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Determination of Dynamic Loads in a High-Frequency Direct-Stress Fatigue Machine

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Donald C. Robinson

A refined test procedure is given for accurately recording the dynamic signals from instrumented test bars used to measure loads during simulated fatigue tests. Loads indicated by the load transducer of a direct-stress fatigue machine are compared with those determined from these instrumented test bar specimens which have been calibrated under static conditions. An application of this procedure is described for a resonant, electromagnetic, direct-stress fatigue machine having an optical dynamometer for indicating programmed loads. The variables investigated were the operating frequency, cyclic load and specimen stiffness. In addition, the influence of test fixture mass on the load measurements was determined at one test frequency. The mean loads indicated by the instrumented test bars are compared with those indicated by the dynamometer to determine the errors in load measurements under various test conditions.

Key words: Dynamic loads; dynamometer; fatigue machine.

1. Introduction

In the fatigue testing of structural and mechanical members, it is necessary to have some means of verifying the loads indicated by the machine, since the fatigue life of a specimen depends critically on the applied loads [1]*. To evaluate the performance of a fatigue-machine load-indicating device a method is to compare the intended, or programmed, loads with those indicated by a test specimen over the machine load and frequency operating ranges [2]. From this information, it is possible to determine corrections to apply to the static calibration of the machine to account for differences in the programmed and indicated loads due to undesired inertial effects, which vary for different types of equipment and test conditions.

In this investigation, instrumented test bars, calibrated statically, were used as dummy fatigue test specimens to determine the loads in a resonant, direct-stress fatigue machine. A new recording procedure is described for measuring the cyclic loads applied to the test bars. The equipment includes a comparator type differential amplifier with an

*Figures in brackets indicate the literature references at the end of this paper.

adjustable offset voltage control for comparison of the alternating signal from the test bars with a reference voltage signal. Due to the wide dynamic range of this unit, it was possible to expand the effective screen height of a conventional type oscilloscope by several orders of magnitude to permit voltage measurements to be made with high resolution.

2. Fatigue Machine Characteristics

The machine used in this investigation is a 15 ton* capacity, electromagnetic, direct-stress fatigue machine which operates at the resonant frequency of the vibrating parts. A schematic of the test machine is shown in figure 1. The principal oscillating members consist of a main moving mass which oscillates on the specimen and dynamometer connected in series. The output from the impulse generator, fixed between the specimen and dynamometer, is amplified and fed back to the driving magnet to maintain operation of the machine at the resonant frequency. The test frequency is varied by manually altering the moving mass.

The deflection of the dynamometer was measured visually by a beam of light which indicated the static and dynamic loads directly on a scale. The static loads were indicated by a sharp line of light and the dynamic loads were indicated by a band of light. The mean load, which appeared as a narrow line when the machine did not oscillate, corresponded to the average of the extreme values of the light band during operation of the machine. The load range was controlled automatically by means of a photo-electric regulating device actuated by the light beam of the dynamometer and thereby controlling the power input to the electrical drive.

When a fatigue machine is in operation, sources of error in load measurements appear due to unrecognized inertial forces. These forces are caused by the flexibility of elastic members and the complicated distribution of masses within a machine. According to the manufacturer's operating manual for the machine investigated, transverse and torsional parasitic oscillations may occur in addition to the desired longitudinal oscillation. By control of the geometry and location of the main moving mass, it is usually possible to keep such parasitic frequencies away from the actual test frequency. The longitudinal frequency of all the oscillating elements of the dynamometer is well above the operating frequency range of the machine. The highest operating frequency is governed by critical frequencies of the upper crosshead which makes control of the machine difficult at a test frequency above 200 Hz. An investigation of the dynamic load indication of the dynamometer is given in reference 3. In this study it was found that the differences between the loads

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*U. S. customary units are used throughout this paper since these are the units most frequently used in fatigue testing work in the U. S. Conversion to SI units can be made by use of the relationships found in ASTM Standard Metric Practice Guide, ASTM Designation: E 380-70 (available from American Society for Testing and Materials, 1916 Race St., Philadelphia, Pa. 19103).

indicated by an instrumented specimen and the dynamometer at high test frequencies was caused by the mass of the dynamometer and the gripping head carried at its end.

3. Test Bar Design

Three test bars were used to determine the dynamic loads in the fatigue machine for a range of specimen stiffnesses. The diameters of the reduced section of the bars were 0.375 in, 0.500 in and 0.750 in and their capacities were 4,500 lbf, 6,500 lbf and 15,000 lbf, respectively. The bars were fabricated from type AISI 4150 steel and their load capacity was based on a design stress of 41,000 lbf/in^2. The geometry of the test bars is given in figure 2a.

Strain gages were attached to the bars in a manner which permitted determining the bending due to misalinement as well as measuring the axial loads while the bars were installed in the fatigue machine. The gage circuit designed for this purpose is shown in figure 2b. This circuit permitted measuring the output of each of the axial gages separately to determine bending in the bar or, by connecting 5 to 6 and 7 to 8, determining the combined strain of the four active gages due to applied axial loads. Connectors with silver plated contacts and shielded cables having the shield grounded were used to simplify the measurement process and minimize noise signals.

4. Instrumentation

A portable strain indicator and a switching and balancing unit were used to determine the amount of bending in the test bars due to eccentric loading while they were installed in the machine. For measuring the average axial strain, the power for the strain gage bridge was provided by a regulated d-c power supply. The recording equipment for the cyclic load measurements consisted of a d-c amplifier, a low-pass filter to suppress noise components, and a conventional oscilloscope with a plug-in unit having modes as a differential comparator and as a differential preamplifier [4].

When used as a differential comparator, the plug-in unit has an adjustable d-c offset voltage control for comparison of an input signal with respect to a reference signal established within the unit. Principal requirements for this equipment were (1) negligible drift of the reference signal, and (2) capacity for measuring the lowest signals of interest, in the order of 100 millivolts. The unit employed in this investigation had a recently improved solid state source follower stage for achieving stability of the reference signal. The measured drift after warm up was within 400 microvolts per hour at room temperature. Similar amplifiers having greater trace stability were not compatible with the recording oscilloscope used. A schematic of the measurement system is shown in figure 3.

The comparison voltage amplitude could be read to four significant figures on a graduated dial. The accuracy of the comparison voltage reading of the comparator amplifier was evaluated by correlating its output with that of a four digit precision voltmeter as a constant voltage was applied. The manufacturer's stated accuracy for the comparison voltage was ±0.15 percent of the indicated value plus 0.05 percent of the full scale range. The full scale range used during the load measurements for the fatigue machine was ±1.1 volts. The indicated voltage on the comparator unit was found, on the average, to occur within 0.03 percent of the digital voltmeter value within this voltage range.

5. Measurement Procedure

5.1. Static Machine

The test bars were calibrated statically by determining their response to a series of axial loads in a 20,000 lbf capacity universal testing machine. The errors in static calibration for the latter machine were less than 1 percent, and it complied with the requirements of ASTM Method E4 [5]. After inserting the test bar in the machine, the bending in the bar due to eccentric loading was determined by measuring the axial strain using the strain indicator and switching and balancing unit. The bar and threaded members connecting it to the machine fixtures were oriented and alined until the strain indicated by any one of the axial gages did not vary by more than 4 percent from the mean strain indicated by all the gages.

The response of a bar to static loads was determined in the orientation where the bending was found to be minimum. Loads were applied in 5 or 6 increments up to the capacity of the bar. Several series of readings were taken using different sensitivity ranges of the differential comparator unit and different values for amplification and filter cutoff frequency. The values of these test parameters which would be used during dynamic load measurements could not be determined in advance.

The output voltage from the gaged test bars was measured using a "slide-back" feature of the differential comparator unit. For this measurement, the display switch of the unit was placed in the $A-V_c$ mode, where A is the input and V_c is an adjustable d-c comparison voltage which is added differentially to the input signal. A reference line for this measurement was established before the test bar was loaded by positioning the trace on the oscilloscope at the center of the screen for the highest sensitivity range which could be conveniently used. For the static tests this range was 5 to 10 mV/cm. After the load was applied to the bar, the comparison voltage was adjusted to slide the signal from the test bar to the reference line. Curves were then plotted of the relationship between the static load and test bar electrical output. These curves were used to determine the dynamic loads during cyclic loading tests.

5.2. Fatigue Machine

The alinement and voltage measurements in the fatigue machine were made in essentially the same manner as during the static tests. Generally, the test bars were installed directly into the machine fixtures by the use of appropriate bushings. For this arrangement, it was possible to orient and aline a bar until the strain indicated by any one of the axial gages did not vary by more than 5 percent from the mean strain indicated by all the gages. For one test arrangement, additional fixtures (connectors) were used to install a test bar into the machine in order to determine the influence of the additional fixture mass placed between the specimen and machine dynamometer. Due to the added play introduced between mating parts when using these connectors, it was possible to aline the bar so that the strain indicated by any one of the axial gages was within 3 percent of the mean strain indicated by all of the gages. Schematics showing the two test arrangements are given in figure 4.

In the determination of the loads indicated by the test bar under cyclic loading, the comparison voltage was adjusted to slide the upper and lower peaks of the oscillating waveform to the reference line. The offset voltage values were recorded and the corresponding loads were determined by use of curves plotted for the output voltage versus the static load. The polarities for the upper and lower portions of the waveform were established by a range switch in the comparator unit.

In order to obtain an adequate sensitivity range for the comparison voltage measurement, it was necessary during some of the tests to adjust the reference line on the oscilloscope to some voltage greater than zero. Generally, it was possible to use the 10 mV/cm range of the comparator unit. Although the noise level was high while the machine was running, spurious signals due to the noise were suppressed by the low pass filter whose cutoff frequency was set at 300 Hz, well above the test frequency range.

The test bars were generally installed directly into the fatigue machine using bushings supplied with the machine. In this arrangement, the lower end of the specimen was in the immediate proximity of the upper end of the machine dynamometer and the bushing mass was negligible. For some fatigue tests, however, it is convenient to employ the connectors to facilitate rapid installation and removal of specimens. These connectors are sometimes large and since it was known that such a mass introduced between the specimen and dynamometer can influence the load measurement, one set of tests was made using the connectors for the 0.375 in diameter test bar.

6. Results

Because of the different capacities of the test bars, the load range varied for each bar. For the 0.750 in diameter bar, the portions of the load range investigated were 300 - 3000 lbf, 600 - 6000 lbf, 900 - 9000 lbf, 1200 - 12,000 lbf, and 1500-15,000 lbf. For the 0.500 in diameter bar, the load ranges investigated were 300 - 3000 lbf, 450 - 4500 lbf, and 600 - 6000 lbf. For the 0.375 in diameter bar, load ranges of 150 - 1500 lbf, 300 - 3000 lbf, and 450 - 4500 lbf were investigated. The ratio of the minimum to maximum load of 1:10 is often used in fatigue testing of airframe fasteners. The minimum loads were selected in multiples of 150 or 300 lbf which were found to be convenient increments for the 15 ton capacity dynamometer used.

A comparison of the programmed and indicated mean loads determined using the 0.750 in diameter test bar is given in table 1 for test frequencies of 150, 183 and 200 Hz. The data for frequencies of 150 and 183 Hz are plotted in figures 5 and 6, respectively, to show the relation between the programmed mean loads and those indicated by the machine dynamometer and test bars. A solid 45 degree line is plotted in these figures showing the locus of points where the programmed and indicated loads would be exactly correlated. No data were recorded at the highest load range at 200 Hz due to difficulty in operating the machine at this frequency.

Test frequencies of 142, 162 and 195 Hz were obtained when using the 0.500 in diameter bar. A comparison of the programmed and indicated mean loads using this test bar are given in table 2.

The test frequencies when using the 0.375 in diameter test bar were 125, 137 and 167 Hz. A comparison of the programmed and indicated mean loads when using this bar are given in table 3. This data and the previously tabulated results were taken when the test bars were installed directly into the machine fatigue fixtures. The tests run at 137 Hz were repeated with the test bar inserted in the connectors. The difference in the loads measured for both installations are listed in table 4 and are plotted in figure 7.

In figure 8, the mean load error is plotted against the test frequency for the three size test bars at a programmed mean load of 1650 lbf. This error is defined as

$$\text{Mean Load Error (percent)} = \frac{(\text{Programmed Mean Load}) - (\text{Indicated Mean Load})}{\text{Indicated Mean Load}} \times 100$$

The average of the mean load error of the test bars at various test frequencies is plotted against the programmed mean load in figure 9.

7. Discussion

A test procedure is presented which can be used to provide more accurate measurement of load data during fatigue tests. By accurately recording the dynamic signals from instrumented test bars simulating test specimens and comparing these signals with the output of the machine dynamometer, it is possible to provide corrections to account for such variables as specimen stiffness and changes in the test fixture mass. A specialized component of the recording system is a differential comparator amplifier used to increase the resolving power of an oscilloscope and to provide a reference voltage with which to compare the electrical output of the test bars. Using the maximum sensitivity which may be achieved, the displayed signal amplitude is magnified by several orders of magnitude, thus increasing the effective oscilloscope screen height. To implement this procedure, it is necessary to ensure that the voltage reference has adequate stability for the environment in which the equipment is used.

When reading the optical dynamometer while the fatigue machine was operating, it was sometimes difficult for the operator to determine the loads in a consistantly reliable manner. Reading errors could perhaps be reduced by photographing the light beam projected on the scale and then examining a magnified portion of the photograph to determine the load. Since the dynamometer readings when using the 0.375 in and 0.750 in diameter bars were taken by one machine operator and the data for the 0.500 in diameter bar by a second operator, some of the difference in the loads determined when using these bars may reflect the operator's ability to read the dynamometer. The use of a lower capacity dynamometer would perhaps have enabled the operator to determine the loads indicated on the light scale with somewhat better resolution than the 15 ton capacity dynamometer employed.

The dynamometer and the optical scale for the machine described in this paper are calibrated under static loading by inserting a measuring spring designed by the manufacturer in place of a specimen. It is recommended that the dynamometer be sent to the manufacturer for checking if its readings deviate by more than 1.5 percent from the indications of the spring. The overall uncertainty in the calibration of the instrumented test bars is estimated to be not more than 1.2 percent. The comparison between the two load measuring devices was complicated somewhat by the difficulty in reading the machine dynamometer and controlling the load. The comparison would have been more direct if both devices were strain gage based transducers.

The mean loads indicated by the dynamometer were larger than those indicated by the test bar. This has been found to be characteristic of the type machine investigated [6]. The load errors, due to the difference in the loads indicated by the dynamometer and test bar, increased with the test speed. Further investigation would be required to verify the apparent tendency for the load errors to increase with the cyclic load range. The load error was found to be greater when the 0.375 in diameter test bar was inserted in the connectors than when it was installed directly in the machine fixtures by use of small bushings. Due to the relatively smaller difference between the loads indicated by the dynamometer and the largest two bars, the load errors determined for the two conditions of fixturing might have been less for the larger bars.

The manufacturer of the fatigue machine supplies correction terms for each dynamometer used with a particular machine. As the results of this investigation and related studies have shown, it is necessary to account for the influence of any mass introduced between the dynamometer and the specimen in applying corrections to load measurements due to undesired inertial effects [6,7].

The results of this investigation indicate that the difference between the loads indicated by the machine dynamometer and the test bars varied with the size, and therefore the stiffness, of the bar. As noted in reference 6, changes in the specimen stiffness cause the dynamic properties of the entire vibrating system to be altered. Furthermore, the influence of the specimen stiffness on the load errors may depend on the position of the specimen in the mass-elastic arrangement of the machine. It is therefore generally necessary to determine a range of test bar sizes, which may be considered representative of the fatigue specimens to be tested, during the calibration of a particular fatigue machine [2].

The author is indebted to Mr. G. Meyer of Standard Pressed Steel Company for permission to conduct tests on fatigue equipment at their plant in Jenkintown, Pennsylvania. The valuable assistance of Mr. R. E. Snyder in the construction of the test bars and Mr. G. D. Boswell in conducting the tests is gratefully acknowledged.

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Table 1 - Comparison of Programmed and Indicated Mean Loads During Cyclic Loading Using the 0.750 in Diameter Test Bar

Test frequency	Programmed load		Indicated mean load[a]	
	Range	Mean	Dynamometer	Test bar
Hz	lbf	lbf	lbf	lbf
150	300 - 3,000	1650	1760	1740
	600 - 6,000	3300	3500	3460
	900 - 9,000	4950	5125	5070
	1,200 - 12,000	6600	6730	6630
	1,500 - 15,000	8250	8520	8380
183	300 - 3,000	1650	1800	1780
	600 - 6,000	3300	3350	3310
	900 - 9,000	4950	5120	5050
	1,200 - 12,000	6600	6775	6670
	1,500 - 15,000	8250	8350	8115
200	300 - 3,000	1650	1390	1372
	600 - 6,000	3300	3325	3275
	900 - 9,000	4950	-	-
	1,200 - 12,000	6600	6825	6710

[a] Mean load $= \frac{1}{2}\left(P_{max} + P_{min}\right)$

Table 2 - Comparison of Programmed and Indicated Mean Loads During Cyclic Loading Using the 0.500 in Diameter Test Bar

Test frequency	Programmed load		Indicator mean load	
	Range	Mean	Dynamometer	Test bar
Hz	lbf	lbf	lbf	lbf
142	300 - 3,000	1650	1765	1750
	450 - 4,500	2475	2550	2535
	600 - 6,000	3300	3410	3385
162	300 - 3,000	1650	1755	1735
	450 - 4,500	2475	2550	2510
	600 - 6,000	3300	3390	3340
195	300 - 3,000	1650	1750	1725
	450 - 4,500	2475	2570	2535
	600 - 6,000	3300	3400	3345

Table 3 - Comparison of Programmed and Indicated Mean Loads During Cyclic Loading Using 0.375 in Diameter Test Bar

Test frequency	Programmed load		Indicated mean load	
	Range	Mean	Dynamometer	Test bar
Hz	lbf	lbf	lbf	lbf
125	150 - 1,500	825	1180	1165
	300 - 3,000	1650	1740	1722
	450 - 4,500	2475	2600	2555
137	150 - 1,500	825	920	910
	300 - 3,000	1650	1735	1710
	450 - 4,500	2475	2590	2545
167	150 - 1,500	825	935	920
	300 - 3,000	1650	-	-
	450 - 4,500	2475	2550	2492

Table 4 - Comparison of Indicated Mean Loads Using 0.375 in Diameter Test Bar With and Without Connectors at 137 Hz

Fixturing	Programmed load		Indicated mean load	
	Range	Mean	Dynamometer	Test bar
	lbf	lbf	lbf	lbf
With connectors	150 - 1,500	825	900	888
	300 - 3,000	1650	1720	1688
	450 - 4,500	2475	2570	2510
Without connectors	150 - 1,500	825	920	910
	300 - 3,000	1650	1735	1710
	450 - 4,500	2475	2590	2545

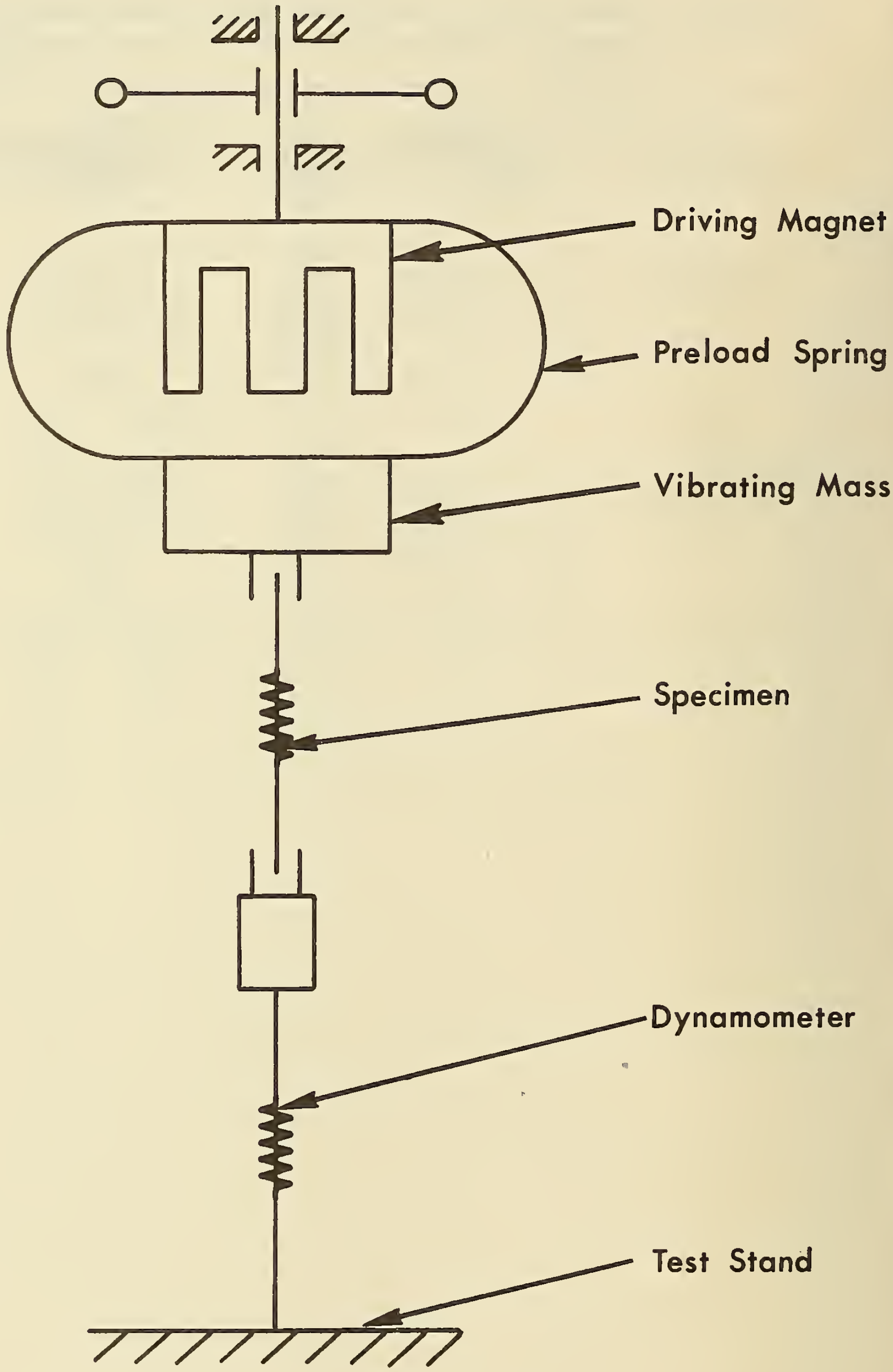


Figure 1 – Schematic of Electromagnetic Direct-Stress Fatigue Machine

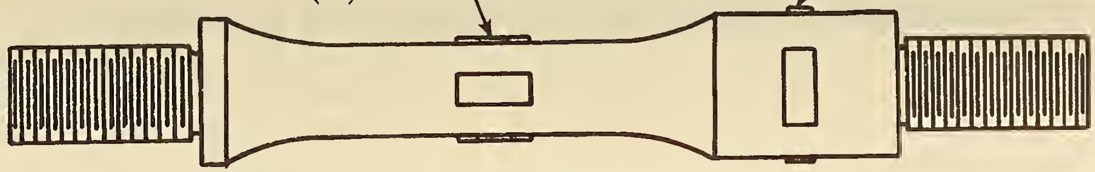
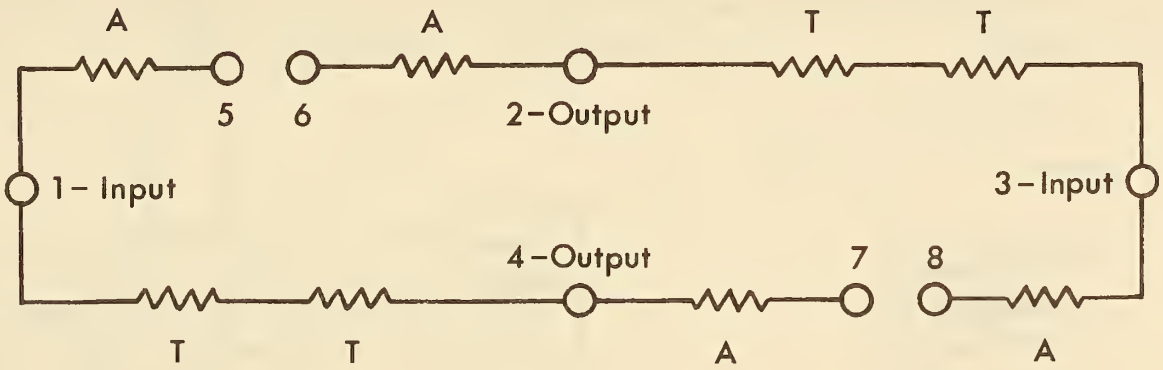


Figure 2a – Geometry of Test Bars



Axial Mode: Open Terminals Connected to Close Circuit

Bending Mode: Output of Each "A" Gage Recorded Separately

Figure 2b – Strain Gage Circuit

Figure 2 – Instrumented Test Bars for Bending and Axial Strain Measurements

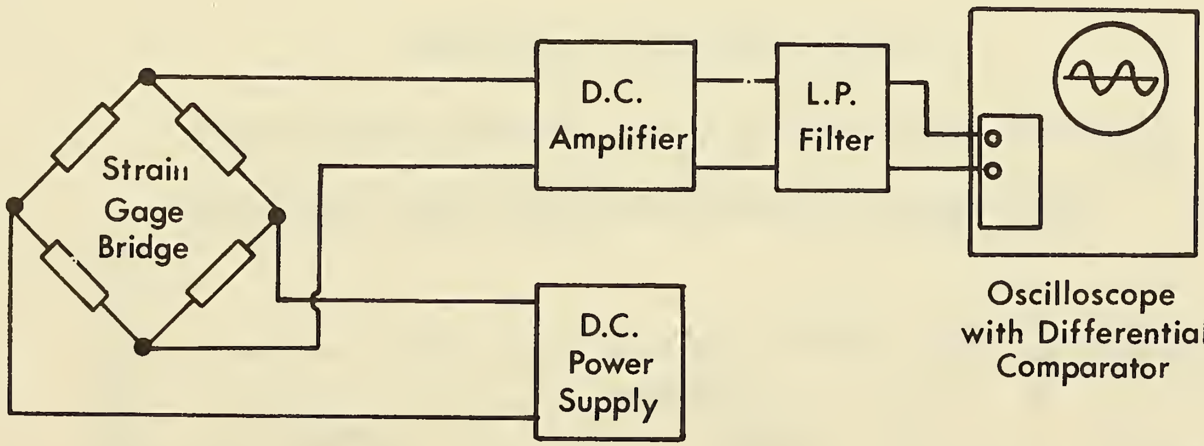
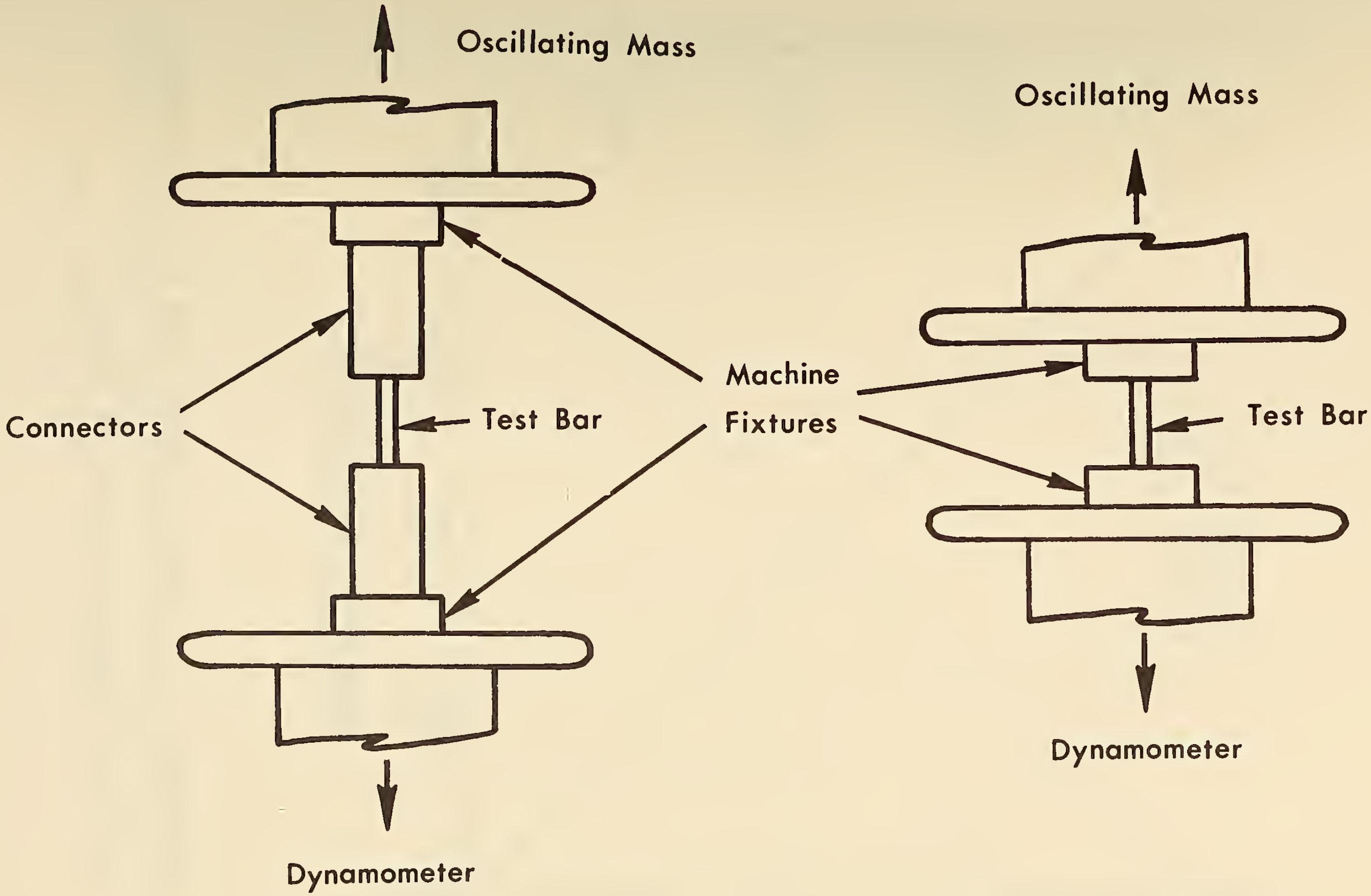


Figure 3 – Schematic of Recording System for Dynamic Strain Measurements



4a – With Connectors

4b – Without Connectors

Figure 4 – Schematic of Test Bar Installed in Fatigue Machine

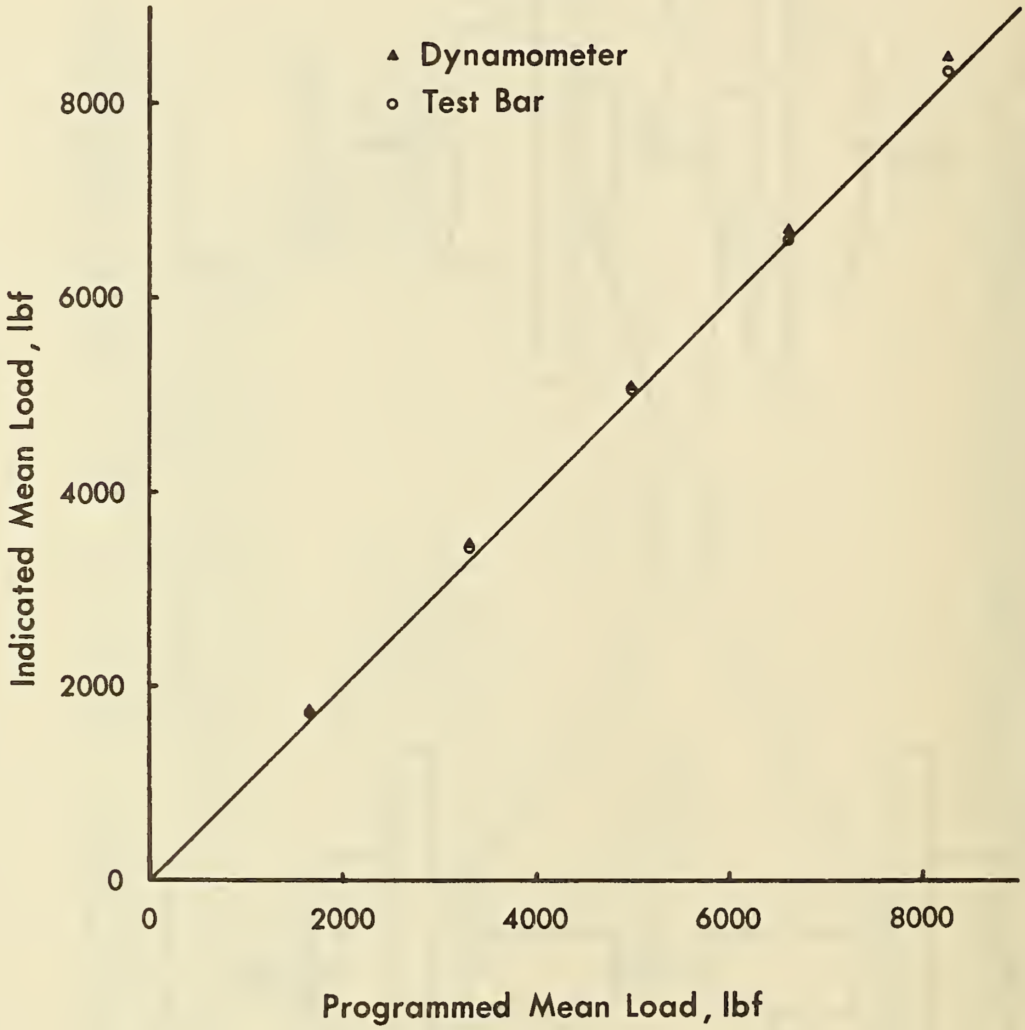


Figure 5 – Programmed versus Indicated Mean Loads for Dynamometer and .750 in. Diameter Test Bar at 150 Hz

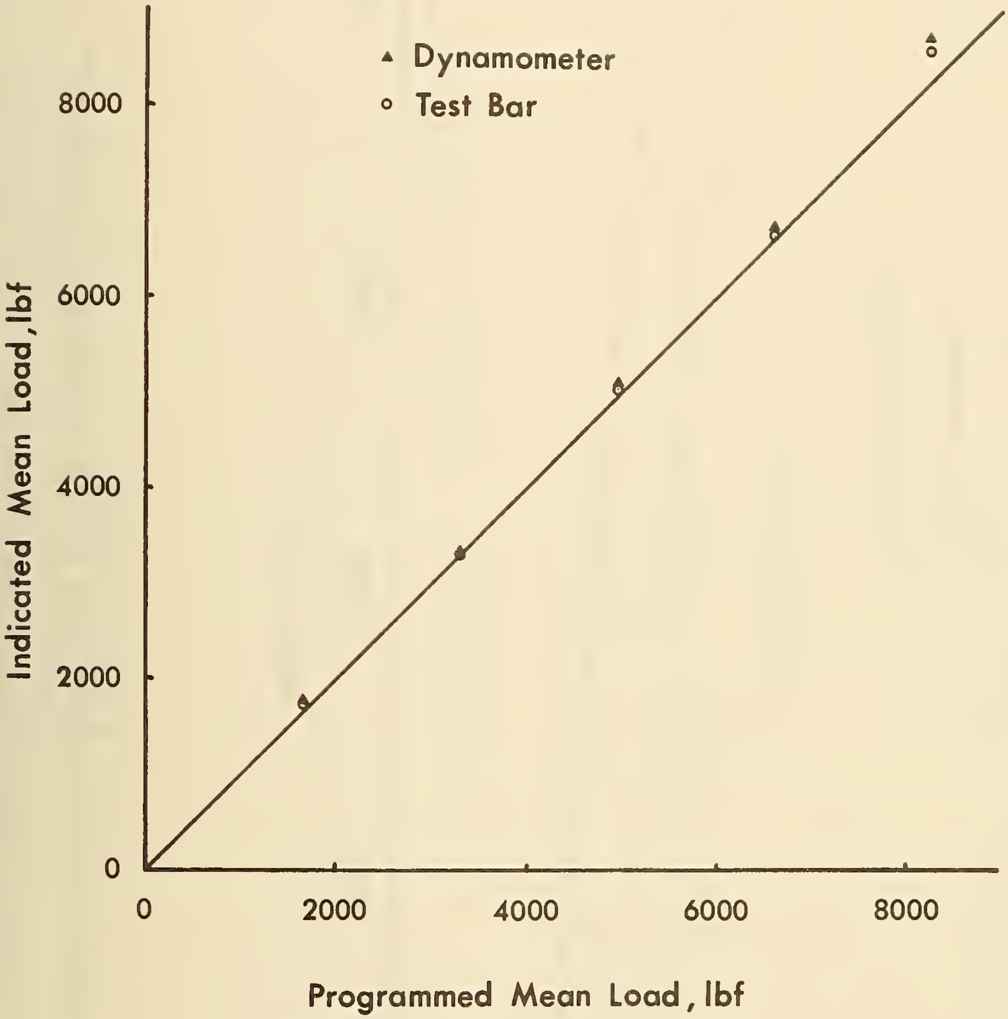


Figure 6 – Programmed versus Indicated Mean Loads for Dynamometer and .750 in. Diameter Test Bar at 183 Hz

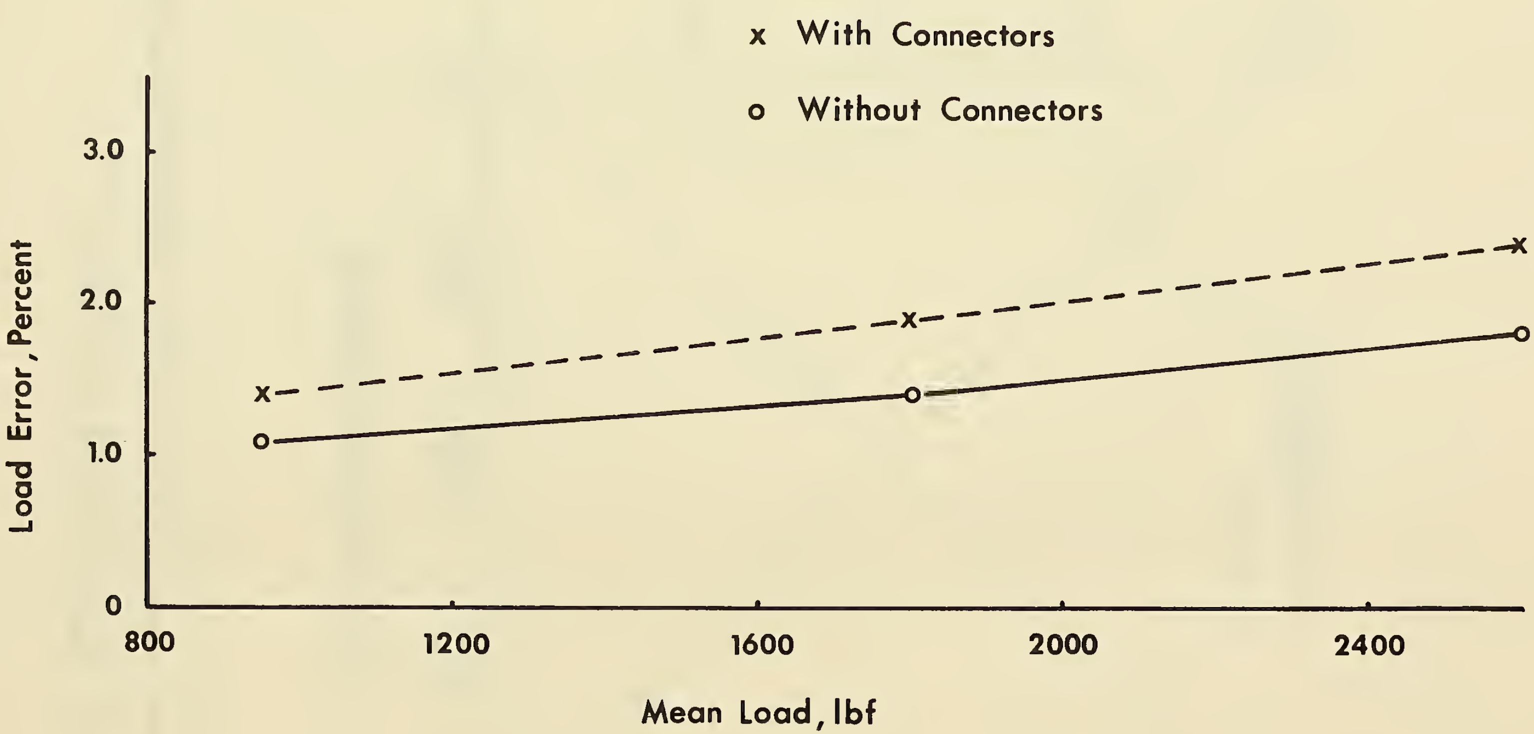


Figure 7 – Load Error versus Mean Load Determined using .375 in Diameter Test Bar With and Without Connectors at 137 Hz

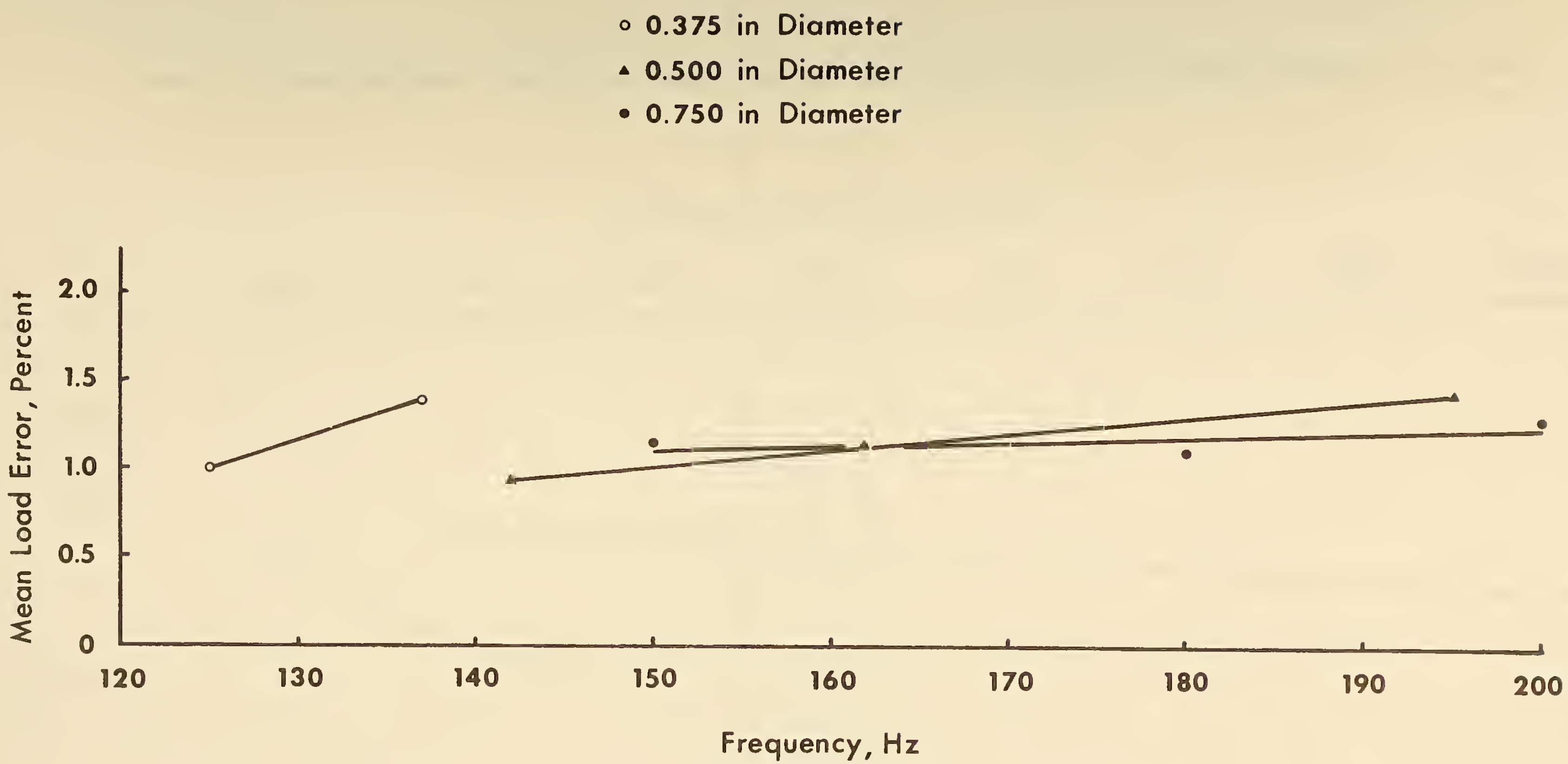


Figure 8 – Error in Mean Load versus Frequency for Various Diameter Test Bars at Programmed Mean Load of 1650 lbf

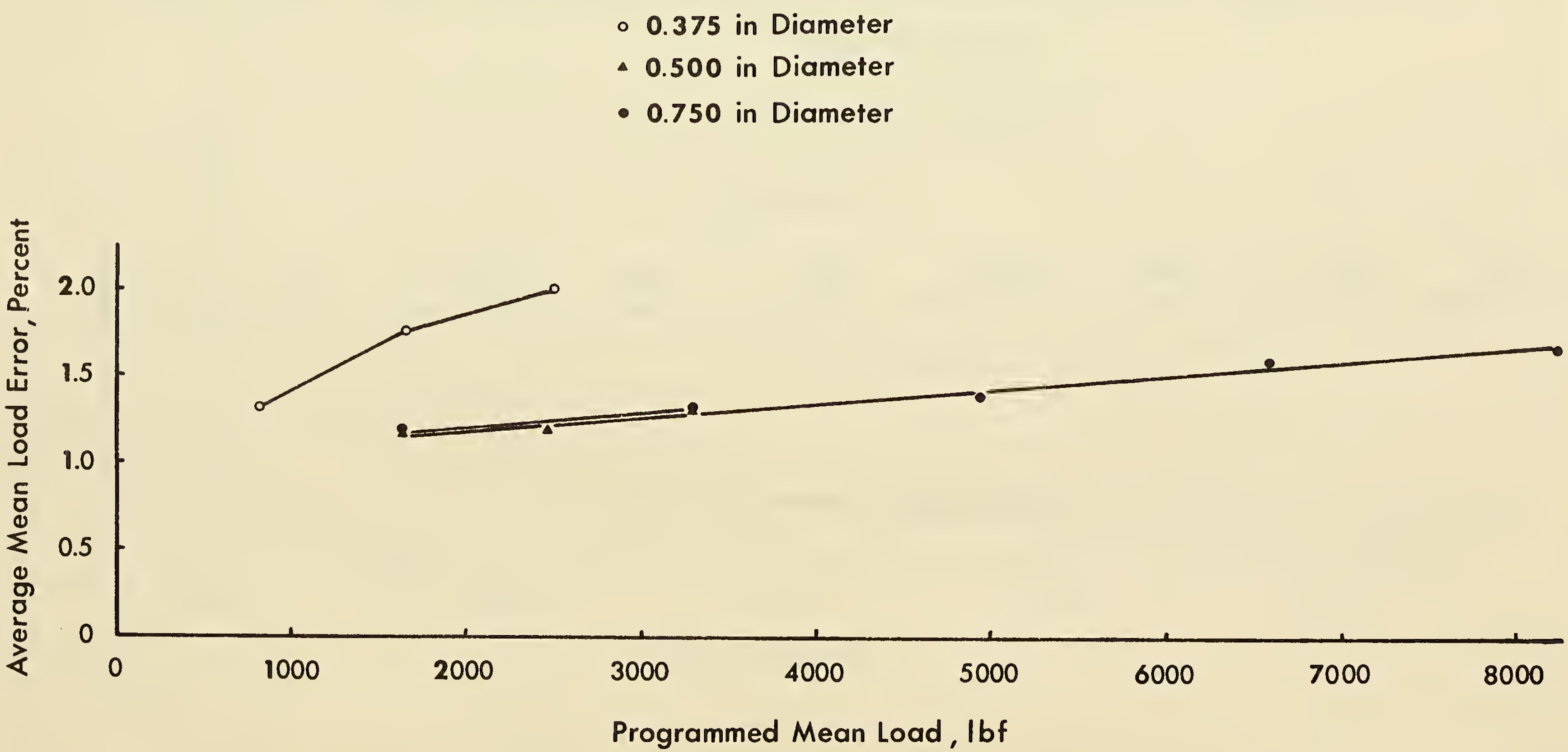


Figure 9 – Average Mean Load Error versus Programmed Mean Load for Various Diameter Test Bars

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A refined test procedure is given for accurately recording the dynamic signals from instrumented test bars used to measure loads during simulated fatigue tests. Loads indicated by the load transducer of a direct-stress fatigue machine are compared with those determined from these instrumented test bar specimens which have been calibrated under static conditions. An application of this procedure is described for a resonant, electromagnetic, direct-stress fatigue machine having an optical dynamometer for indicating programmed loads. The variables investigated were the operating speed, cyclic load and specimen stiffness. In addition, the influence of test fixture mass on the load measurements was determined at one test frequency. The mean loads indicated by the instrumented test bars are compared with those indicated by the dynamometer to determine the errors in load measurements under various test conditions.

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