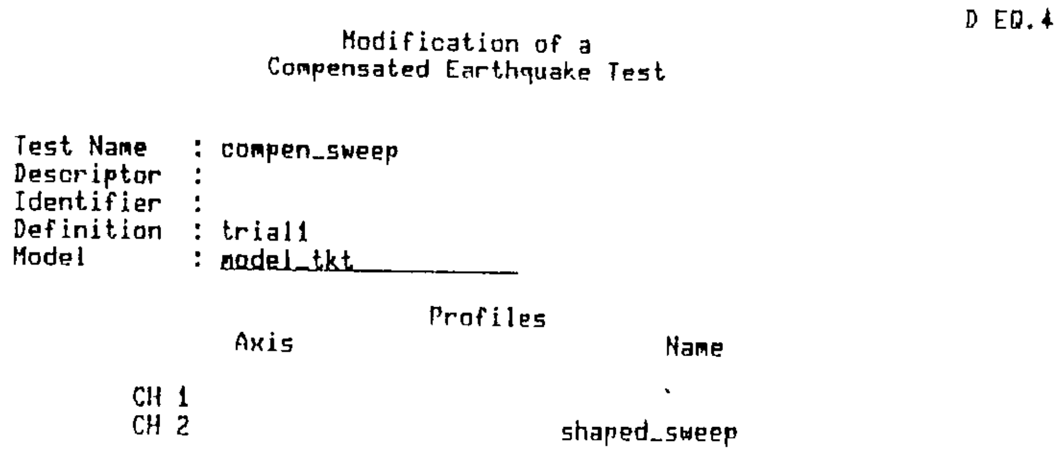
D EQ.19C is shown in Figure 2.25.

On confirming to continue with the excitation, the system displays D EQ.8, shown in Figure 2.26, prompting the confirmation of the filter settings made in the System Configuration library. At this point, the Loop Back Jack must be in place in the digital console. This prevents the signal from going to the actuator, but lets the signal to loop back into the console making the signals to pass through the filter channels. This enables the system to take into account the effect of filtering through the anti-aliasing filters. Once this process is over, the system returns to the Test Execution menu.

The rest of the procedure leading to the execution of the test is similar to that explained in Section 2 of Part I. The user is advised to refer this section for further guidance in execution.

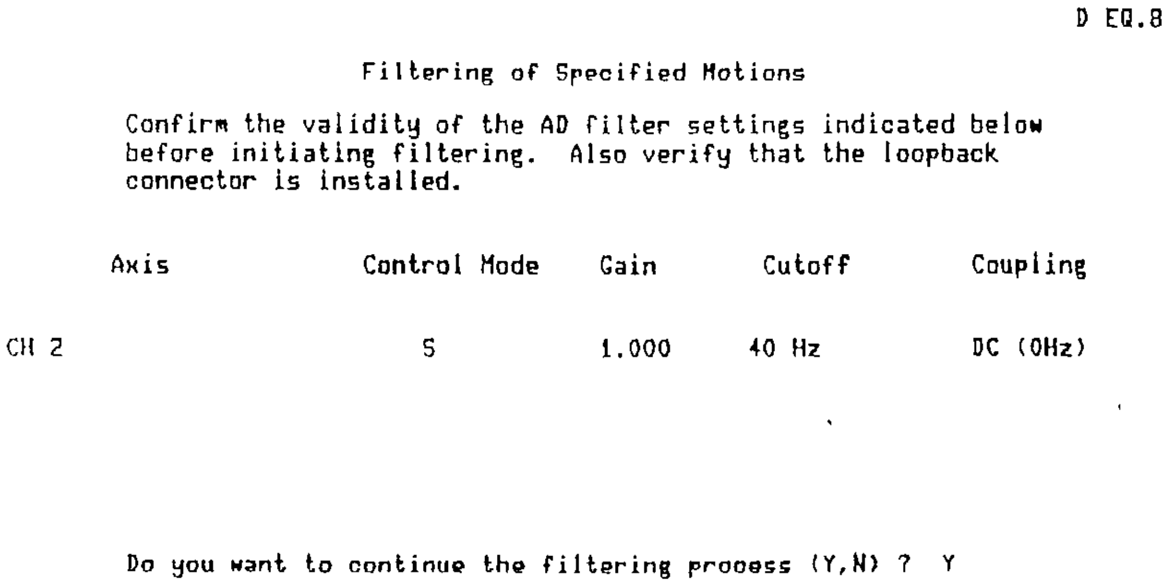
STEP 10. TUNING THE DRIVE SIGNAL

A successful completion and saving of the compensated test prompts the user with the Testing Control Options menu **M EQ.2C**. This menu is shown in Figure 2.27. The option **T** of this menu enables tuning the system. This option initiates the calculation of the difference (errors) between the achieved and the desired signals, and then calculate the correction to the drive signal.



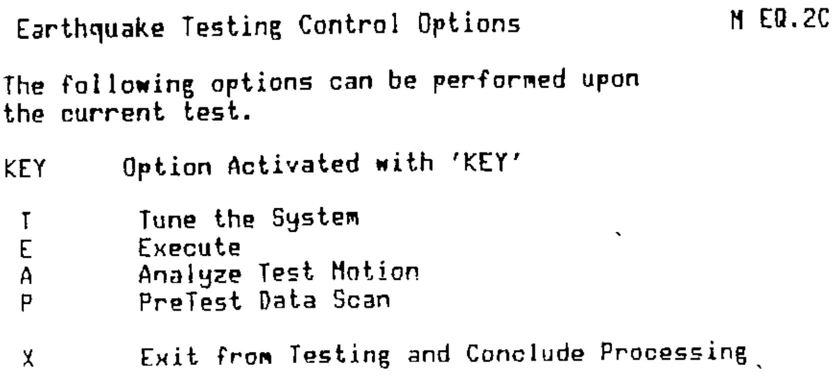
```
                                                        D EQ.4
                     Modification of a
                 Compensated Earthquake Test

Test Name   : compen_sweep
Descriptor  :
Identifier  :
Definition  : trial1
Model       : model_tkt

                          Profiles
             Axis                         Name

     CH 1
     CH 2                              shaped_sweep
```

Fig. 2.25



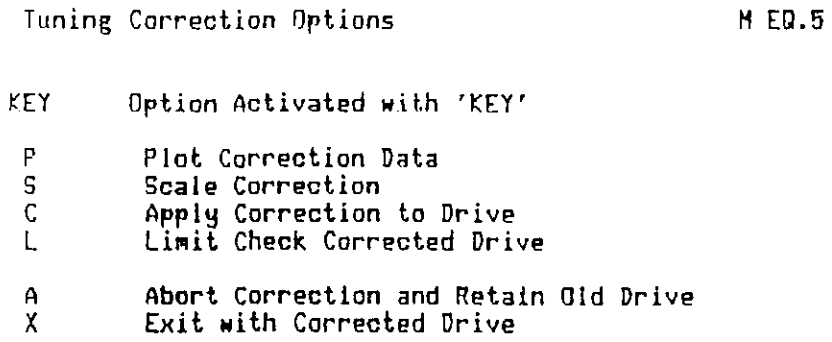
```
                                                              D EQ.8

                    Filtering of Specified Motions

     Confirm the validity of the AD filter settings indicated below
     before initiating filtering.  Also verify that the loopback
     connector is installed.

       Axis              Control Mode   Gain      Cutoff       Coupling

CH 2                          S         1.000    40 Hz         DC (0Hz)



     Do you want to continue the filtering process (Y,N) ?  Y
```

Fig. 2.26



```
Earthquake Testing Control Options                M EQ.2C

The following options can be performed upon
the current test.

KEY      Option Activated with 'KEY'

 T        Tune the System
 E        Execute
 A        Analyze Test Motion
 P        PreTest Data Scan

 X        Exit from Testing and Conclude Processing
```

Fig. 2.27



```
Tuning Correction Options                        M EQ.5


KEY      Option Activated with 'KEY'

 P        Plot Correction Data
 S        Scale Correction
 C        Apply Correction to Drive
 L        Limit Check Corrected Drive

 A        Abort Correction and Retain Old Drive
 X        Exit with Corrected Drive
```

Fig. 2.28

After it calculates the first correction, it displays the Tuning Corrections Options **M** EQ.5 which is shown in Figure 2.28. This option allows the user to plot the correction, scale it if required, apply the correction to the drive signal, check the limits of the corrected drive and exit with or without applying the correction to the drive signal.

For the example test, the corresponding achieved signal is shown in Figure 2.29 an overlay plot with the achieved signal of the uncompensated test in the time range between 20 and 35.0 seconds. It can be observed from this Figure that the compensated test has performed better producing larger amplitudes throughout this range.

The correction calculated is shown in Figure 2.30. It can be understand from this signal that there is not much correction required upto 20 seconds while huge corrections are required in the later part of the signal where the frequency becomes high. The drive signal after the correction has been applied is shown in Figure 2.31. It can be understood from this signal that the drive signal has been overprogrammed to push the hardware to pump out more oil per second (hence more displacement) to compensate for the effects which reduce the amplitude at the higher frequencies. This would be the drive signal for the next compensated test.

STEP 11. EXECUTION OF COMPENSATED TEST WITH THE CORRECTED DRIVE.

Exiting with the corrected drive in M EQ.5 prompts the system to proceed with the test execution. After the execution and successful saving of the test the system calculates the error and displays Tuning Options Menu **M EQ.6**.

This allows the user to analyze the newly achieved data, create new correction signals, store the old or corrected signals and rescale a correction signal. If the user opts to reiterate with the corrected drive or the old drive, the system prompts with the Tuning Corrections Menu, M EQ.5.

For the example test, the RMS error calculated was 0.070 and the overlay plot of the achieved signal at the end of the first compensated test and the first iteration is shown in Figure 2.32 for the time range of 20-35 seconds. It can be observed from this Figure that the first iteration of compensated test has performed only as good as the previous compensated test. This clearly indicates that it is due to the limitation of the hardware and it would not perform any better for the given forcing function. Hence, the test was stopped with the first iteration.

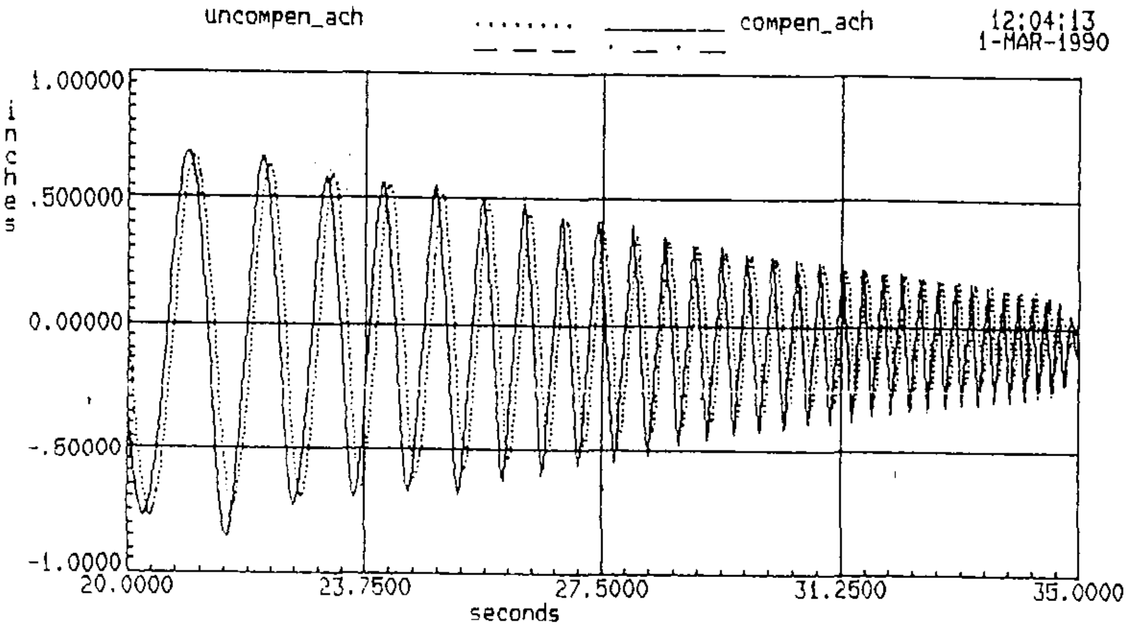


Fig. 2.29

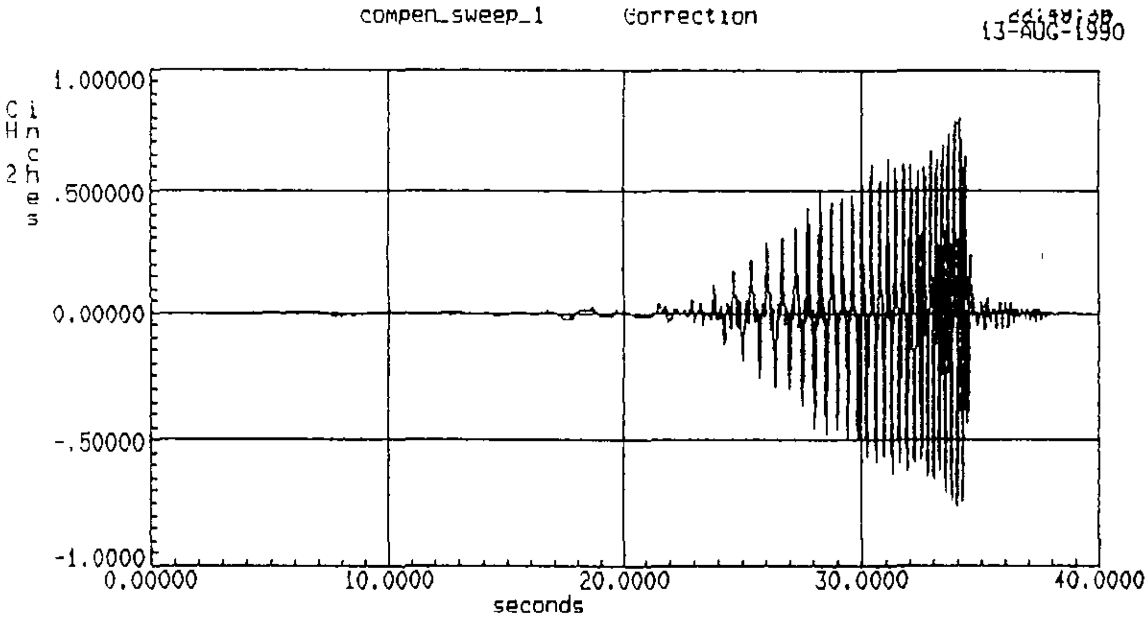


Fig. 2.30

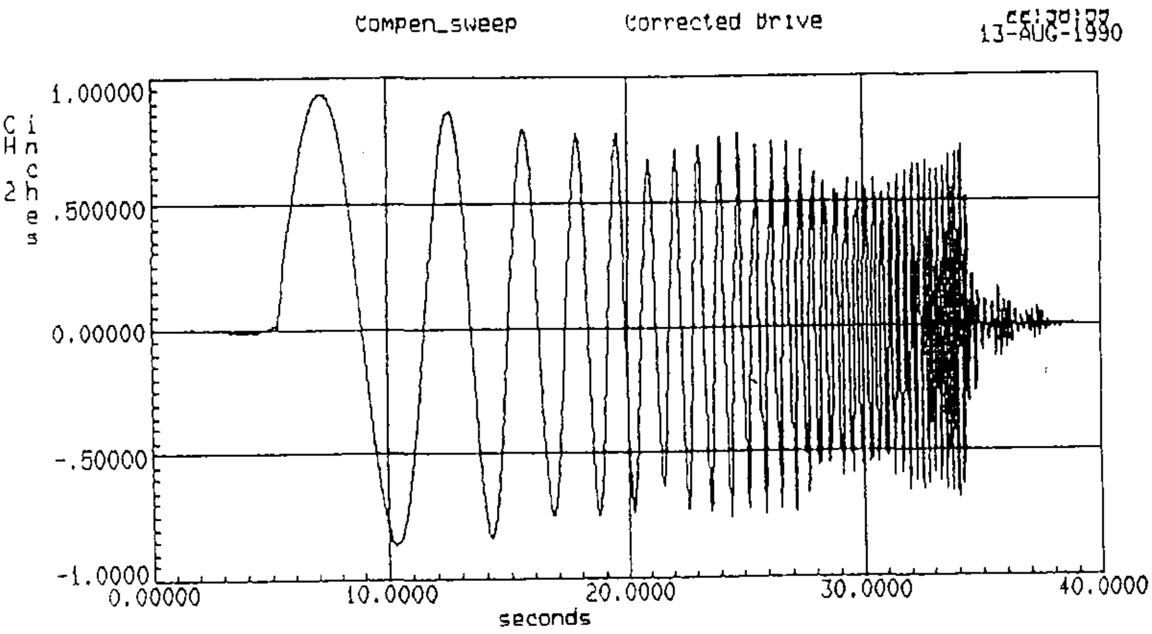


Fig. 2.31

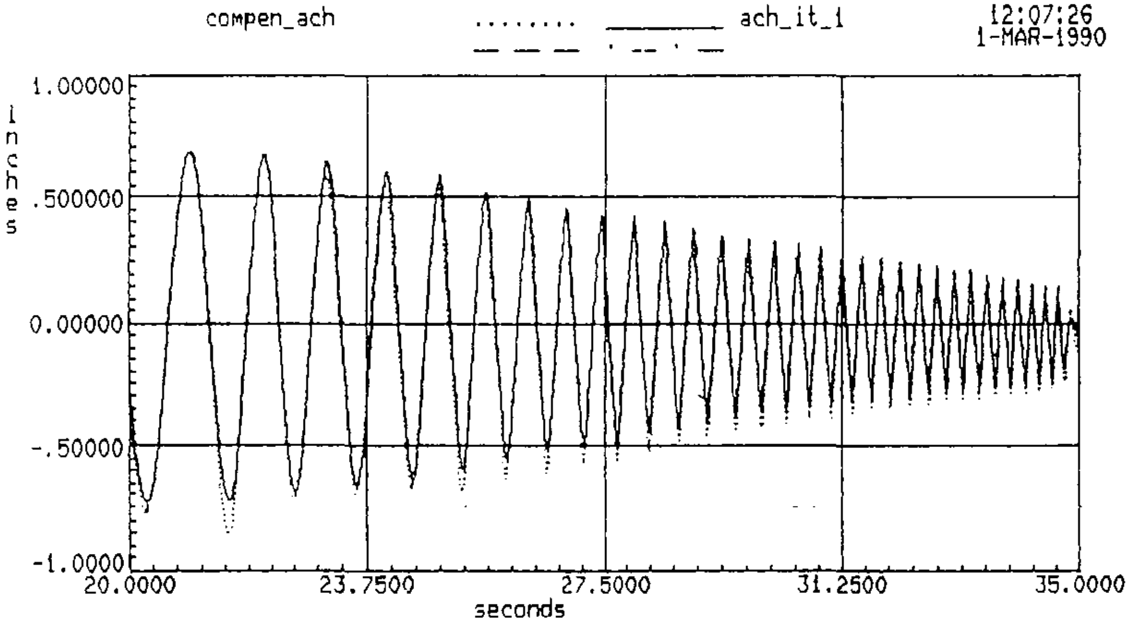


Fig. 2.32

PART III

PSEUDODYNAMIC TESTING

PSEUDODYNAMIC TEST PROCEDURE USING STEX

The Pseudodynamic test procedure consists of three major tasks. These three tasks are contained in the three sections as shown below.

SECTION A.	Setting up of a pseudodynamic test.
SECTION B.	Hardware setup and test execution.
SECTION C.	Post test analysis.

The procedure in each of the section is illustrated with the example discussed below.

DESCRIPTION OF THE EXAMPLE TEST

Test structure:

This test has been conducted on a W12*14 beam. The beam was set up with the objective of having a flexible member which would produce some visible deflections within the elastic limit. Hence the beam was set to be bent about the minor axis.

Forcing function:

The forcing function considered is shown in Figure 3.1.

COMPUTATION OF DYNAMIC CHARACTERISTICS

Stiffness calculation:

Theoretical stiffness (K_t)= 48 EI/ L^3 = 5342.8 lb/in.

Actual measured stiffness of the beam (K_a) = 5340 lb/in.

The actual stiffness was determined by applying a known displacement and measuring the restoring force. This procedure has been described in Section (ii) of Part I.

Mass calculation:

The mass value which is an input in the test need not be the actual mass. The mass value is calculated for an assumed natural frequency of the beam and the actual stiffness. This mass is called the

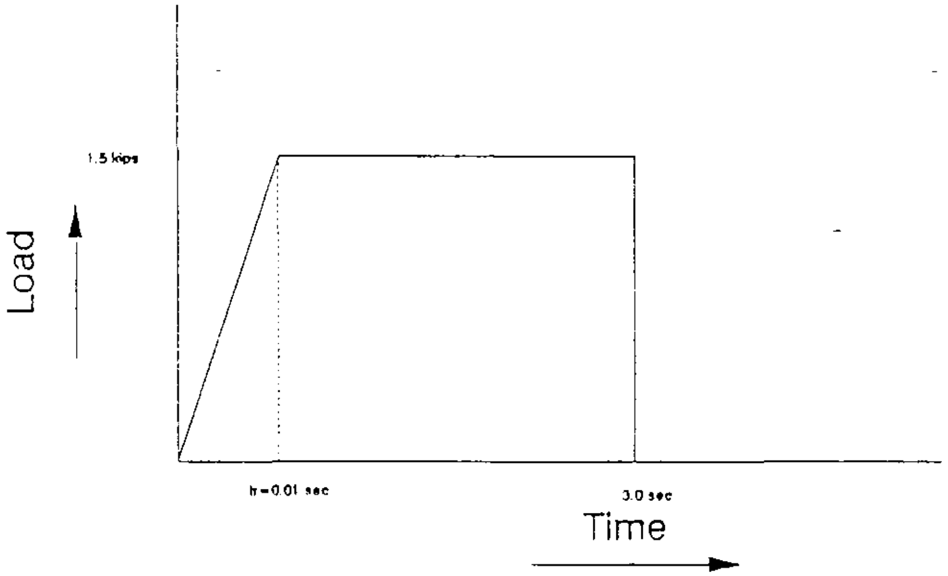


Figure 3.1 Forcing function used

pseudodynamic mass.

Frequency(w) assumed = 5 Hz. = 31.41 rad/sec.

Pseudodynamic mass(m) = K_a / w^2 = $5.340/(31.41)^2$
= 0.005412 Kip-sec^2/ inch

Calculation of the peak acceleration:

Peak force, F_1 = 1.500 kips.

Peak acceleration, a(f) = Peak force / Pseudodynamic mass

= F_1 / m = 1.500 / 0.005412

a= 277 inches / sec^2.

Calculation of damping coefficient:

This is another input for the test.

Critical damping coefficient (C_{cr}) is given as below.

$$C_{cr} = 2 * \sqrt{K_a * m}$$

C_{cr} = 2 / 5.34 * 0.005412

= 0.340 kip-sec/ in.

Damping coefficient (C) = B * Ccr

Let us choose a B value of 0.0 %.

Hence C = B * C_{cr} = 0.0

DYNAMIC ANALYSIS

Calculation of static deflection:

Static deflection, X_s = F_1 / K_a

= 1.5 / 5.34

= 0.281 inch.

Computation of elastic limit of deflection:

The restoring force at the elastic limit for a simply supported beam centrally loaded is **Rm** = (4 * Plastic moment strength)/span
= (4 * M_p)/L = 4 * 68.4 K-in/86.0 in.

= 3.1814 Kips.

Elastic deflection , Y_{el} = Rm/ K_a = 3.1814/ 5.34 = 0.596 in.

Computation of X_{max} and T_{max}:

(Using the standard graphs available in BIGGS)

Period of the structure, T = 1 / f = 1 / 5 hz. = 0.20 sec.

Ramping period of the forcing function, t_r = 0.01 sec.

Ratio of the periods = t_r/ T = 0.01 / 0.2 = 0.05

From Figure 2.9 of Biggs, $(DLF)_{max}$ a= 1.98

The maximum deflection, X_{max} = X_s * $(DLF)_{max}$ = 0.556 inch.

For t_r / T = 0.05, T_{max} / t_r a= 10; Hence T_{max} = 0.10 sec.

Note : The behaviour is in the elastic range as it can be seen that $X_{max} < X_{el}$

SECTION A. SETTING UP OF A PSEUDODYNAMIC TEST.

The various steps involved in setting up a pseudodynamic test are listed below.

STEP 1. Defining the system configuration in the SYSTEM DEFINITION library.

STEP 2. Creating the time history of the forcing function in the DATA ANALYSIS library.

STEP 3. Creating the profile in the PROFILE library.

STEP 4. Defining the test structure in the PSEUDODYNAMIC TEST library.

STEP 5. Setting up of the test in the PSEUDODYNAMIC TEST library.

STEP 1. DEFINING THE SYSTEM CONFIGURATION

This is set up in the SYSTEM DEFINITION library. As the setup of the system configuration is similar to that made for the dynamic test, the procedure outlined in step 1 of section 1 (of Part I) holds good with the following exceptions.

Command mode: This is always STROKE, as at each step of the pseudodynamic procedure the deflection is imposed on the structure.

Feedback mode: This is always LOAD. At the end of each ramp the restoring force is measured and this data becomes an input for the computation of the deflection at the next step.

Additional feedback: This must be STROKE.

Filter cutoff frequency: This should always be set to "Bypass" for command, feedback, additional feedback and the transducer channels.

STEP 2. CREATING THE FORCE TIME HISTORY FUNCTION

Unlike the real time dynamic test, the force time history here consists of the corresponding acceleration time history obtained by dividing the force by the pseudomass. This is created using the **CTH** command.

The time history creation screen for the example is shown in Figure 3.2. The peak acceleration value has been calculated earliar.

Note: 1. The unit of the acceleration is always inches/sec^2.

2. The acceleration specified should always be negative. This adjustment is required to take care of the negative sign of the force term on the right side of the dynamic equilibrium equation, as shown below.

$$Ma + Cv + R = - Ma(f)$$

where a(f) is the acceleration of the forcing function, M is the pseudo mass, C is the damping coefficient and R is the restoring force.

The created time history of the acceleration is shown in Figure 3.3.

STEP 3. CREATION OF THE PROFILE

The acceleration profile is created in the PROFILE library.

The procedure for the creation of the profile is the same as for the dynamic test outlined in step 3 of section 1 (of Part I), with the following exceptions in the setup.

Leading zeros: No leading zeros need to be provided.

Initial taper and final taper: No initial or final taper need to be provided.

The created profile is shown in the Figure 3.4.

STEP 4. DEFINITION OF THE TEST STRUCTURE

The test structure is defined in the PSEUDODYNAMIC TESTING library. The structure library options are obtained by selecting "O" in the main menu of the pseudodynamic testing library.

The definition of a test structure consists of the following tasks.
(i) Providing the node and the actuator information.
(ii) Providing the matrix information.

Node and actuator information.

```
r_0.01_1.5_277              Scale : 1.00000                        D DA.9P

seconds       inches/sec^2
----------    ----------
 0.00000       0.00000        Index : 1
 .010000       -277.13
 3.00000       -277.13
 3.01000       0.00000
 5.00000       0.00000



                                Control field : I

                                   I - Insert pair into array
                                   D - Delete pair from array
                                   E - Edit dependent values
                                   A - Advance window position
                                   X - Exit from dialog
```

Fig. 3.2

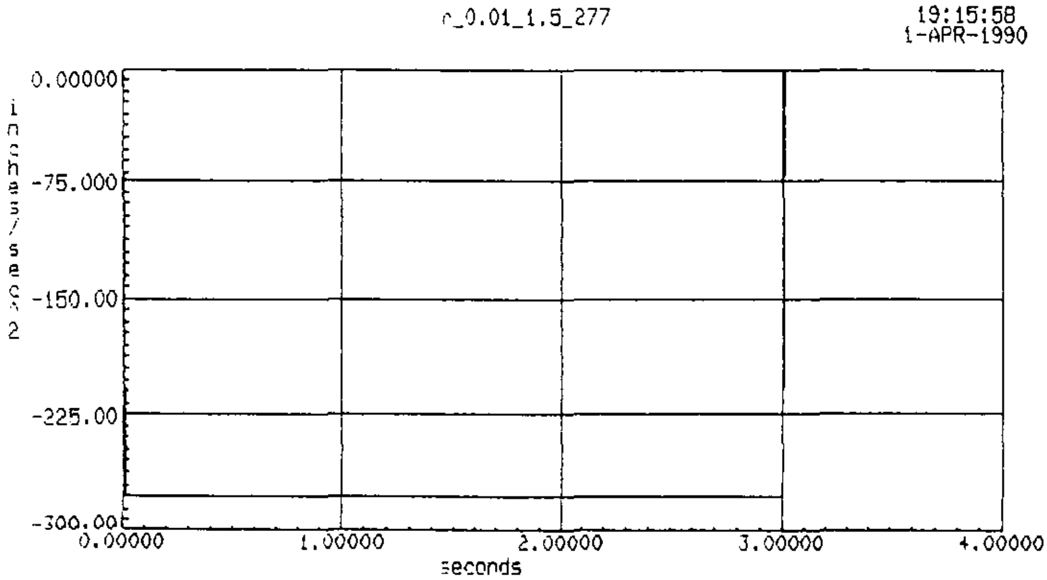


Fig. 3.3

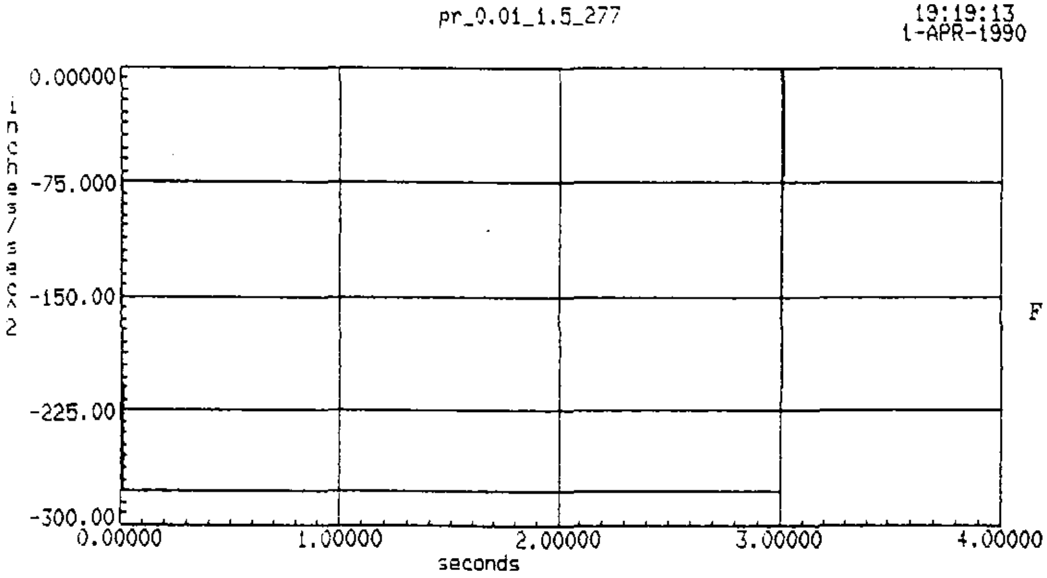


Fig. 3.4

This consists of defining the following:

(i) Active degree of freedom (DOF).
(ii) Number of actuators used.
(iii) Node center coordinates of the DOF.
(iv) Actuator head coordinates.
(v) Actuator base coordinates.

All these definitions are made in the dialog **D PT.5**. This dialog is prompted when you choose to create a new structure from the structure library options by pressing **N**.

Degree of freedom (DOF): The active DOF is defined with respect to the system of coordinate axes defined. In the example test the vertical DOF was defined as active. The longitudinal direction is considered to coincide with the longitudinal axis of the beam. A different coordinate system may also be used, in which case the user must to careful to be consistent in defining the various nodes corresponding to that coordinate system being used.

Number of actuators: The number of actuators used is defined. In the example test only one actuator was used.

D PT.5 with the above two entries, for the example, is shown in Figure 3.5.

On pressing 'ENTER', once these defintions are made, the same dialog prompts the **node center coordinates** of the DOF as shown in Figure 3.6 for the example test.

On pressing 'ENTER' now, the same dialog prompts for the **actuator base coordinates** and the **actuator head coordinates**, as shown in Figure 3.7 for the example test.

Note: The coordinates should correspond to the **global** or **world** coordinates axes.

Structure matrix information

A review of section **PT** 1.3.2 of the STEX manual would be helpful to the user in following the material presented here.

The structure matrices pertain to the following characteristics of the structure.

(i) Mass
(ii) Explicit damping
(iii) Implicit damping and
(iv) Implicit stiffness.

The charateristics which need to be input varies with the numerical algorithm which is chosen for the test.This is shown on Figure 3.8.

```
                                                      D PT.5

          Definition of Node 1


    Degrees of Freedom -
        Longitudinal : Not active
        Lateral      : Not active
        Vertical     : Active
        Roll         : Not active
        Pitch        : Not active
        Yaw          : Not active


    Number of Actuators : 1     ( zero defines node as implicit )
```

Fig. 3.5

```
                                                      D PT.5

          Definition of Node 1


    Degrees of Freedom -
        Longitudinal : Not active
        Lateral      : Not active
        Vertical     : Active
        Roll         : Not active
        Pitch        : Not active
        Yaw          : Not active


    Node center coordinates -
        World Long   : 43.0000 inches
        World Lat    : 0.00000 inches
        World Vert   : 0.00000 inches
```

Fig. 3.6

```
                                                      D PT.5

          Definition of Node 1


    Degrees of Freedom -
        Longitudinal : Not active
        Lateral      : Not active
        Vertical     : Active
        Roll         : Not active
        Pitch        : Not active
        Yaw          : Not active

                  Actuator 1

              Control Channel : CH 2

Actuator Base Coordinates -             Actuator Head Coordinates -
 World Long : 43.0000 inches             World Long : 43.0000 inches
 World Lat  : 0.00000 inches             World Lat  : 0.00000 inches
 World Vert : -59.412 inches             World Vert : -5.6000 inches
```

Fig. 3.7

The selection of the algorithm is based on the type of the structure, the structural idealisations made, the nature of the test and whether or not substructuring is done.

Though the algorithm is defined at the test definition stage, we need to select the algorithm at this stage itself so as to input the pertaining matrix information only. Those matrices which do not pertain to the chosen algorithm contain zeros by default.

The example test uses **'Newmark Explicit Method'**, which requires the **mass** and the **explicit damping** only as inputs. The matrices of the structure, which has been named **b3**, are shown in Figures 3.9 a through 3.9 d.

The **order** of these matrices corresponds to the number of DOFs involved in the test. As our example involves only one DOF, all the matrices are of the single order.

Note that the implicit stiffness and implicit damping matrices contain zeros.

STEP 5. SETTING UP OF A PSEUDODYNAMIC TEST

This consists of the defining the following.

- (i) Test name
- (ii) Pertinent system definition
- (iii) Profile of the forcing acceleration
- (iv) Pertinent structure
- (v) Numerical algorithm and
- (vi) Pseudodynamic graphics

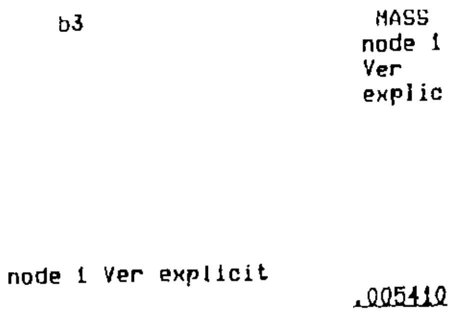
These first five entries are made in D **PT**.12, which is shown in Figure 3.10, for the example. The graphics setting is made in D **PT**.15 which is shown in Figure 3.11 for the example.

Once the entry into D PT.15 is over, pressing ENTER displays the dialog D **PT**.17 which is shown in Figure 3.12. The test may be executed from here if the hardware settings have been made already.

Type of Algorithm	Required Matrices for Algorithm			
	MASS	EXPLICIT DAMPING	IMPLICIT DAMPING	IMPLICIT STIFFNESS
Implicit Explicit (IE)	yes	yes	yes	yes
Newmark Explicit (NE)	yes	yes	no	no
Modified Newmark Explicit (MN)	yes	no	no	no

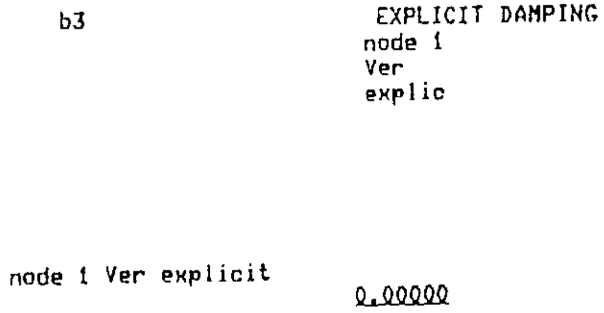
The system will ignore any matrices not required for the algorithm.

Fig. 3.8



```
b3                        MASS
                         node 1
                         Ver
                         explic



node 1 Ver explicit
                         .005410
```

Fig. 3.9a



```
b3                        EXPLICIT DAMPING
                         node 1
                         Ver
                         explic



node 1 Ver explicit
                         0.00000
```

Fig. 3.9b

b3

IMPLICIT STIFFNESS
node 1
Ver
explic

node 1 Ver explicit

0.00000

Fig. 3.9c

b3

IMPLICIT DAMPING
node 1
Ver
explic

node 1 Ver explicit

0.00000

Fig. 3.9d

```
                                                               D PT.12
               Define a New Pseudodynamic Test


       Test Name     - b3_0.01_1.5_277
       Descriptor    - RAMP
       Definition    - P2
       Structure     - b3
       Algorithm     - Newmark Explicit method
       Algorithm Parameter 1 - 0.00000  IE - Beta,  MN - Alpha, NE - not used
       Algorithm Parameter 2 - 0.00000  IE - Gamma, MN - Rho,   NE - not used

                                Profiles
               DOF                            Name

           Longitudinal
           Lateral
           Vertical                     pr_0.01_1.5_277
```

Fig. 3.10

```
                                                             D PT.15
              Define the Pseudodynamics Graphics


   Display :         1              2              3              4

   Defined :        Yes            Yes            Yes            No

   Title   : ACHIEVED VS TIME               RES. FORCE VS DISP.
                             RES. FORCE VS TIME

   X Data  : Time                           Node_1_Ver_stroke
                             Time                           Time
     X Min :      0.000000      0.000000       0.000000
     X Max :      3.000000      3.000000       .6000000

   Y Data  : Node_1_Ver_stroke              Node_1_Ver_load
                             Node_1_Ver_load                Node_1_Ver_stroke
     Y Min :      0.000000      0.000000       0.000000
     Y Max :      .6000000      3.500000       3.500000
```

Fig. 3.11

SECTION B. HARDWARE SETUP AND TEST EXECUTION

This consists of the following tasks.

1. Setting up of the hardware for the pseudodynamic test.
2. Executing the test.

1. Hardware setup.

All of the hardware setups made for the dynamic test as explained in Section B of Part 1 holds good for the pseudodynamic test except the following. Please refer to the pertaining section under PART 1 for this information.

1. Make sure that the PROGRAM SELECTOR is set to **"R" (Remote)**. This is set to "**Random**" for the real time dynamic test.

2. As the FEEDBACK SELECTOR should be selected for the command mode, this has to be set to **stroke**. Number 2 in the dial represents the stroke. When the correct selection is made, the STROKE button on the front panel of 443 controller is lit up.

NOTE: The stroke limit value may be selected to be less than the elastic limit of deflection if it is desired not to get the beam bent during the test.

2.Test Execution.

The user is urged to review the section PT.8 before going further.

While the various definitions leading to the setup of the test can be made from any one monitor, the execution of the test requires two monitors. The first monitor serves as the control monitor while the second serves as the test graphic display terminal.

In the current setup available at the Structures laboratory, a VT 320 (without graphic capability) is used as the control monitor while a VT 240 (with graphic capability) is used as the graphic display monitor.

The command which switches the VT 240 monitor to the graphic display monitor is given below.

```
$ @MTS$TOOLS:SETUP_FOR_PSEUDO_G_VT240
```

The following command is used to set a plotter (LVP16 available in structures lab) as the graphic display device.

```
$ @MTS$TOOLS:SETUP_FOR_PSEUDO_G_LVP16
```

NOTE: This command should be executed from VT 320 before entering into STEX.

The test can be executed either immediately after the definition of the test as described in step 5 of section 1 or a previously defined test can be chosen for execution from the pseudodynamic main menu. In either of these cases D **PT**.17 is displayed for the user to confirm the validity of the servo control modes before initiating the test execution. D PT.17 is shown in Figure 3.12.

Opting to continue the execution process enables the system to display the STATUS CHECK PANEL. These checks are the same as the checks shown in the Figures 1.29a through 1.29i. Note that 1.29j is not displayed here. The explanations to these checks are given in Section 3 of Part 1 on page .

CAUTION: At this stage the span is set to 0% only. This is to avoid sending any signal accidentally which might damage the actuator and/or the specimen.

After all the checks are okayed the system displays a PSEUDODYNAMIC INFORMATION WINDOW with the message '**Initiating the processes**'. This is shown in Figure 3.13 a. Once this message is displayed, the graphics settings on the display monitor is initiated. The graphics screen of the example test is shown in Figure 3.13 b. Towards the end of the graphic setup, the message shown on Figure 3.13 c is displayed on the control monitor in the same window.

CAUTION: Wait until the graphs are fully setup on the display monitor before pressing the **RUN** button. Otherwise it may lead to crashing of the software?!.

NOTE: Before pressing the RUN button, make sure that the load and the displacement feedback signals are zeroed at the analog console.

Once the graphs are setup, press the RUN button and set the controller span to 100% Once the RUN button is pressed, the system closes the PSEUDO INFORMATION WINDOW and displays the CONTROL window which is shown in Figure 3.14 a. The options available in this window allows the user to define and modify the test ramp time, start, hold and terminate the test.

By defining a suitable test ramp time the following objectives can be obtained.

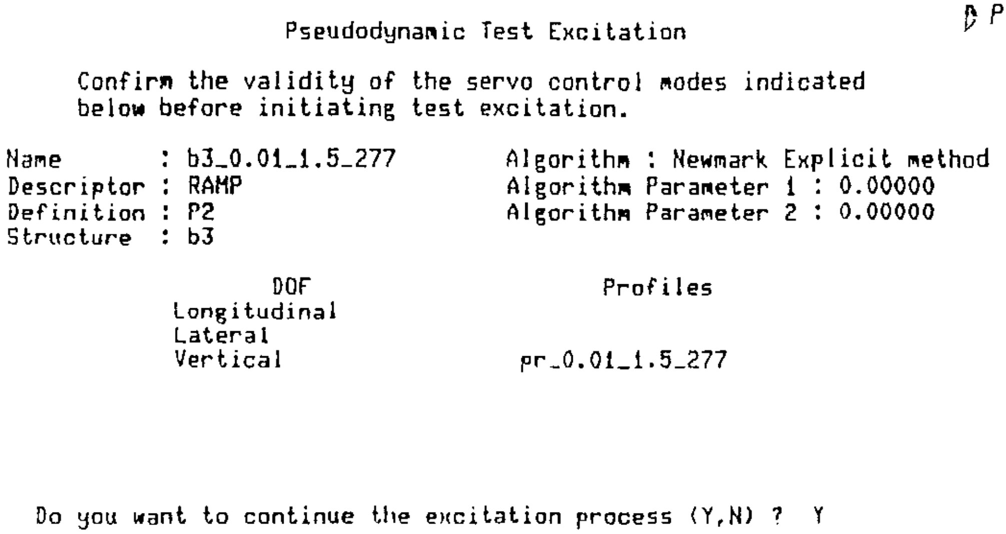
(i) A steady actuator motion can be ensured between the points on the time history.

(ii) An even application of the load is facilitated.

(iii) The rate of loading can be controlled.

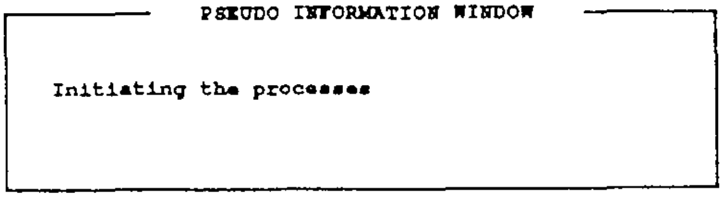
NOTE: Refer section **PT.8.2** of the STEX manual for a complete

D PT·17



```
                  Pseudodynamic Test Excitation

     Confirm the validity of the servo control modes indicated
     below before initiating test excitation.

Name       : b3_0.01_1.5_277        Algorithm : Newmark Explicit method
Descriptor : RAMP                   Algorithm Parameter 1 : 0.00000
Definition : P2                     Algorithm Parameter 2 : 0.00000
Structure  : b3

                DOF                         Profiles
          Longitudinal
          Lateral
          Vertical                  pr_0.01_1.5_277



  Do you want to continue the excitation process (Y,N) ?  Y
```

Fig. 3.12



```
PSEUDO INFORMATION WINDOW

Initiating the processes
```

Fig. 3.13a

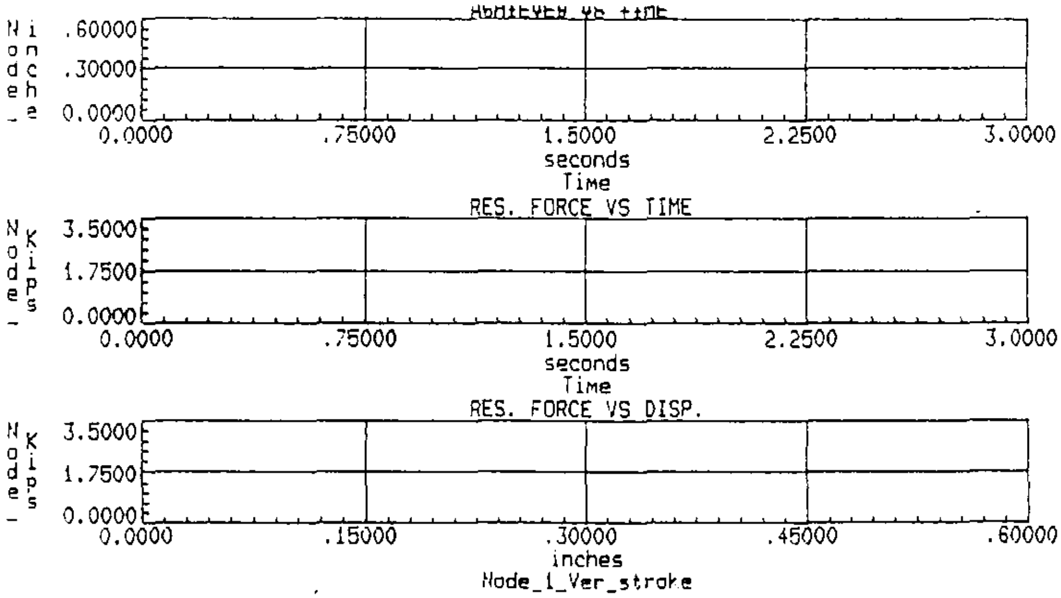
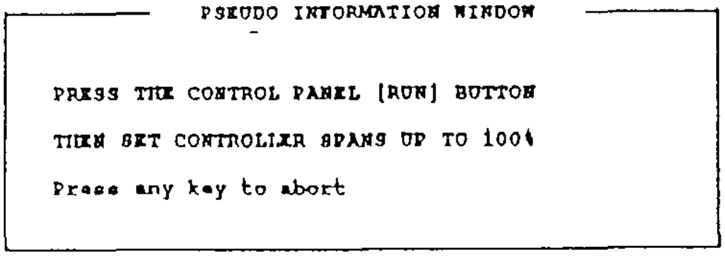


Fig. 3.13b



```
PSEUDO INFORMATION WINDOW

PRESS THE CONTROL PANEL [RUN] BUTTON
THEN SET CONTROLLER SPANS UP TO 100%
Press any key to abort
```

Fig. 3.13c

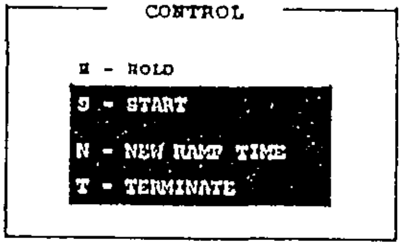
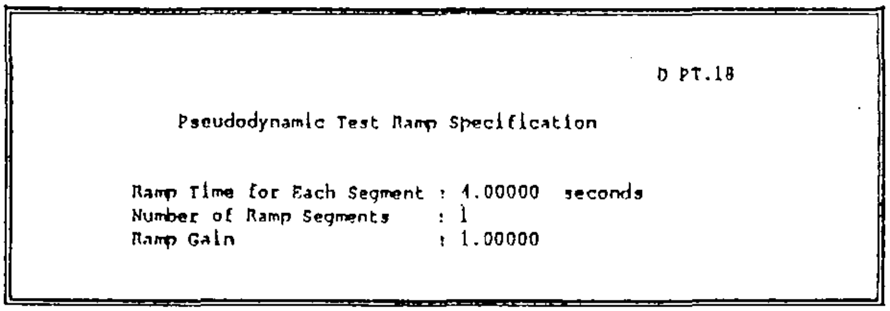


Fig. 3.14a



```
                                           D PT.18

    Pseudodynamic Test Ramp Specification

Ramp Time for Each Segment : 4.00000  seconds
Number of Ramp Segments    : 1
Ramp Gain                  : 1.00000
```

Fig. 3.14b

information on ramp specification.

Pressing **'N'** on the control window displays the ramp specification dialog **D PT.18** which is shown in Figure 3.14b with the default settings. The sensitivity of the parameters involved in setting the ramp is not discussed in this manual.

For the example test, a ramp time of two seconds with two ramp segments at a ramp gain of 90% was chosen.

The test can be started by pressing **'S'** and can be put on hold by pressing **'H'**. The test can be restarted by pressing **'R'** and terminated by pressing **'T'**. Refer to section **PT.8.3** for a detailed explanation on using these options.

While the test is running, the graphs on the display monitor is continually updated which cannot be interacted. This is shown in Figures 3.14c and 3.14d.

Once the test is terminated, the pseudo infomation window is again displayed as shown in Figure 3.15. Now, set the controller span to 0% and press the program **STOP** button. Once the STOP button is pressed the following message is displayed.

'Normal test completion'

'Press any key to continue'

Pressing any key, the system returns to **Pseudodynamic Test Initiation Options menu.**

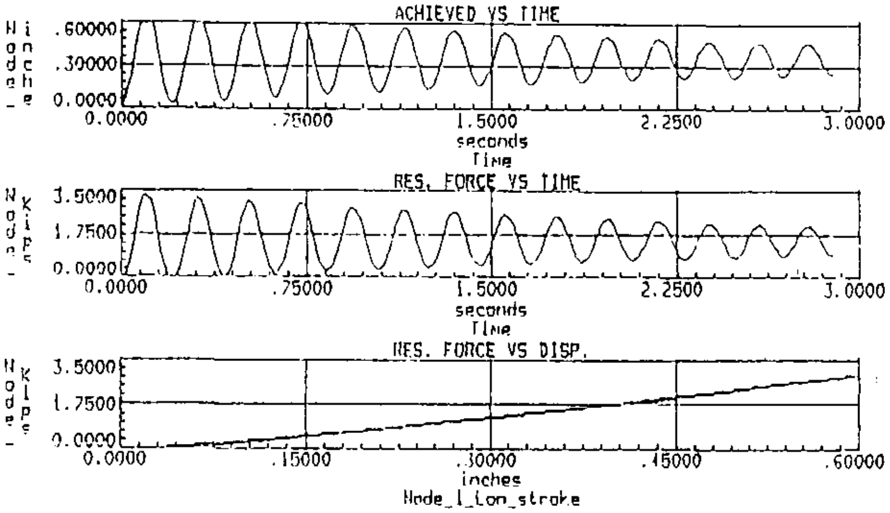


Fig. 3.14c

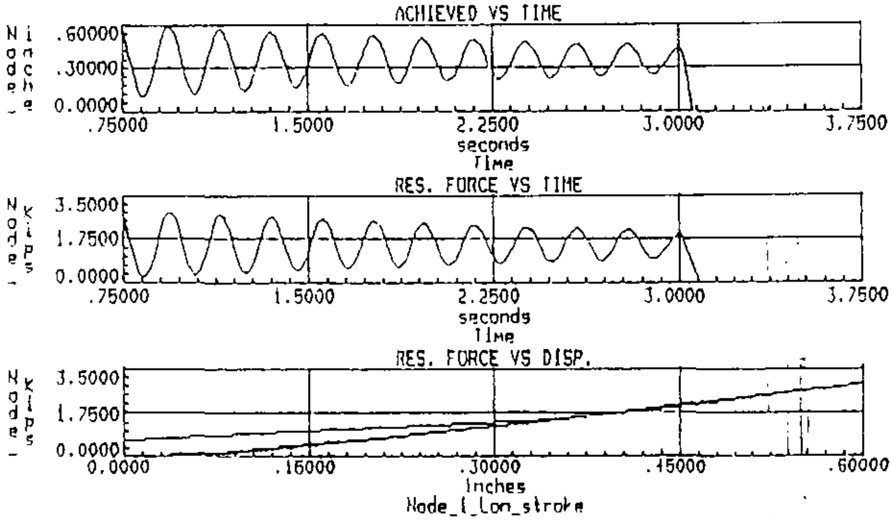
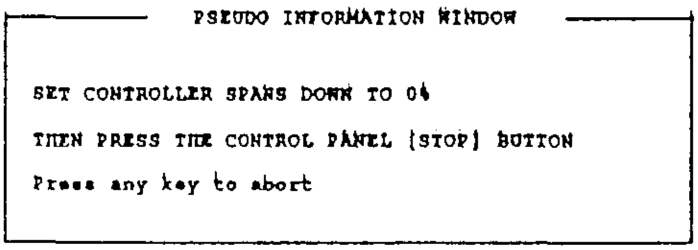


Fig. 3.14d



PSEUDO INFORMATION WINDOW

SET CONTROLLER SPANS DOWN TO 0%

THEN PRESS THE CONTROL PANEL [STOP] BUTTON

Press any key to abort

Fig. 3.15

SECTION 3. POST TEST ANALYSIS

The test results can be retrieved for analysis by one of the following procedures.

1. Choose the option V at the pseudodynamic test initiation options menu. Note that this option does not allow any overlay plotting. Hence only one result can be viewed at a display.

2. Initiate an analysis session at the Data Analysis library and use the access (assignment) command **APSE** to import the various results of the test from pseudo test mode into the current session. Once the desired results are imported, they may be plotted either individually (using the **PLT** command) or selectively together (using the **PLTO** command).

DEFINITION OF SOME SALIENT TERMS

DOF Feedback response : This is the response at the nodes defined in the structure for the specified degrees of freedom (DOF). This can be either the LOAD or the STROKE response. The load response is measured by the **load cell** while the stroke response is calculated by the software for the defined geometry of the structure, actuator base and head locations, and other data from the analog console.

Actuator Feedback response : This consists of the response of the load or the stroke measured by the instrumentation present in the actuator. The load is measured by the **load cell** and the stroke is measured by the **dcdt** housed inside the actuator assembly.

Transducer response : This is the response measured by the external transducers.

DOF acceleration history: This is the acceleration time history defined earliar in the Data Analysis library.

DOF calculated displacements: This is the displacement calculated by the **algorithm** at the end of each step of ramping after the restoring **force** at the previous step is measured.

DISCUSSION OF THE RESULT OF THE EXAMPLE TEST

The DOF Feedback stroke response is shown in Figure 3.16. The following points are evident from this graph.

1. The actual maximum displacement and the corresponding time agrees well with the theoretical results.

Actual Xmax = 0.5400 inches (0.556 inches)
Actual Tmax = 0.0900 secs (0.100 secs)

The paranthesis contains the results of the analysis done in the beginning of this part.

2. The system response fades down as time increases though the viscous damping has been made zero in the test. This is due to the effect of the Coulomb damping present in the system contributed by the friction present in the actuator.

The Actuator Feedback stroke response is shown in Figure 3.17. This must actually be the same as the DOF feedback stroke response. This was due to a bug in the software which has been fixed now.

The DOF Feedback and Actuator Feedback of the load response are shown respectively in Figures 3.18 and 3.19. Note that these two responses are just the same, which is correct.

The DOF calculated displacement with the DOF Feedback is shown as an overlay plot in Figure 3.20. It can be seen that the response has exactly followed the displacement that was calculated at each step.

The DOF Acceleration time history is shown in Figure 3.21. This is the same as the acceleration time history defined in the Data Analysis library.

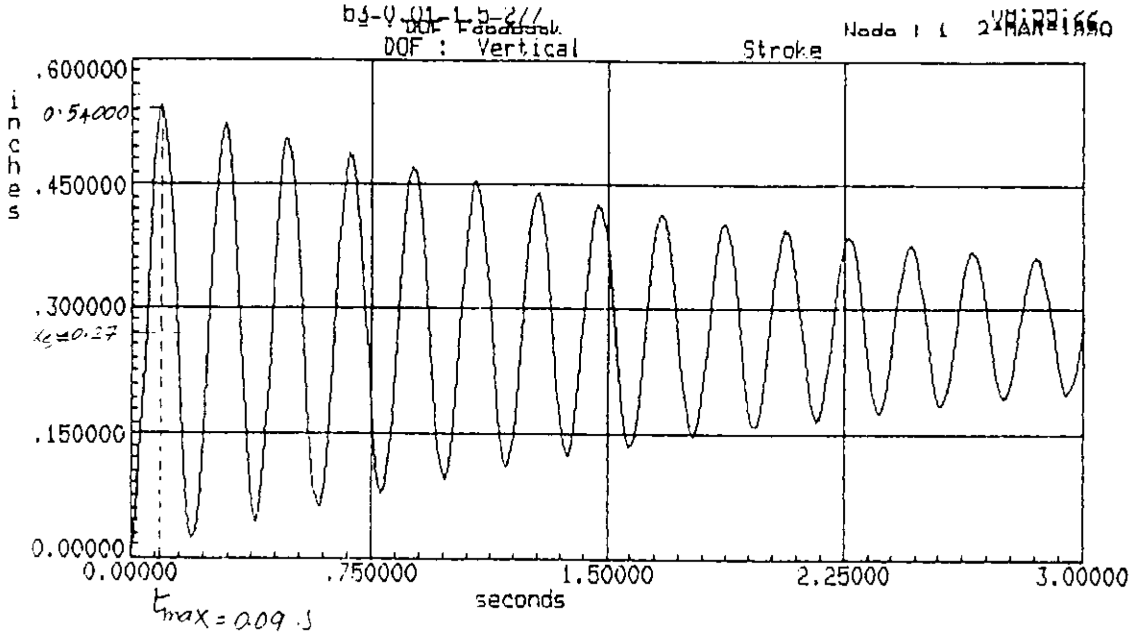


Fig. 3.16

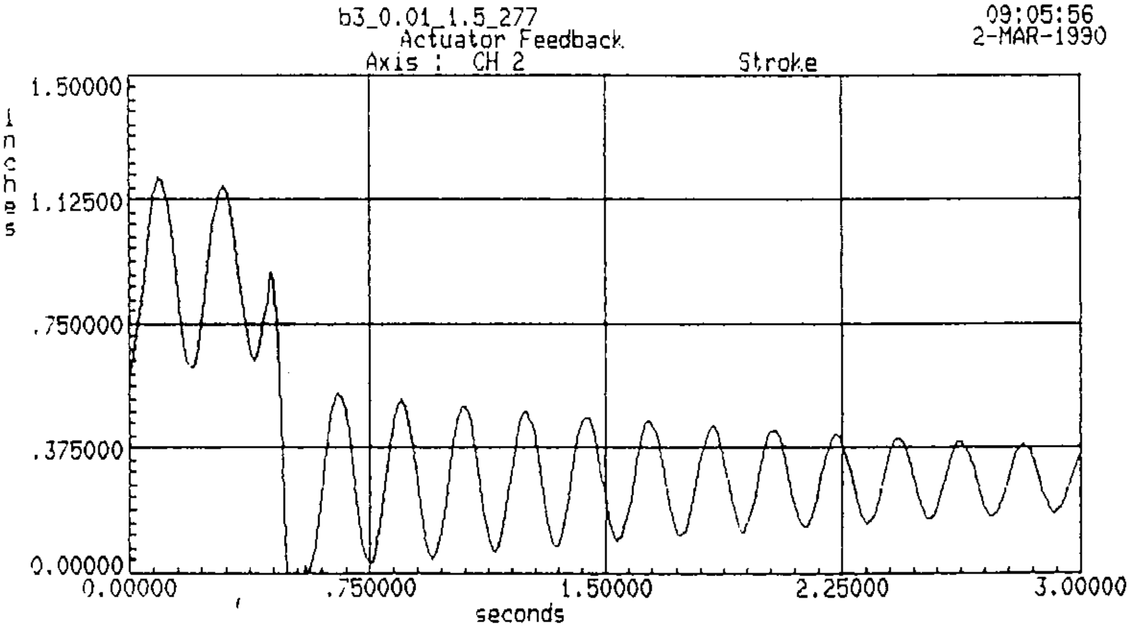


Fig. 3.17

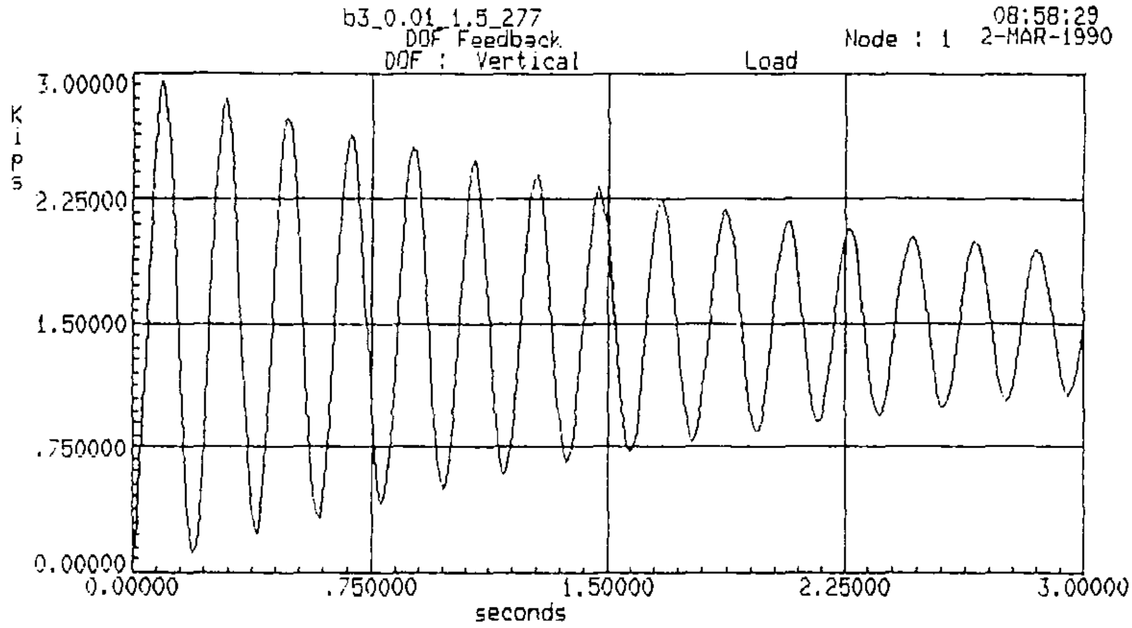


Fig. 3.18

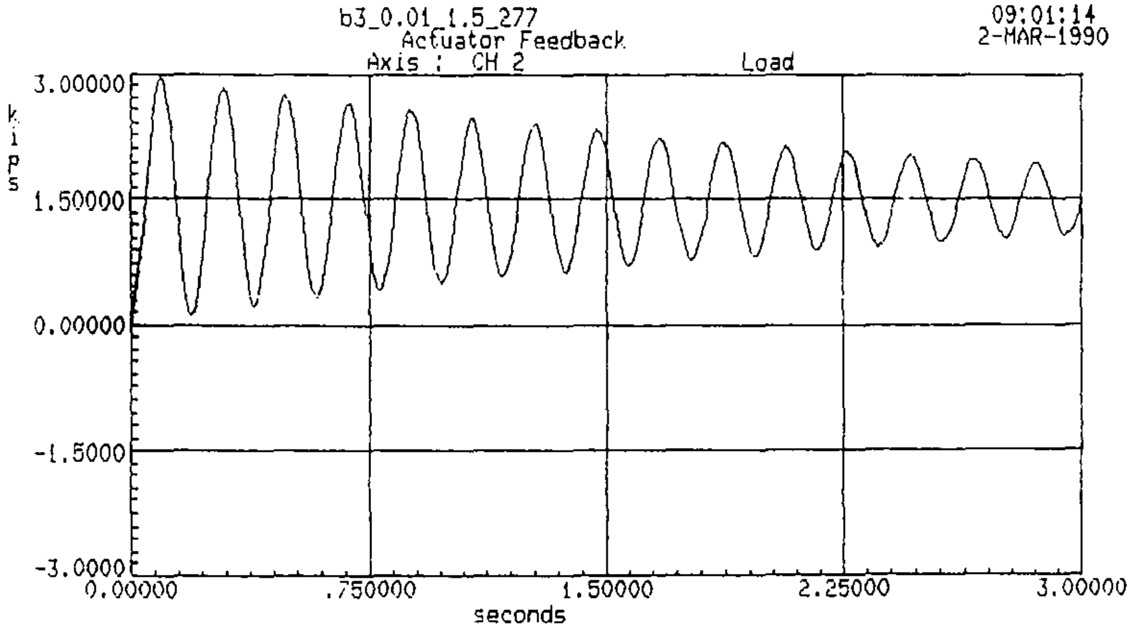


Fig. 3.19

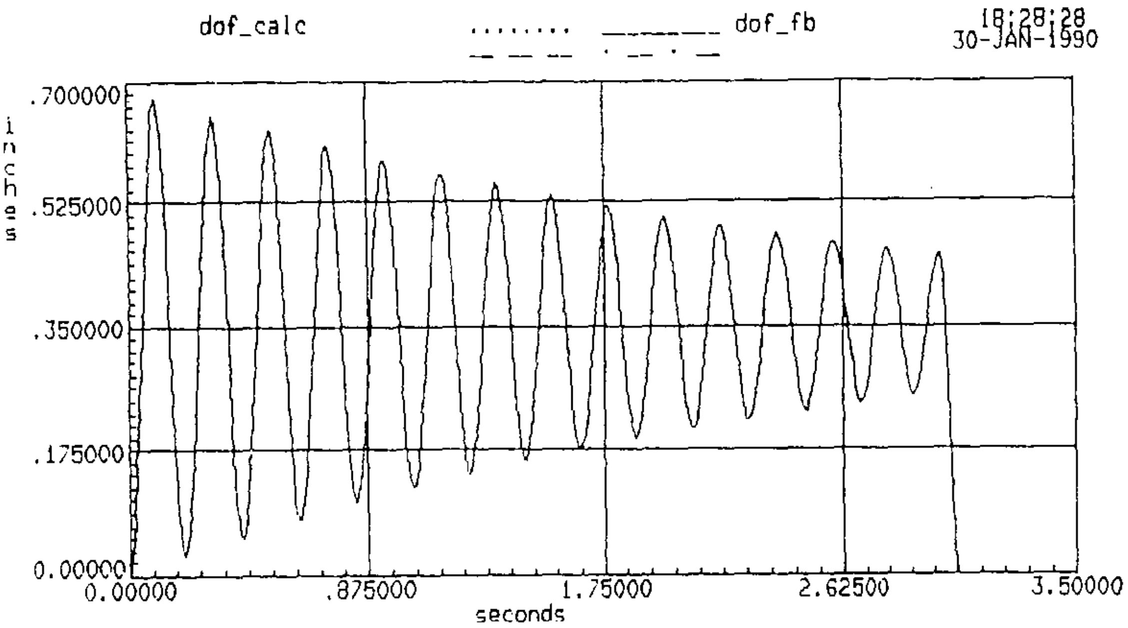


Fig. 3.20

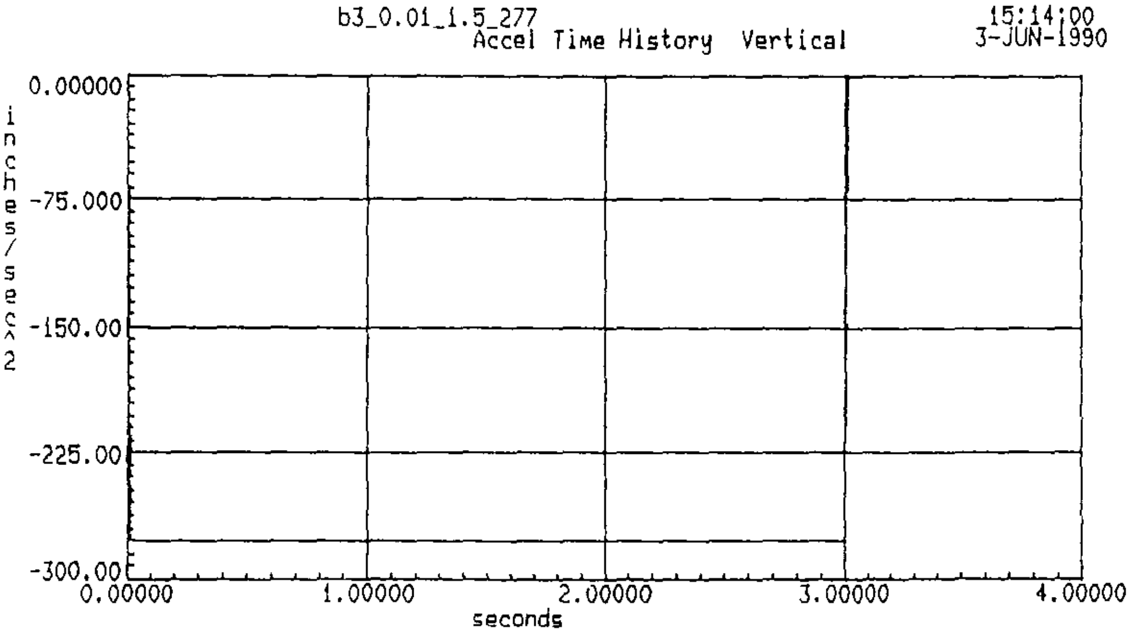


Fig. 3.21

APPENDIX B: TEST DATA

Table 1a. Strain readings of readings of cycle 1

LOAD	STROKE	STIFFNESS	STRAIN GAUGE READINGS						
			1	2	3	4	5	6	7
kips	inches	kips/in.	strain in micro strains						
0.00	0.00	0.00	1	2	2	1	-1	0	0
0.50	0.48	1.04	620	569	597	-707	54	290	265
1.00	1.05	0.96	1292	1310	1348	-1384	225	608	530
0.50	0.50	0.99	634	591	622	-725	59	301	276
0.00	0.00	0.00	0	1	3	-3	0	5	3

Table 1b. Strain readings of readings of cycle 2

LOAD	STROKE	STIFFNESS	STRAIN GAUGE READINGS						
			1	2	3	4	5	6	7
kips	inches	kips/in.	strain in micro strains						
0.00	0.00	0.00	0	1	3	-3	1	0	0
0.50	0.50	1.01	630	579	607	-718	60	301	270
1.00	1.07	0.93	1300	1321	1357	-1392	245	615	536
0.50	0.52	0.96	645	599	630	-735	66	315	284
0.00	0.00	0.00	1	1	2	-2	0	2	1

Table 2a. Computed stress concentration in cycle 1

LOAD kips	CORRESPONDING STRESS CONCENTRATIONS 1	2	3	4	5	6	7
0.00	------	------	------	------	------	------	------
0.50	2.31	2.12	2.23	-2.64	------	1.07	0.98
1.00	2.41	2.44	2.51	-2.58	------	1.12	0.98
0.50	2.37	2.21	2.32	-2.71	------	1.11	1.02
0.00	------	------	------	------	------	------	------

Table 2b. Computed stress concentration in cycle 2

LOAD kips	CORRESPONDING STRESS CONCENTRATIONS 1	2	3	4	5	6	7
0.00	------	------	------	------	------	------	------
0.50	2.35	2.16	2.26	-2.68	------	1.11	1.00
1.00	2.43	2.46	2.53	-2.60	------	1.13	0.99
0.50	2.41	2.24	2.35	-2.74	------	1.16	1.05
0.00	------	------	------	------	------	------	------

Table 3a. Observed strain readings

WIND SPEED	NO. OF CYCLES	PEAK LOAD	DISP.	STIFFNESS	STRAIN GAUGE READINGS 1	2	3	4	5	6	7
mph	-	kips	inches	kips/in.	strain in micro strains						
4	100	1.23	1.34	0.92	1530	1670	1872	-1641	300	1037	993
8	100	1.43	1.87	0.77	1598	*	2775	-2229	*	1353	1280
12	100	1.64	2.09	0.79	1875	*	3055	-2464	*	1526	1444
16	100	1.85	2.41	0.76	1392	*	2434	-1942	*	1163	1093
20	100	2.05	2.63	0.78	1545	*	2622	-2114	*	1278	1202
24	100	2.26	2.88	0.78	1722	*	2816	-2289	*	1400	1322
26	100	2.37	2.98	0.80	1820	*	2869	-2379	*	1456	1383
26	2000	2.37	2.81	0.84	1800	*	2963	-2689	*	1500	*
26	4000	2.37	2.84	0.83	1737	*	1363	-2704	*	1595	*

NOTE: * sign represents defective gage

Table 3b. Observed permanent strains

WIND SPEED	NO. OF CYCLES	PEAK LOAD	DISP.	STIFFNESS	PERMANENT STRAINS OBSERVED AT ZERO LOAD						
					1	2	3	4	5	6	7
mph	-	kips	inches	kips/in.	strain in micro strains						
4	100	1.23	1.34	0.92	17	20	25	-13	0	9	6
8	100	1.43	1.87	0.77	-117	*	612	-371	*	137	111
12	100	1.64	2.09	0.79	-175	*	637	-392	*	150	118
16	100	1.85	2.41	0.76	-151	*	612	-383	*	152	119
20	100	2.05	2.63	0.78	-160	*	610	-398	*	160	123
24	100	2.26	2.88	0.78	-158	*	612	-403	*	157	126
26	100	2.37	2.98	0.80	-150	*	571	-406	*	153	151
26	2000	2.37	2.81	0.84	-155	*	1229	-689	*	297	*
26	4000	2.37	2.84	0.83	-175	*	1900	-684	*	285	*

NOTE: * sign represents defective gage