# ENGINEERING STUDIES

STRUCTURAL RESEARCH SERIES NO. 35

# INDUCTIVE GAGE FOR MEASUREMENT OF LOAD



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**Please Note:**
Preprint of paper to be delivered at the Conference of the Instrument Society of America, September 8-12, 1952, Public Auditorium, Cleveland, Ohio.
Discussion sent to the I.S.A. will be considered if received by October 1, 1952.

Price to members 25c. to non-members 50c

Paper No. 52-2-3



# Inductive Gage for Measurement of Load

By HOWARD C. ROBERTS*

This paper describes the design and construction of an inductive-type gage for the measurement of load, intended especially for use in a fatigue machine, but applicable to other uses as well. Its performance, in terms of sensitivity, stability, and accuracy, is also described.

The measuring element is a balanced inductance-type displacement-measuring gage, installed in a mechanical ring-type dynamometer. Excitation is by alternating current at 13,500 cycles per second; output is direct current at low impedance, with polarity of output current indicating direction of application of load. Sensitivity, stability, and accuracy are all high. For static measurements a null system is used, but the instrument may also be used for dynamic measurements as a deflection-type instrument.

The application of such an instrument in fatigue machines is described, as well as an alternate form of primary element.

SEVERAL years' experience in the operation of lever-type fatigue machines in the Structural Engineering Laboratory of the University of Illinois had indicated that the mechanical load gages customarily used were not sufficiently sensitive, stable, and accurate for some new types of tests, although adequate for their normal uses. A new type of load-measuring device was desired, having greater sensitivity, stability, and accuracy, better compensation for temperature effects, and capable of providing continuous dynamic records if desired. The development described here fulfills these requirements.

## Use of Mechanical Type Gage

Load measurements have been customarily taken with elastic load-rings and dial gages; the change in diameter of the ring under diametral load being the indication of force. It is usual for such a load-ring to experience a change in diameter of perhaps 0.001 inch for 1,000 pounds load. Thus, with a dial gage reading to 0.0001 inch, in a fatigue machine containing a 10:1 lever system, one division on the dial represents approximately 100 pounds on the specimen. Ordinary dial indicators are not considered accurate enough to read closer than one division.

In use, the dial-gage dynamometer is satisfactory only for static measurements, since the dial indicator cannot well follow the cyclic loads applied by the machine, and in order to protect it from damage it is removed from the machine during a test. The general procedure is this:

The dial indicator is inserted in the gage-holes in the load-ring, and a reading is taken. Load is then applied, and another reading taken; the difference in these dial readings is proportional to the load change. If it is desired to check the load over a period of days (or even hours), the effect of temperature must be considered; this requires the use of a standard bar. The standard bar is a piece of the same type of material as the load-ring and exposed to the same temperatures, but not loaded. Similar changes of dimension in both load-ring and standard bar result from temperature effects; differences between them are the result of load.

## Limitations of Mechanical Type

Such a mechanical load-gage is calibrated either by dead weights, or by applying known loads in a testing machine. In order to permit measurement of load over a period of time, without removing the load, it is necessary to apply the dial indicator at intervals; for this the machine is stopped, but the load is not released.

It is not possible in practice to eliminate all the errors in such a load-measuring device, no matter what precautions may be taken. This is primarily because perfect temperature compensation is possible only when all portions of the device change in temperature at the same time and at the same rate. In normal use, this condition is far from being realized.

In a fatigue machine, for example, there is a source of heat in the shaft bearings and the eccentric bearing just below the load-ring, and in operation this produces a thermal gradient from the lower to the upper portion of the load-ring. There are other sources of heat, too, both within the machine and without it, which combine to introduce errors.

For these and for other reasons, it was felt that a load-measuring device of greater accuracy, greater long-time stability, and capable of producing dynamic records, was needed.

## Selection of Gage Type

The principal requirements for the load-measuring device were these:

(1) High long-time stability and accuracy.

(2) High sensitivity.

(3) Dynamic response, up to at least five cycles per second (the speed of the fatigue machine).

(4) Freedom, so far as possible, from disturbances caused by changes in ambient conditions (temperature, vibration, and the like).

(5) Ability to produce a graphic record.

For convenience and economy, it also seemed desirable to employ, if possible, the existing load-ring as a load-sensitive element, changing only the measuring element itself.

Preliminary studies, using the same load-ring dynamometer, with different arrangements of dial indicators, showed promise, but not enough promise to justify extended study. It was found possible to eliminate much of the temperature error by making measurements of the changes in both horizontal and vertical diameters of the load-ring, thus dispensing with the standard bar (which might be at a slightly different temperature than the load-ring. A linkage was worked out by which a mechanical gage gave the ratio of the change in these two diameters, without the necessity for measuring both separately.

None of these expedients, however, offered much promise of fulfilling the last three requirements in the list. It was, consequently, decided to employ some form of electric sensing element, which would (1) eliminate errors from mechanical friction, (2) provide means for producing a graphic record, and (3) give extremely high sensitivity through careful circuit design.

Of the several different basic types of electrical strain gages which might be employed in such an installation, the variable-inductance gage (and especially the balanced form, the inductance-ratio gage) offered so many more advantages than any other that its choice was inevitable. The special advantages for this application were these:

(1) It is sensitive to total strain rather than to unit strain.

(2) Sensitivity can be made as high or as low as desired, if the range can be restricted proportionately; thus the load-ring might have any of a wide variety of characteristics.

(3) Properly designed, such a gage can be given excellent temperature compensation.

(4) The gage can be used in a null circuit for the highest accuracy, but

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such a circuit need not prohibit its use as a deflection-type instrument for dynamic use.

(5) Vacuum-tube amplifiers are not needed; this eliminates certain complexities, as well as greatly simplifying maintenance. Since amplifiers were not to be used, permanent calibration was facilitated.

## Design of Inductance-Ratio Gage

In the final analysis, the quality of the primary element (and the closeness by which its final characteristics fit those specified) depends equally upon (1) the design of the components, (2) the quality or uniformity of the material used in construction, and (3) the precision of construction, assembly, and adjustment. If all three of these are satisfactory, the completed instrument may be expected to be stable, accurate, and efficient.

Since freedom from temperature errors and long-time stability were two of the most important desiderata in the load-measuring system, symmetric and stable design, both mechanical and electrical, was obviously required. After the characteristics of several of the commonly-used gage and circuit designs were analyzed, the circuit shown in Fig. 1 was selected as best suited to the purpose.

In this circuit, four separate inductances are used; they are arranged in two pairs, one pair being those in the gage-head, and the other pair in the balancing unit. The actual construction of each pair is as indicated in Fig. 1-B; two iron-cored coils are connected together mechanically with a laminated iron armature between them, and the whole is attached to the load-ring or other device so that the movement to be measured changes the position of the armature without changing the separation of the two coils. Movement, therefore, produces a change in the ratio of the two airgaps, and thus a change in the ratio of the inductances of the coils.

## Electrical Circuit of Gage

When the inductance units are connected in the circuit, shown in Fig. 1-A, one coil of the balancing unit and one coil of the gage-head are connected in series (that is, $L_{ba}$ and $L_{ga}$) and become one "arm" of the circuit. The other two coils ($L_{bb}$ and $L_{gb}$) are similarly connected in series, and become the other inductive "arm" of the circuit.

The characteristic of this circuit is that when the impedances of the two inductive "arms"—one composed of $L_{ba}$ and $L_{ga}$ in series and the other composed of $L_{bb}$ and $L_{gb}$ — are equal, no current flows through the indicating instrument $G$. If one impedance is greater than the other, current will flow, its magnitude being a function of the difference in the two impedances, and its direction indicating which of the two is greater.

This is not a bridge circuit, but an impedance-comparison circuit. It is excited by alternating current but employs a direct-current galvanometer as an indicating device, and it has most of the desirable characteristics of a phase-sensitive alternating current bridge, while much simpler in construction.

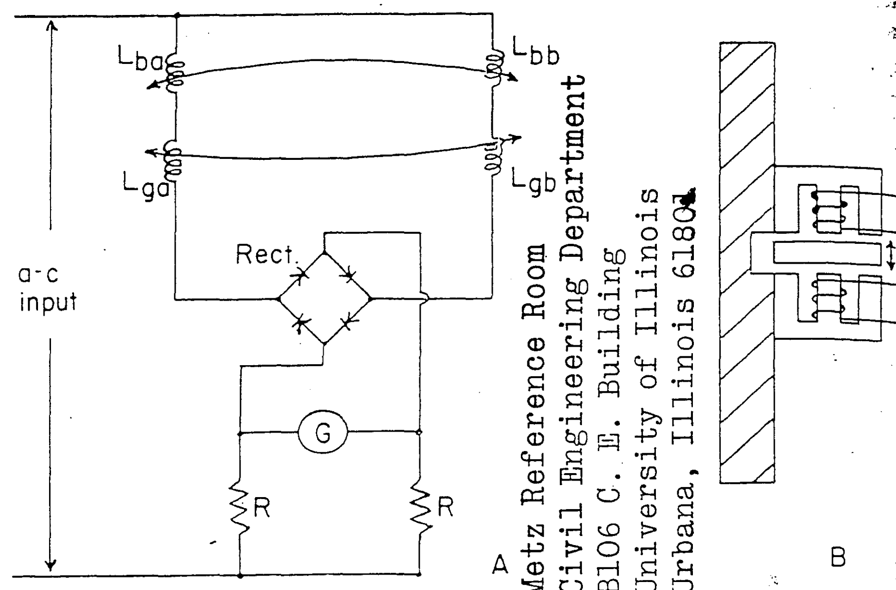



Fig. 1 Inductance-ratio gage: (A) schematic wiring diagrams and (B) construction of inductance pair.

In this circuit, however, anything which causes a change in the impedance of either of the inductive "arms" will cause a change in circuit output. It is therefore necessary to insure that changes in gage resistance will not occur, nor changes in capacitance which would affect the impedances of the critical circuit branches. Likewise, to provide most stable operation and highest sensitivity, the circuit impedances should be made as nearly completely inductive as possible.

## Design of Inductance Coils

These requirements were met by winding the gage coils on laminated silicon-steel cores of approximately 5/16-inch square cross-section, and matching the resistances of the two coil assemblies to better than ½ per cent. Each coil-and-core assembly comprises a U-shaped core carrying two coils; each coil contains 100 turns of 24-gage copper wire. The two coils on each core are connected in series-aiding, to make the inductance of the coil assembly as high as possible. The finished coil assembly is small, and has small leakage inductance, so that its inductance is not greatly affected by nearby metallic objects.

The inductances used in the balancing unit were less critical in dimensions and in characteristics; those used were made by taking the coils from small commercial transformers (Swain-Nelson No. 6P169) and rearranging the laminated core-material. Only the low-impedance winding, of about 140 turns, was used; the other windings were left in place, open-circuited.

Mounting of the gage coils, to permit unrestricted movement with changes in load-ring diameter, and yet to resist the forces produced by acceleration while the machine was in operation, was a difficult problem. The solution finally selected was a clamping system, with the actual clamping force applied through steel balls set in indentations for locating the parts accurately. This arrangement permits quite rigid clamping action without danger of creep of any parts during operation. The clamping members were made rather heavy, and the entire assembly was made symmetrical, insuring that so far as possible no change in leakage reactance could occur during operation.

## Construction of Gage Assembly

The photograph, Fig. 2, shows the general appearance of the load-ring with the clamp-on gage; the clamping members are visible, but the actual coil-and-core assemblies which make up the gage-head are concealed within the clamp.

The balancing unit is also shown in this photograph, and the manner of assembly may be clearly seen. The moving armature is inset into the lever, which may be moved by the

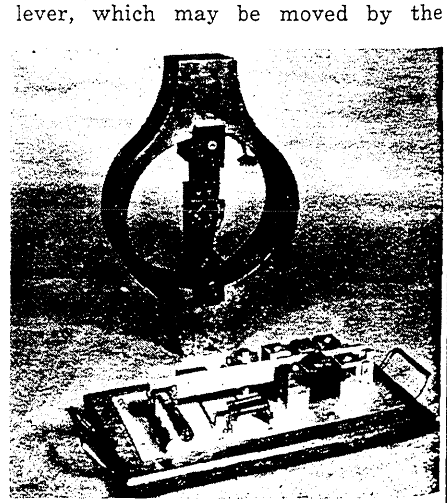

Fig. 2 View of load-ring with clamp-on gage. Balancing unit in foreground.

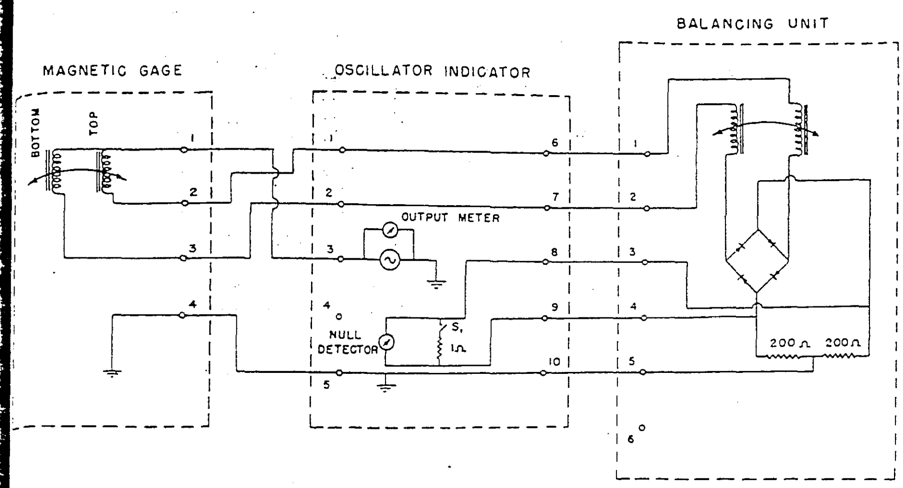


**Fig. 3 Circuit diagram for dynamometer (magnetic gage).**

micrometer screw at the left-hand end of the instrument. The pivot at the fulcrum end of the lever is a pair of crossed springs, of phosphor bronze; this provides a moving system having no discoverable hysteresis, and good temperature stability.

All metallic parts of the balancing unit are of brass, except the silicon-steel coil cores and the micrometer screw. On this same base are mounted the two resistors, *R* (Fig. 1) which make up the third and fourth "arms" of the impedance-comparing circuit, and the ring-modulator unit which rectifies the circuit output.

The entire instrument is assembled in three units, namely: (1) the load-ring and its gage-head, (2) the balancing unit with the micrometer screw to adjust balance, and (3) the case containing the other electrical elements—the oscillator for providing exciting current for the gage, and the indicating instruments. The diagram of Fig. 3 shows the interconnections of these three units, and the operating circuit. The interconnections are made with polarized connectors, of different types, so that it is not possible to connect the units improperly.

### Oscillator Indicator

It may be noted that in the "oscillator-indicator" unit two indicating instruments are shown—an output meter which provides a continuous indication of the voltage of the exciting current, and a null detector which indicates balance of the circuit. The null detector is a center-zero milliammeter with a current range of one milliampere in either direction from center; for protection during first rough adjustments it is shunted with a one-ohm resistance. This diagram does not show the circuitry of the oscillator and the power supply; these are indicated only by the symbol for a source of alternating current.

The external appearance of the oscillator-indicator unit is shown in the photograph, Fig. 4. The instrument at the left is the null-detector, at its right is the output meter—which has only two marks on its scale, indicating zero and operating voltage. Across the bottom are the controls—on-off switch, high and low sensitivity switch, jack for connecting external instrument, pilot light, and output voltage control.

The electrical circuit of the oscillator unit and its power supply are shown in Fig. 5. It is an orthodox resistance-capacity type oscillator, with its output voltage controlled by altering the amount of negative feedback.

### Installation in a Fatigue Machine

Fig. 6 shows the load-ring installed in a fatigue machine. Only part of the machine is visible; at the top is the end of the walking beam or main lever of the machine, and below the dynamometer ring is the eccentric and shaft-bearing assembly. It is the rotation of this eccentric that applies the cyclic load of the machine, through the dynamometer load-ring. Under load, these bearings, run warm, causing a temperature gradient through the load-ring from bottom to top; this is one of the most troublesome sources of error.

A calibration curve for the complete unit is given in Fig. 7; for actual use this is drawn to a more convenient scale. The average sensitivity is about 3 1/3 pounds per division on the micrometer screw, and with the built-in indicating instrument changes of 3 pounds are easily detected. The completed instrument is considered accurate to about 10 pounds, with a range of 7,000 pounds or a little more; reproducibility or comparative accuracy is about 5 pounds.

The sensitivity can be increased by a factor of as much as 100 by using a sensitive external indicating instrument, externally connected. When this is done the sensitivity is limited by the precision of the balancing micrometer screw. For dynamic measurements, and using a deflection method, sensitivities as great as 1/20 of a pound have been achieved.

### Accuracy and Stability

Since the primary need for the instrument was for relatively long-time tests, a rather extensive study of its accuracy and stability was made. The lower curve in Fig. 7 shows one of the most important results of this study, namely: the effects of unequal heating of the magnetic gage.

In order to simulate a temperature gradient across the load-ring (such as might be caused by a heated bearing) a small source of heat (3½ watts)

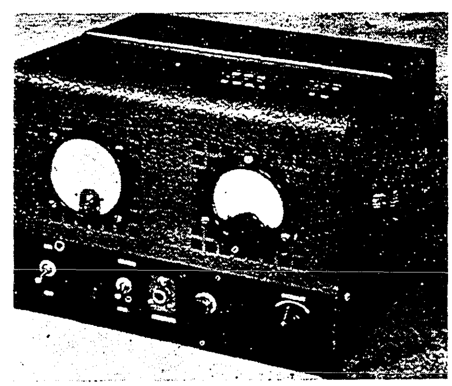

**Fig. 4. External view of oscillator-indicator unit.**

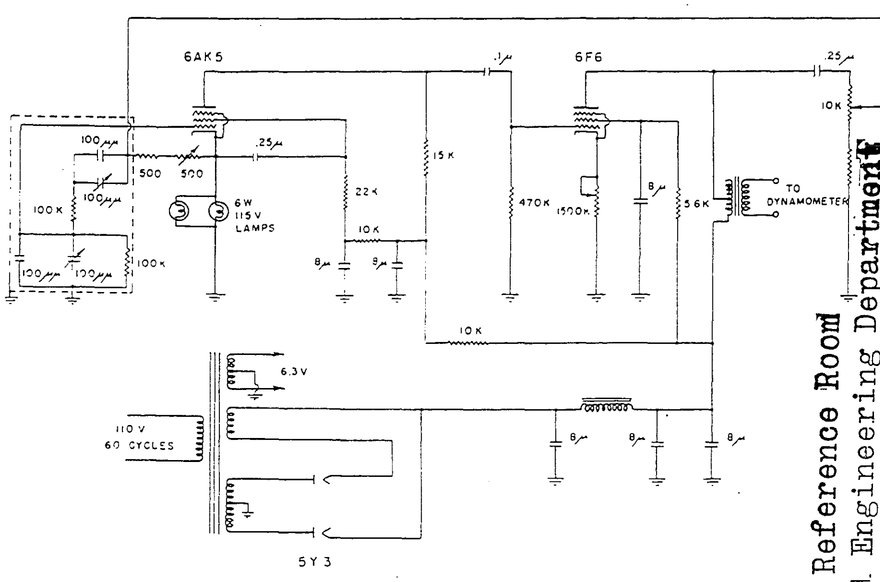


**Fig. 5 Electrical circuit of oscillator for the magnetic gage.**

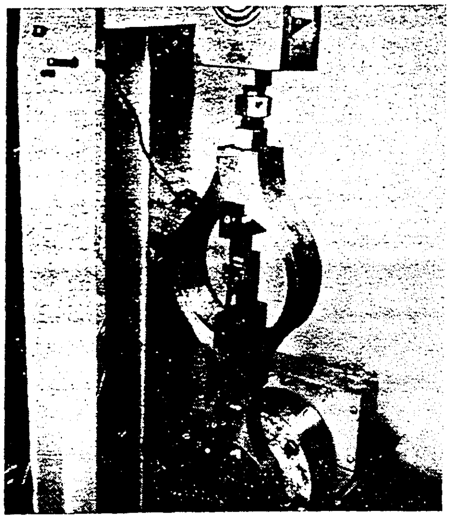

Fig. 6 Load-ring installed in a fatigue machine.

was applied at the lower end of the gage-head bracket. The micrometer screw adjustments required to maintain balance were then plotted; the curve shows a gradual change in circuit balance, continuing slowly for about 3 hours, then changing little for the next 16 hours or so, at which time the test was stopped because of failure of the heater.

This is essentially what one would expect, since after a considerable time a temperature equilibrium is reached, following which little change occurs. The change in gage-balance during this long warm-up period is about 20 divisions, or about 70 pounds of load.

This warm-up, it should be noted, is the warm-up time for the machine, and not for the measuring equipment.

Further tests confirmed this finding, and indicated that after the machine had reached its operating temperature, there should be no apparent change in load greater than perhaps 15 pounds from this source, and that this could be reduced somewhat by applying thermal insulation to the load-ring.

To ascertain the effect of ambient temperature (as contrasted to temperature gradients within the load-ring) the entire instrument was subjected to temperatures ranging from about 60° to 90° F. This required some cooperation with the weather, and actually the tests were conducted over a period of about 15 months. All of these tests were made in a lever-type static testing machine, having a total range of 10,000 pounds, and maintained by dead-weight checks to well within 1 per cent accuracy—usually ½ per cent. A considerable amount of data was taken, and a statistical analysis made to determine the true correction factors.

The conclusions reached were as follows:

(1) At the midpoint of its range, no change in instrument indication was caused by change in temperature.

(2) At any other point, the temperature correction required was 0.3 per cent of the difference between actual load reading and the midpoint scale reading.

Consequently it was possible to draw a family of calibration curves, all intersecting at the midpoint of the range, and read loads directly from these curves, taking cognizance of room temperature. If no temperature correction is made, the maximum error that could occur as the room temperature rose from 65 to 75° F could be as great as 200 pounds—far from negligible. If the temperature correction is made, this will be reduced to 20 pounds, or perhaps a little less.

The fact that all these calibration curves, run at several different temperatures, intersect at the midpoint of the scale is worth noting. This is the point at which the two air-gaps in the gage-head are equal, as are the similar air-gaps in the balancing unit; and this is the only condition in which the instrument is perfectly symmetrical mechanically and electrically.

It is possible to compute from these data that the temperature error is a function of the difference in thermal expansion of the air-gaps and the equivalent length of steel; and also to design a thermal device to compensate this systematic error. This correcting device has not been constructed, since correction is so easily handled with the calibration curves.

### Alternate Form of Gage-Head

During the exploratory period of this project, another form of gage-head was designed and tested, and although it was not used for this instrument, it has proved useful in other applications. It will be described briefly.

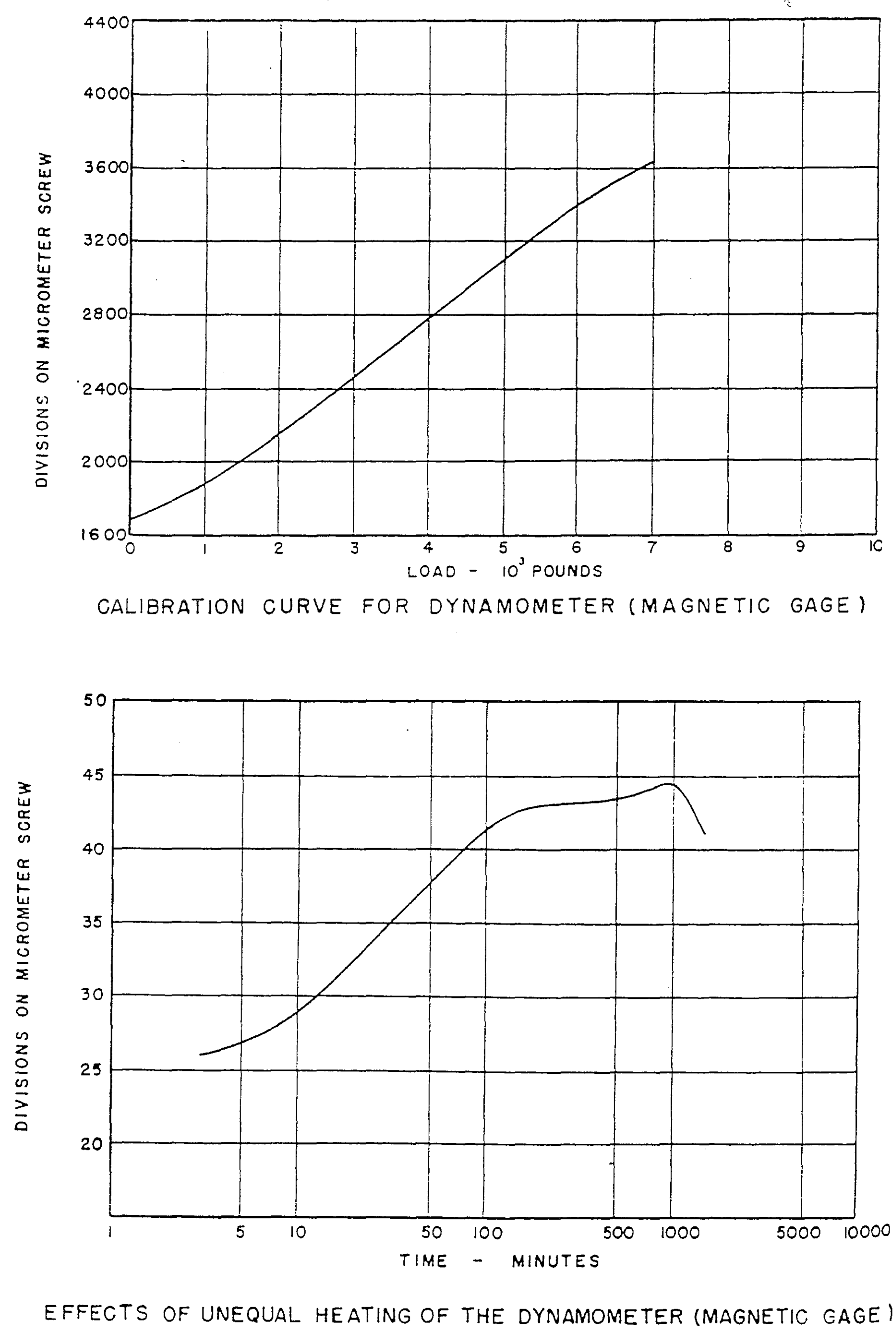


Fig. 7 Calibration curves for the magnetic gage.

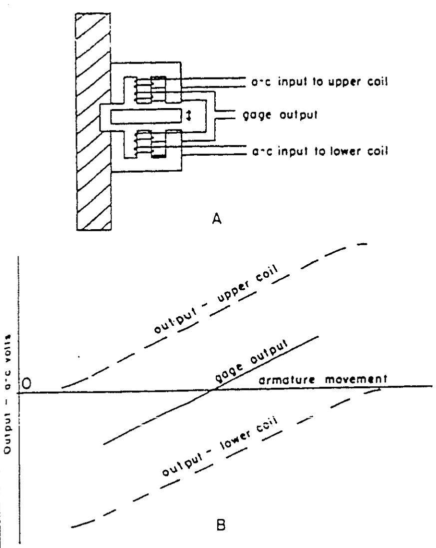


Fig. 8 Alternate form of gage-head: (A) construction of inductance pair and (B) curves of output voltage.

Its general form is shown in Fig. 8-A. It comprises two coil-and-core assemblies, connected together mechanically, with a laminated armature moving between them. Like the gage described previously, its output is a function of the ratio of these two air-gaps.

Each core carries two coils—a high-impedance coil excited by alternating current, and a low-impedance coil which provides the output. Various modes of connection can be used, but best results were had by connecting the two exciting coils in parallel, and to the source of alternating current; and the two output coils were connected in series.

In operation, each coil-and-core assembly acts with the moving armature as a variable-air-gap transformer. The two output coils are connected in series-opposition; thus their combined output is the algebraic sum of the individual outputs. This is indicated graphically in Fig. 8-B. The final gage output is alternating current, with zero magnitude when the armature is at its mid-position, and increasing as the ratio of air-gaps changes from the value of 1. Thus, the amplitude of motion is indicated by the magnitude of the output, and the direction (from the central position of the armature) by the phase relation of the gage output to the voltage of the exciting current.

Such a gage can be made with a wide variety of characteristics; for example, it can be powered directly by the 115-volt, 60-cycle line. Its output can be provided at any reasonable impedance, by selecting proper coils. It must be used with a phase-sensitive output circuit, if its characteristics are to be employed. It is classed as a mutual-inductance gage, of the ratio type.

This alternate form of gage is now being used in a high-speed, high-capacity controlling and programming system in our research program on cumulative damage of structures.