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FORCE SENSOR-MACHINE INTERACTION

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ABSTRACT

Although a force sensor is designed to respond primarily to an axial component of applied force, the sensor may also produce a significant error signal in response to non-axial load components that result from small misalignments in the loading setup. There may also be significant time-dependent machine-sensor-interaction errors involving creep or mechanical oscillation. This paper describes techniques that are being used to reveal, identify, and quantify these sources of error. The techniques involve the use of high-resolution readout instruments and a dedicated microcomputer/graphics system to make rapid comparisons of the response of force sensors to different loading conditions.

KEYWORDS: Force; force calibration; force measurement; load cell; machine-sensor interaction; proving ring; remainder plot.

INTRODUCTION

Mechanical interaction between a force sensor and the machine that applies the force to the sensor is the most insidious source of systematic error in many force measurement applications. A force sensor must be strong enough and stiff enough to support the entire force that it is measuring. This is in contrast with sensors that only probe a small region within a field, e.g., strain, temperature, and pressure sensors. Because of the relatively high stiffness of a force sensor, significant non-axial load components can result from relatively small misalignments of the loading setup, even in deadweight calibration setups. Therefore, a force sensor that is designed to respond primarily to an axial component of force may also produce a significant error signal in response to non-axial load components such as bending, torsion, or shear.

There may also be significant systematic errors due to time-dependent machine-sensor interactions. Such errors can result from an inability of the readout instrument to track mechanical oscillation of the loading setup. Another form of error involves the sequence of the application of forces to the sensor in relation to the creep characteristics of the sensor.

Because of these machine-sensor interactions, when a force sensor is calibrated in one machine and then installed and used in a different machine, there may be a shift in response that is significant in relation to the accuracy requirements of the application. This paper describes an approach used to identify and quantify the machine-sensor interaction errors that occur during a force calibration process. An understanding of these errors for a particular sensor should be a useful basis for judgment about potential machine-sensor interaction errors in the end-use application of the sensor.

APPROACH

The approach involves using high-resolution readout instruments and a dedicated microcomputer/graphics system to compare the results from different force calibration setups in the same or different machines. The results are compared in terms of remainder plots. Figure 1 shows schematically the method of obtaining a remainder plot of the data from a single calibration run. The sensor response data are first fitted by least squares to an analytical function of the applied load, usually a polynomial and most frequently a second degree polynomial. In Figure 1 the response data points are fitted to a first degree polynomial represented by the inclined straight line. The fitted analytical function values are then subtracted from the corresponding response data at each load level and these remainders are plotted as a function of applied load.

When two or more calibration runs are to be compared, a single analytical function is fitted to the data from one or more of the runs. The corresponding values of this function are then subtracted from each data point. The resulting remainder plot indicates the differences in response of the compared runs. This is illustrated in the following examples.

EXAMPLES OF MACHINE-SENSOR INTERACTION

The following examples are all from force calibrations in the NBS deadweight machines. One example shows evidence of probable overload damage to a sensor during the time interval between calibrations. Each of the other examples suggests an explanation in terms of an interaction between the force sensor and the deadweight machine used to apply the load.

Each of the remainder plots shown below was obtained by fitting a second degree polynomial to the combined set of data represented by the plot. The separate data points are plotted as numerals which identify the different calibration runs. Where two or more data points have the same plot coordinate, only the numeral of greatest value is plotted.

Bending, Torsion, and Shear

A remainder plot for nine compression calibration runs performed on a 240 000 lbf (1 067 600 N) capacity load cell in the 300 000 lbf (1 334 500 N) deadweight machine (Figure 2) is shown in Figure 3. The units of the remainder (vertical) axis are digital readout instrument units. The one-unit resolution of the instrument is indicated by the horizontal dashed lines. The readout instrument was spanned to indicate about 104 600 units at capacity load. Thus, the spread of the data indicated at capacity load is about 0.03 percent.

The fan-shaped distribution of data (Figure 3) indicating roughly load-proportional systematic errors is commonly observed, particularly in compression calibrations. It is believed to be caused primarily by bending of the load cell due to misalignment of the machine and the cell. If bending is present as the dominant non-axial component of load, torsion and shear components of lesser magnitude may also be coupled to the bending component.

It would be reasonable to assume that there is always some misalignment in a setup of the type used in these calibration runs. The load cell is centered on the compression platen (Figure 2) and loaded through a soft steel block that is placed between the loading platen and the load cell. As the lifting frame is raised by the hydraulic piston, the applied weight stack is raised by a force acting through the load cell. The vertical gravitational force causes the center of gravity of the applied weights to assume a position directly under the hydraulic piston. Since the machine frame and the load cell setup are not initially in perfect alignment, non-axial loading components are induced as the frame and load cell setup tend to straighten out. Actually, the relatively small misalignment that is apparent in such a calibration setup can be seen as having some benefit in that it produces an indication of the relative sensitivity of the load cell to non-axial loads.

Figure 4 is a remainder plot for nine tension calibration runs performed on a 500 000 lbf (2 224 100 N) capacity load cell in the 1 000 000 lbf (4 448 200 N) deadweight machine. This deadweight machine is functionally similar to the smaller machine shown in Figure 2. The load cell was connected between the tension platen and the loading platen. The readout instrument was spanned to indicate about 183 500 units at capacity load. Thus the spread of the data indicated at capacity load is about 0.01 percent. The serpentine shape of the band of data indicates that the data could be better fit by a model other than the second degree polynomial used. The distribution of the data suggests that there was effectively a zero shift between runs. That is, a vertical translation of the data from most of the runs would give a much narrower serpentine band. A possible explanation for the apparent zero shift is that bending moments were locked into the tensile load cell and connecting fixtures as the assembly and machine frame straightened out during the application of the first weight increment. Subsequent load increments apparently caused relatively little additional straightening.

Mechanical Interference

Figure 5 is a remainder plot for nine tension calibration runs performed on a 300 000 lbf (1 334 500 N) capacity load cell. At mid-range the data clearly separate into two parts; the upper branch represents the first six runs and the lower branch represents the last three runs. An examination of this plot led to the discovery that during the last three runs the loading platen of the deadweight machine had apparently bottomed out against one or more of the safety nuts located directly below the platen (Figure 2). When this happened a part of the deadweight load was supported by the safety nuts rather than the load cell and the load cell output was reduced as indicated in Figure 5. The resulting error indicated at capacity load is about 1 percent.

Sensor Overload

Figure 6 is a remainder plot for 43 calibrations of a 10 000 (44 482 N) capacity compression proving ring performed between 1938 and 1980. The units of the vertical scale are dial divisions of the micrometer screw readout of the ring; full scale output of the ring is about 382 divisions. The data points plotted as numeral 1 were obtained between 1938 and 1951, the other data points (numeral 2) were obtained between 1952 and 1980. The proving ring was apparently overloaded in compression between the 1951 and 1952 calibrations. Such a compression overload would be expected to cause an increase in the width of the ring and a decrease in the height of the ring. This would cause the ring to be less stiff in compression, as indicated by the upward rotation of the band of later data (numeral 2) relative to the band of earlier data. This plot indicates that the ring was quite stable for over 40 years except for the apparent overload.

Loading Sequence

The influence of loading sequence on the response of a force sensor is greatly dependent on the creep characteristics of the sensor. Creep is defined here to be the change in sensor output that takes place after the initial response to the force increment, excluding any transient inertial response caused by the force increment. Figure 7 is a remainder plot for nine tensile calibration runs performed on a 10 000 lbf (44 482 N) capacity load cell in two different deadweight machines. The load cell was equipped with flexures to effectively prevent significant bending errors. The data represented by numerals 1 through 5 were obtained using the 112 000 lbf (498 200 N) deadweight machine and the data represented by numerals 6 through 9 were obtained using the 25 300 lbf (112 540 N) deadweight machine. The larger machine applies loads incrementally without returning to zero load between successively higher loads; the smaller machine requires returning to zero load between load changes. In an attempt to maximize the agreement between calibrations in the two machines, data for each load level were recorded after the same amount of time had elapsed since the initial zero-load condition. The elapsed time between successive readings was one minute and the total elapsed time for each run was ten minutes. In the smaller machine, however, each one minute interval included several seconds during which the weights were being changed and there was no load on the load cell. During these several seconds under no load there was apparently enough creep recovery to account for the shift of about 0.01 percent of full scale output that is evident in Figure 7. A creep test on this load cell indicated a negative creep of about 0.04 percent of full scale output in one hour.

Pendulum Oscillation

Evidence of significant compound pendulum oscillation has sometimes been observed during the calibration of load cells in the larger NBS deadweight machines. The null meter pointer of a 100 000 count readout instrument has been observed to swing in two dominant modes. One mode apparently corresponds to the lateral motion of the weight stack that is suspended by the loading frame from the load cell being calibrated (Figure 2). The other mode may correspond to the lateral motion of the load cell as it approximates a pivot between the loading frame and the lifting frame. The observed amplitude of oscillation of the readout instrument reading is ordinarily less than 0.01 percent of full scale output. By manually balancing the swing of the meter pointer on each side of null one can average out this error.

Pendulum oscillation is also sometimes evident in the digital display of a self balancing 1 000 000 count readout instrument used in these calibrations. This digital instrument has a settling time that may be comparable to the period of the first mode of pendulum oscillation. Consequently, pendulum oscillation can result in a noise-like variation in the last two digits of the output.

Bounce-Mode Oscillation

The relatively low stiffness of an elastic ring force sensor (proving ring) can result in troublesome low frequency bounce-mode oscillations during a deadweight machine calibration. The spring-mass system consisting of the ring (the spring) and the combination of loading frame and weights (the mass) can have a resonance frequency of the order of 10 Hz or less. The low-frequency oscillation can be excited by the operation of the deadweight machine itself or by structural noise transmitted through the building. These oscillations are visible in elastic rings equipped with a mechanical dial gage readout, although they may be effectively masked by the low resolution of rings equipped with a micrometer screw readout.

CONCLUSION

Remainder plots are a powerful tool for use in maintaining control over machine-sensor interaction errors in a force calibration process. The plots also can serve as one basis for estimating machine-sensor interaction errors in end-use applications.

For this approach to be effective, the sensors and readout instrument must have adequate resolution and stability. Also, a system must be available for efficiently processing and managing the relatively large base of calibration data involved in making comparisons between calibration runs.

ACKNOWLEDGMENT

Robert W. Peterson and Saul M. Baker have made important contributions to the work reported here.

REFERENCES

The following papers further discuss NBS studies of machine-sensor interaction and other sources of systematic error in force measurement such as creep, pressure sensitivity, hysteresis, and thermoelastic effects:

(1) Mitchell, Richard A. and Baker, Saul M., "Characterizing the Creep Response of Load Cells," VDI Berichte Nr. 312, 1978, pp. 43-48.

(2) Pontius, Paul E. and Mitchell, Richard A., "Inherent Problems in Force Measurement," Fourth SESA International Congress on Experimental Mechanics, Boston, May 25-30, 1980.

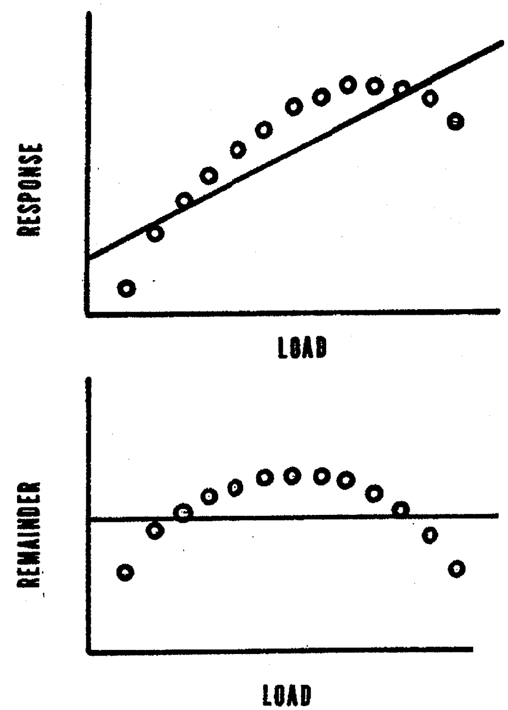

FIG. 1. REMAINDER PLOT SCHEM/

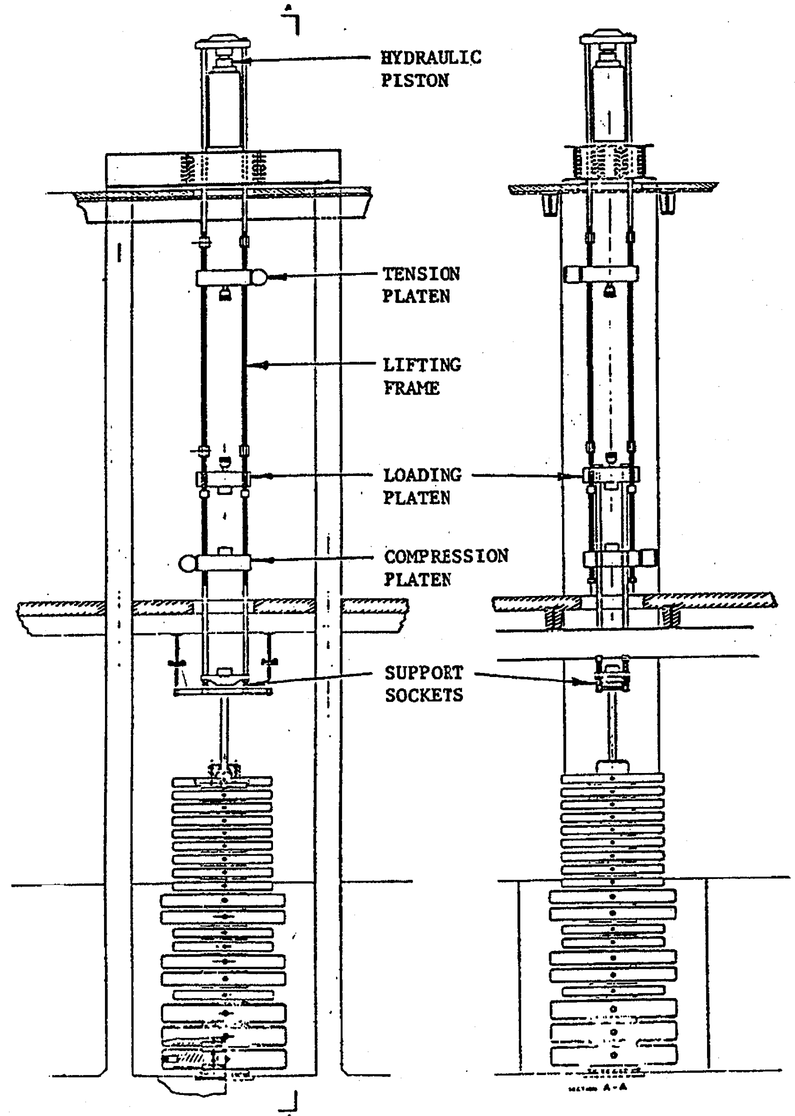

FIG. 2. DEADWEIGHT MACHINE (300,000 lbf.)

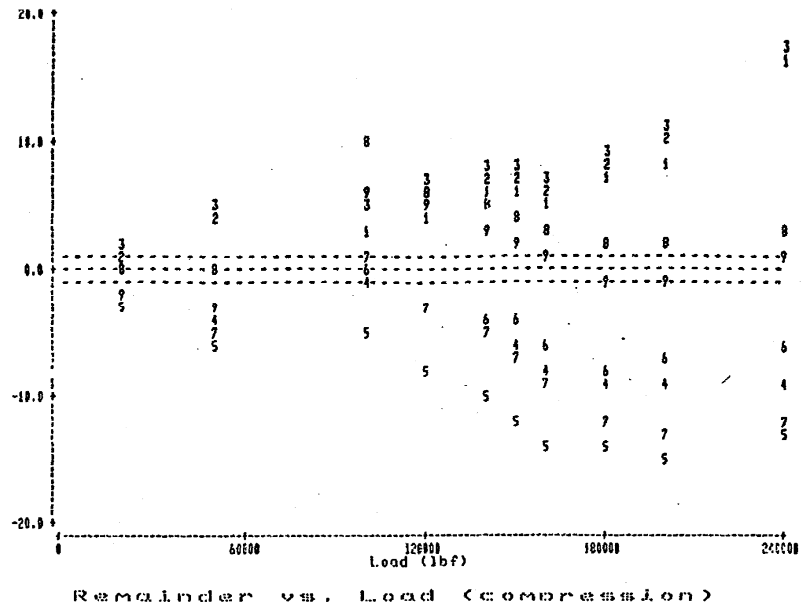

FIG. 3. LOAD PROPORTIONAL ERRORS.

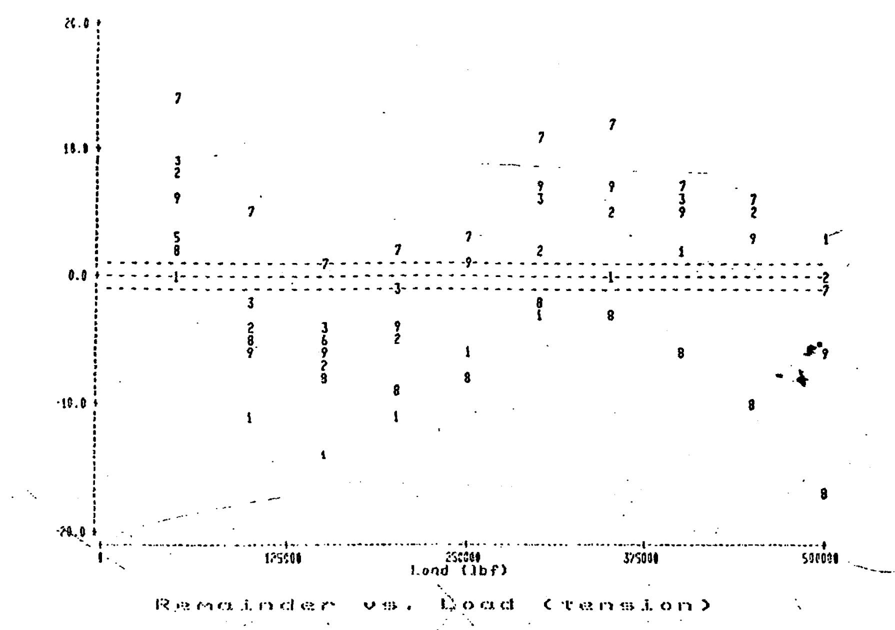

FIG. 4. APPARENT ZERO SHIFT.

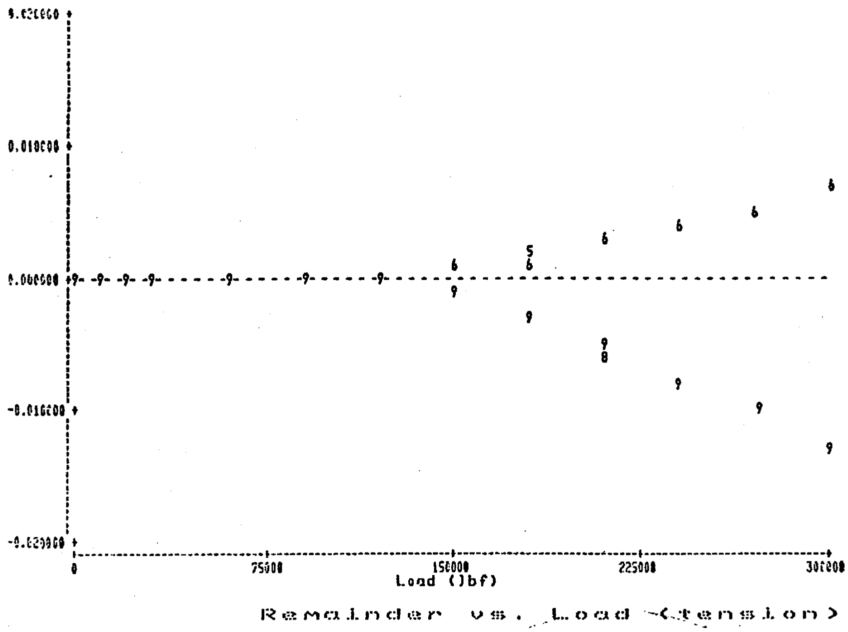

FIG. 5. EFFECT OF MECHANICAL INTERFERENCE.

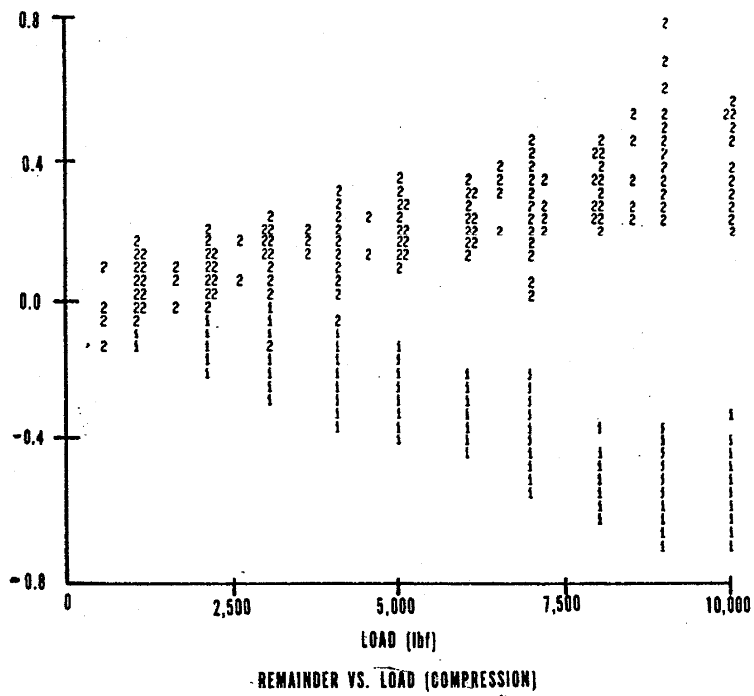

FIG. 6. EFFECT OF SENSOR OVERLOAD.

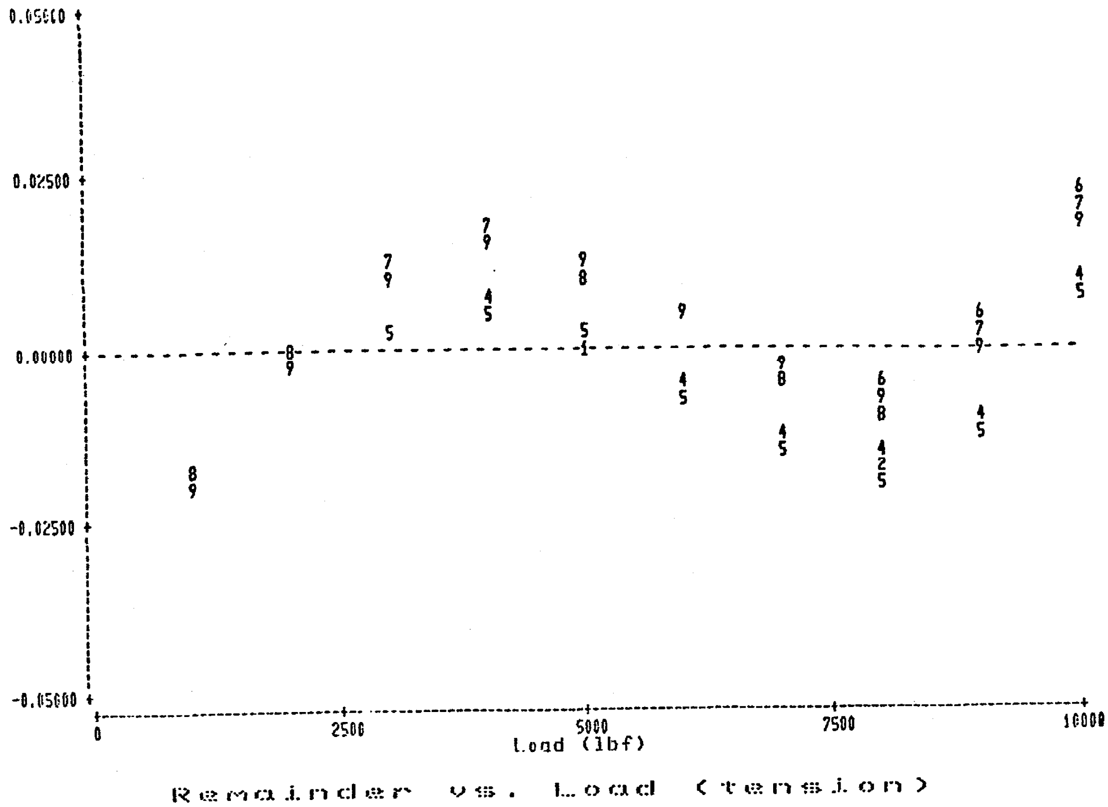

FIG. 7. EFFECT OF LOADING SEQUENCE.