

DESIGN OF A TEMPERATURE-COMPENSATED INDUCTION EXTENSOMETER

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ABSTRACT

By proper choice of materials, dimensions and circuit parameters, it is possible to design a linear displacement transducer, or extensometer, to have zero net thermal drift over any given temperature range. The chief limitation is the inability of wires and insulation to withstand very high temperatures. An extensometer has been designed and tested which could theoretically measure displacements up to 150 mm with a maximum error of ± 0.15 mm caused by thermal effects over the temperature range from 0° to 1000°C . Experimental limitations prevented testing at temperatures higher than 500°C , but measured and theoretical results were in good agreement over that range. The principles involved in the temperature compensation will be discussed.

When eddy current tests must be made over a range of temperatures, there are several possible thermally-caused errors. The resistance of the coils may change; the resistivity of the samples may change; thermal expansion may change all of the dimensions, and, at very high temperatures, the structural integrity of the coils may fail.

In the design of an induction extensometer to be used at high temperatures,¹ ways were found to compensate for all of these sources of error, except the last. The extensometer coils were wound on a fused quartz coil form and should be usable to 1000°C . The driver and pickup coils were interwound as a bifilar coil with a common ground, as shown in Fig. 1. The associated electrical circuit is shown in Fig. 2, where Z_D is the driver coil impedance, Z_{PU} is the pickup coil impedance, and M is their mutual inductance. The discriminator measures the phase difference between the driving current I_1 , and the output current I_4 . Actually, changes in the phase difference from the value when the coils were in air were measured and called the "phase shift."

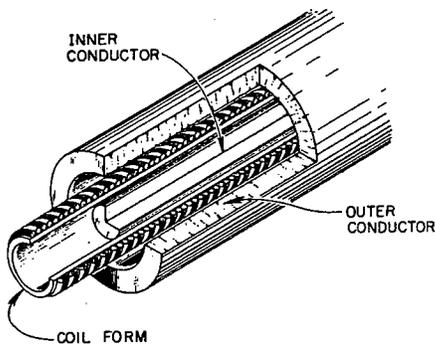


FIG. 1. Cutaway drawing of solenoidal coil coaxial with inner and outer conductors.

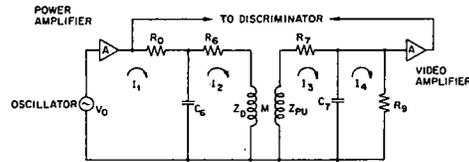


FIG. 2. Designation of various components and connection to measuring equipment. Designations and values: $V_0 = 10$ V; $C_6 = C_7 = 150$ pF; $R_0 = R_9 = 681.5$ Ω ; $R_6 = R_7 = 37$ Ω ; $TN = 300$ turns.

The performance of the system was calculated using computer programs² developed at Oak Ridge National Laboratory. If the coils are wound on a coil form of negligible thermal expansion (such as fused quartz) and are inside a conducting tube, the tube will expand away from the coils as the temperature is raised, decreasing the "fill factor" (or increasing the "lift-off"), and producing a decrease in the phase change, as shown in Fig. 3. On the other hand, if the coils encircle an inner conducting rod or tube, the inner conductor will expand toward the coil, increasing the "fill factor" and increasing the phase difference, as shown in Fig. 4. Since the expansions of the inner and outer conductors produce phase shifts in opposite directions, the combination can be made to produce zero phase shift over a given temperature range if the coil is sandwiched between an inner conductor and an outer tube, as shown in Fig. 1 and the top part of Fig. 5. The inner radius of the outer conductor necessary to compensate for the thermal expansion effect is plotted as the curve marked R in the lower part of Fig. 5 as a function of the outer radius of the inner conductor. Both radii have been "normalized" by dividing by the mean coil radius, \bar{r} , and the point marked "A" indicates the combination of radii for the extensometer as constructed.

The dimensionless quantity $\bar{r}^2 \omega \mu \sigma$, where ω is the angular frequency, μ and σ the permeability and conductivity of the metal, respectively, describes the dimensions of the coil in terms of the penetration depth of the eddy currents at the given frequency. For given geometrical dimensions and material properties, there will be an operating frequency, $\omega/2\pi$, for which the total phase shift produced when the coil is inserted between the

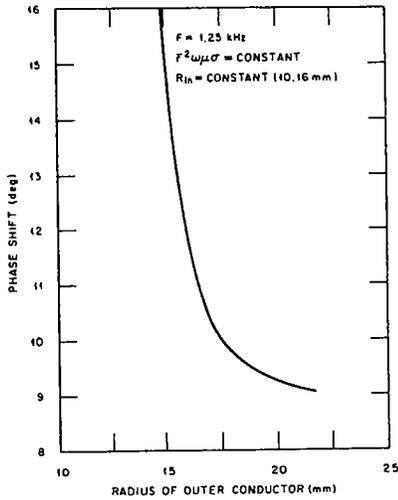


FIG. 3. Phase shift versus radius of outer conductor for constant R_{in} .

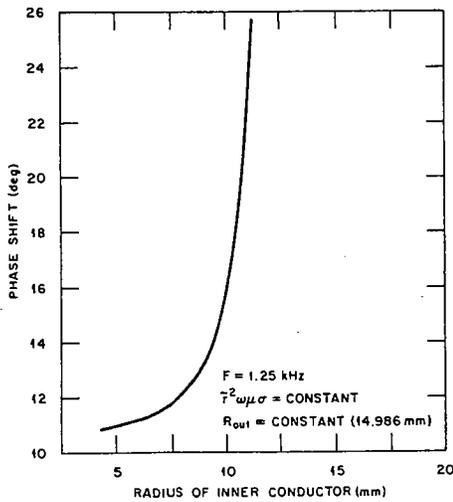


FIG. 4. Phase shift versus radius of inner conductor for constant R_{out} .

extensometer actually constructed), the point marked "B" corresponds to the same inner conductor radius as the points "A" and "C" and indicates that there should be a phase shift of 25.48° as the coil is withdrawn from the conductors. Figure 7 shows the measured phase shift versus displacement for the actual coil, which was 150 mm long; the non-linearity was caused by end effects and was quite reproducible.

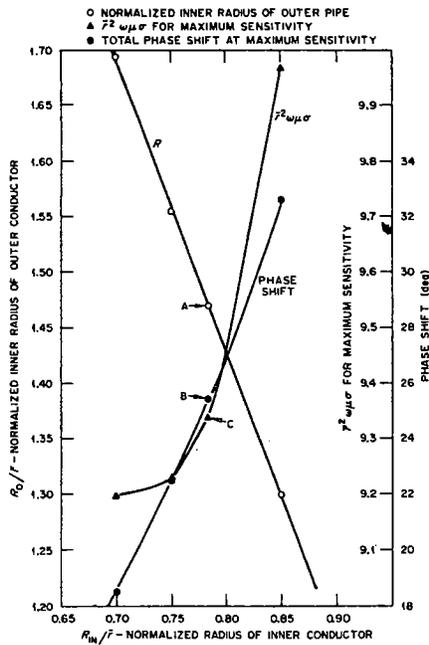
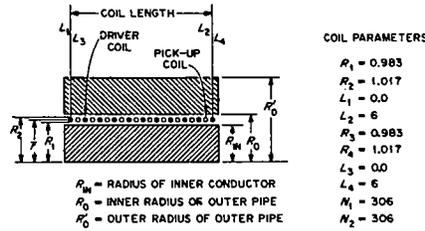


FIG. 5. Outer conductor radius, optimum $\bar{r}^2 \omega \mu \sigma$, and phase shift as functions of inner conductor radius.

conductors (or withdrawn from them) will be a maximum. Figure 6 shows the variation in this total phase shift for various values of $\bar{r}^2 \omega \mu \sigma$ near the maximum. From this we see that, if the conductivity σ and permeability μ of the material change over the prescribed temperature range, the value of ω can be chosen so that the extreme values of $\bar{r}^2 \omega \mu \sigma$ will be equally spaced on opposite sides of the maximum, for example, at the points marked $\Delta\phi_{20}$ and $\Delta\phi_{1000}$ in Fig. 6, corresponding to phase shifts at 20°C and 1000°C , respectively. Thus, the phase shifts at the extremes of temperature will be the same, and the errors at intermediate temperatures will be very small. The curve marked $\bar{r}^2 \omega \mu \sigma$ in Fig. 5 gives the value of that quantity producing the maximum phase shift as the coil is withdrawn from between the conductors; it is shown as a function of the normalized radius of the inner conductor, and the point marked "C" is the value corresponding to the radii designated by the point "A" (in this case, $\bar{r}^2 \omega \mu \sigma = 9.34$). Using the frequency necessary to produce this "optimum" value of $\bar{r}^2 \omega \mu \sigma$, the phase shift that will be produced is shown by the curve marked "PHASE SHIFT." For this example (and the

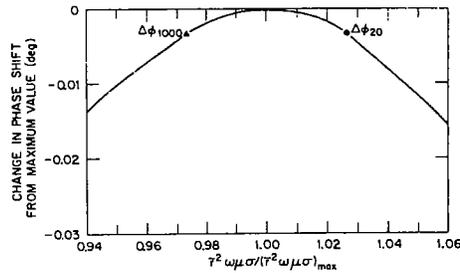


FIG. 6. Change in phase shift versus relative value of $\bar{r}^2 \omega \mu \sigma$.

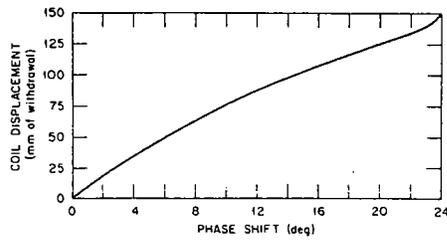


FIG. 7. Phase shift versus coil displacement.

The final source of thermal drift to require compensation is the change in DC resistance of the coils. If the series resistance R_0 in the driver circuit and the shunt resistor R_9 in the pickup circuit have the proper relationship to the other circuit parameters in Fig. 2 (the cable capacitances, C_6 and C_7 , the coil resistances, R_6 and R_7 , and the coil inductances, Z_D , Z_{PJ} and M), then the output phase shift can be made to have zero net change as the coil resistances are changed from their minimum to their maximum values, thus compensating for the final source of possible thermal error.

The extensometer design indicated by the values listed in Table I was constructed using Inconel for the conductors and Secon alloy wire for the coils on a quartz coil form 150 mm long. It could only be tested to 500°C, but the measurements accurately confirmed the theoretical predictions. If the values of R_0 and R_9 had been chosen properly, the maximum thermally caused error of displacement measurements would have been 0.1% of full scale over the full temperature range from 0° to 1000°C.

TABLE I. Dimensions of Inconel extensometer.

	Actual (mm)	Normalized
Mean coil radius	6.07	1.000
Inner radius of inner conductor	0.00	0.00
Outer radius of inner conductor	4.76	0.784
Inner radius of outer conductor	8.93	1.471
Outer radius of outer conductor	10.2	1.673

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