Design of a Temperature-Compensated Induction Extensometer

W.E. Deeds  
University of Tennessee - Knoxville

A. R. Yazdi  
University of Tennessee - Knoxville

C. V. Dodd  
Oak Ridge National Laboratory

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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.

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Disciplines
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DESIGN OF A TEMPERATURE-COMPENSATED INDUCTION EXTENSOMETER

W. E. Deeds and A. R. Yazdi
Department of Physics and Astronomy, University of Tennessee
Knoxville, Tennessee 37916

C. V. Dodd
Metals and Ceramics Division, Oak Ridge National Laboratory
Oak Ridge, Tennessee 37830

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°F 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, ways were found to
compensate for all of these sources of error, ex­
cept the last. The extensometer coils were wound
of Secon alloy wire with baked-ceramic insulation
on a fused quartz coil form and should be usable to
1000°C. The driver and pickup coils were inter­
wound 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 meas­
ures the phase difference between the driving cur­
rent \( I_1 \), 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."

The performance of the system was calculated
using computer programs 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 tem­
perature is raised, decreasing the "fill factor" (or
increasing the "lift-off"), and producing a de­
crease in the phase change, as shown in Fig. 3.
On the other hand, if the coils encircle an inner con­
ducting rod or tube, the inner conductor will ex­
and 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 con­
donctor necessary to compensate for the thermal ex­
pansion 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, \( R \), and the point marked "A" indicates the
combination of radii for the extensometer as con­
structed.

The dimensionless quantity \( F_0 = \sqrt{\frac{\omega}{2\pi\mu\sigma}} \), where \( \omega \) is
the angular frequency, \( \mu \) and \( \sigma \) the permeability and
conductivity of the metal, respectively, describes
the dimensions of the coil in terms of the penetra­
tion depth of the eddy currents at the given fre­
quency. For given geometrical dimensions and mate­
rial properties, there will be an operating fre­
quency, \( \omega/2\pi \), for which the total phase shift
produced when the coil is inserted between the

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; \( C_0 =
150 \) pF; \( R_x = R_y = 681.5 \) \( \Omega \); \( R_5 = R_6 = 37 \) \( \Omega \); \( TN = 300 \)
turns.
conductors (or withdrawn from them) will be a maximum. Figure 6 shows the variation in this total phase shift for various values of \( \frac{2\omega}{u_p} \) near the maximum. From this we see that, if the conductivity \( \sigma \) and permeability \( \mu \) of the material change over the prescribed temperature range, the value of \( \omega \) can be chosen so that the extreme values of \( \frac{2\omega}{u_p} \) will be equally spaced on opposite sides of the maximum, for example, at the points marked \( \Delta \theta_1 \) and \( \Delta \theta_2 \) 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 \( \frac{2\omega}{u_p} \) 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, \( \frac{2\omega}{u_p} = 9.34 \)). Using the frequency necessary to produce this "optimum" value of \( \frac{2\omega}{u_p} \), the phase shift that will be produced is shown by the curve marked "PHASE SHIFT." For this example (and the 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.
The final source of thermal drift to require compensation is the change in DC resistance of the coils. If the series resistance R₀ in the driver circuit and the shunt resistor R₉ in the pickup circuit have the proper relationship to the other circuit parameters in Fig. 2 (the cable capacitances, C₆ and C₇, the coil resistances, R₆ and R₇, and the coil inductances, Z₀, Z₉ 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 R₀ and R₉ 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°C to 1000°C.

<table>
<thead>
<tr>
<th>Actual (mm)</th>
<th>Normalized</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean coil radius</td>
<td>6.07</td>
</tr>
<tr>
<td>Inner radius of inner conductor</td>
<td>0.00</td>
</tr>
<tr>
<td>Outer radius of inner conductor</td>
<td>4.76</td>
</tr>
<tr>
<td>Inner radius of outer conductor</td>
<td>8.93</td>
</tr>
<tr>
<td>Outer radius of outer conductor</td>
<td>10.2</td>
</tr>
</tbody>
</table>

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REFERENCES
