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A PHASE-SENSITIVE LVDT TRANSDUCER TESTING SYSTEM

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P. C. Turner

UNION CARBIDE

OAK RIDGE Y-12 PLANT
OAK RIDGE, TENNESSEE

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P.O. Box Y, Oak Ridge, Tennessee 37830

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ABSTRACT

A system has been developed to measure mechanical and electrical parameters of ultralinear [0.05% (full scale) nonlinearity] displacement transducers of the linear variable differential transformer (LVDT) type. From these measurements, transducer pretravel, over travel, maximum percent nonlinearity, null voltage, and half-range output voltage can be determined. The system measures transducer stylus position with a precision digital micrometer. Corresponding output/input voltage ratio (transfer ratio) data are measured using a phase-sensitive, AC bridge circuit. From these measurements the maximum percent nonlinearity of an LVDT transducer is determined with an accuracy of ± 0.024% (full scale) for a 0.200-inch (5.08-mm) transducer.

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SUMMARY

A system has been developed which measures mechanical and electrical parameters of linear variable differential transformer (LVDT) displacement transducers. From these measurements, transducer pretravel, over travel, maximum percent nonlinearity, null voltage, and half-range output voltage can be determined. This system was developed for the Physical and Electrical Standards Laboratory of the Y-12 Plant to improve the accuracy of their transducer linearity certification program.

An LVDT transducer produces an output voltage that corresponds to its stylus position. Ideally, this correspondence would be linear over the gaging range. Since an actual transducer is not perfectly linear, its deviation from the ideal (linear) characteristic must be determined. This deviation is usually stated as a maximum percent nonlinearity. Maximum percent nonlinearity is calculated from a set of transducer stylus position data and corresponding output/input voltage ratio (transfer ratio) data.

For this measuring system, stylus positions are measured with a digital micrometer which has an accuracy of ± 43 μin (11×10^{-4} mm). Transfer ratios are measured using an AC bridge circuit with a phase-sensitive null indicator. When the bridge ratio transformer dials are set to balance the bridge, the ratio transformer setting equals the transfer ratio of the transducer. Transducer and bridge excitation are provided by an oscillator coupled to a power amplifier. This transfer ratio measuring technique produces an error of ± 0.0092% full scale (FS) in the transducer nonlinearity determination. From these measurements, the maximum percent nonlinearity of an LVDT transducer can be determined with an accuracy of ± 0.024% (FS) for a 0.200-inch (5.08-mm) transducer.

INTRODUCTION

A system has been developed at the Oak Ridge Y-12 Plant[(a)] to measure mechanical and electrical parameters of ultralinear [0.05% (FS) nonlinearity] displacement transducers of the linear variable differential transformer (LVDT) type. LVDT transducers are used extensively in the Y-12 Plant for dimensional certification of manufactured components. Ultralinear LVDT transducers are now being used in dimensional certification gages to measure component dimensions more precisely. Before an LVDT transducer is used, the Physical and Electrical Standards Laboratory of the Y-12 Plant must determine transducer pretravel, over travel, maximum percent nonlinearity, null voltage, and half-range output voltage, and certify that these parameters conform to specifications. (The Appendix contains detailed definitions of LVDT transducer terminology used in this report.) The existing, outdated measuring system lacked the accuracy necessary to determine the maximum percent nonlinearity of ultralinear transducers. The system described in this report provides this measuring capability.

An LVDT displacement transducer has a stylus which moves in a low-friction, sleeve-type bearing that contacts the component to be measured. Inside the transducer body is a core of magnetic material which is attached to the stylus and moves freely within a cylindrical coil form when the stylus is displaced. Three coils are wound on the coil form: a primary coil in the center and a secondary coil on each end. When the primary coil is excited with a sinusoidal voltage, another sinusoidal voltage is induced on both secondary coils. As the core is moved within the coil form, the magnetic coupling between the primary coil and the secondary coils varies, causing the induced voltages on the secondary coils to vary. When the secondary coils are connected in series opposition, the resulting output voltage is the difference between these two induced voltages. For a particular stylus position (the null position), the output voltage is a minimum. The phase angle between the input voltage and output voltage changes 180 degrees when the stylus passes through the null position. A plot of output voltage amplitude versus stylus position for an ideal LVDT transducer would be a V-shaped curve with its apex at the origin. Since a real LVDT transducer is not perfect, its deviation from the ideal characteristic must be determined.

(a) Operated by the Union Carbide Corporation's Nuclear Division for the US Atomic Energy Commission.

AN LVDT TRANSDUCER TESTING SYSTEM

SYSTEM DESCRIPTION

General

A system for determining transducer pretravel, over travel, maximum percent nonlinearity, null voltage, and half-range output voltage must incorporate devices which can: (1) accurately measure any stylus position within the total travel of a transducer, (2) excite the LVDT primary coil with a reasonably stable sinusoidal voltage, and (3) accurately measure the LVDT output/input voltage ratio (transfer ratio) at each stylus position throughout the full gaging range.

Figure 1 provides an overall view of the system developed to provide this capability. As shown, a digital micrometer is used to measure the stylus position of the transducer under test. Transducer electrical connections to the system are made through the PAV (phase angle voltmeter)-system panel. An oscillator and power amplifier comprise the excitation source. Major components of the phase-sensitive AC bridge used to measure the transfer ratio are: a phase-angle voltmeter and a ratio transformer. A DC digital voltmeter, used to improve measurement precision, and an oscilloscope, used for a cursory examination of transducer output response to stylus displacement, complete the system. (Other components in this figure are part of the original measurement system which was replaced by the system described herein.) A complete operating procedure has been developed that

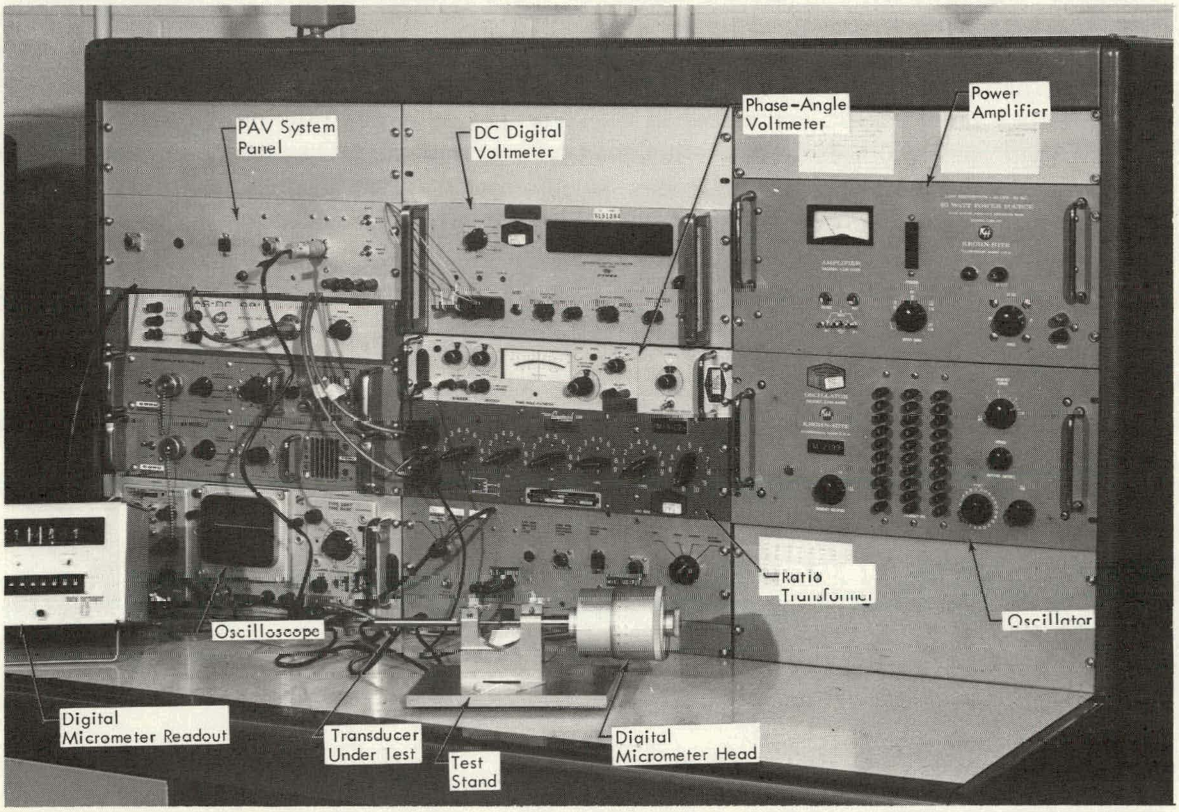

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Figure 1. OVERALL VIEW OF THE PHASE-SENSITIVE LVDT TRANSDUCER TESTING SYSTEM.

utilizes this system to determine transducer pretravel, over travel, null voltage, maximum percent nonlinearity, and half-range output voltage.

Stylus Position Measurement

To accurately position the stylus of the transducer under test, a precision, 0 - 2 in (0 - 5.08 cm) micrometer with a digital readout is used. The digital readout allows the operator to read the stylus position with a resolution of $10\,\mu$in (2.5×10^{-4} mm) and to set the readout "zero" to coincide with the transducer null position. Positions on either side of null are then read directly from the readout, along with a sign to indicate on which side of null the stylus is located.

The test stand seen in Figure 1 holds the transducer and micrometer in proper alignment. The stand is made of Meehanite cast iron and is designed such that its elongation, resulting from thermal expansion, closely matches the elongation of the micrometer spindle and transducer stylus. This arrangement compensates for dimensional changes due to uniform temperature variations. Since the temperature of the Certification Laboratory is controlled to within $\pm\ 1^{o}$ C, uncompensated dimensional changes are negligible.

LVDT Excitation

Three characteristics of the excitation source which can affect the measurement of LVDT transducer linearity are: amplitude stability, frequency stability, and harmonic distortion. Measurement errors due to changes in amplitude and frequency are virtually eliminated by measuring the transfer ratio of the transducer, rather than simply measuring the output voltage. Harmonic distortion originating in the excitation source can substantially increase the transducer null voltage and reduce its linearity. By measuring the transfer ratio using a phase-sensitive method, these harmonic effects can be reduced, but not eliminated. For this reason, an excitation source with ultralow (0.01%) harmonic distortion is used. The oscillator has pushbutton frequency selection from 20 Hz to 20 kHz and precision amplitude adjustments from 0 to 100 V_{rms}. Frequency and amplitude adjustments are needed for measuring the different types of LVDT transducers used in the Y-12 Plant. A 50 W_{rms} linear power amplifier provides the power necessary to excite the transducer and the ratio transformer simultaneously without loading the oscillator.

LVDT Transfer Ratio Measurement

Figure 2 is a block diagram of the transfer ratio measuring circuit. This circuit is basically an AC bridge with a phase sensitive null detector. A six-decade ratio transformer, a phase-reverse switch, and an isolation transformer form the reference element of the bridge. The LVDT transducer under test is the measured element. A phase-angle voltmeter (PAV), seen in Figure 3, functions as the phase-sensitive null detector. A DC digital voltmeter, connected to the PAV recorder output, improves the measurement precision.

To analyze the operation of this circuit, the phase relationships of the various voltages must be explained. Figure 4 (a) is a phasor diagram relating the output voltage, $\overrightarrow{V_{OUT}}$, of a typical LVDT to its input voltage, $\overrightarrow{V_{IN}}$. The term $\overrightarrow{V_{IN}}$ is also the input voltage to the ratio transformer and the reference voltage for the PAV. $\overrightarrow{V_{T}}$ represents an output voltage from

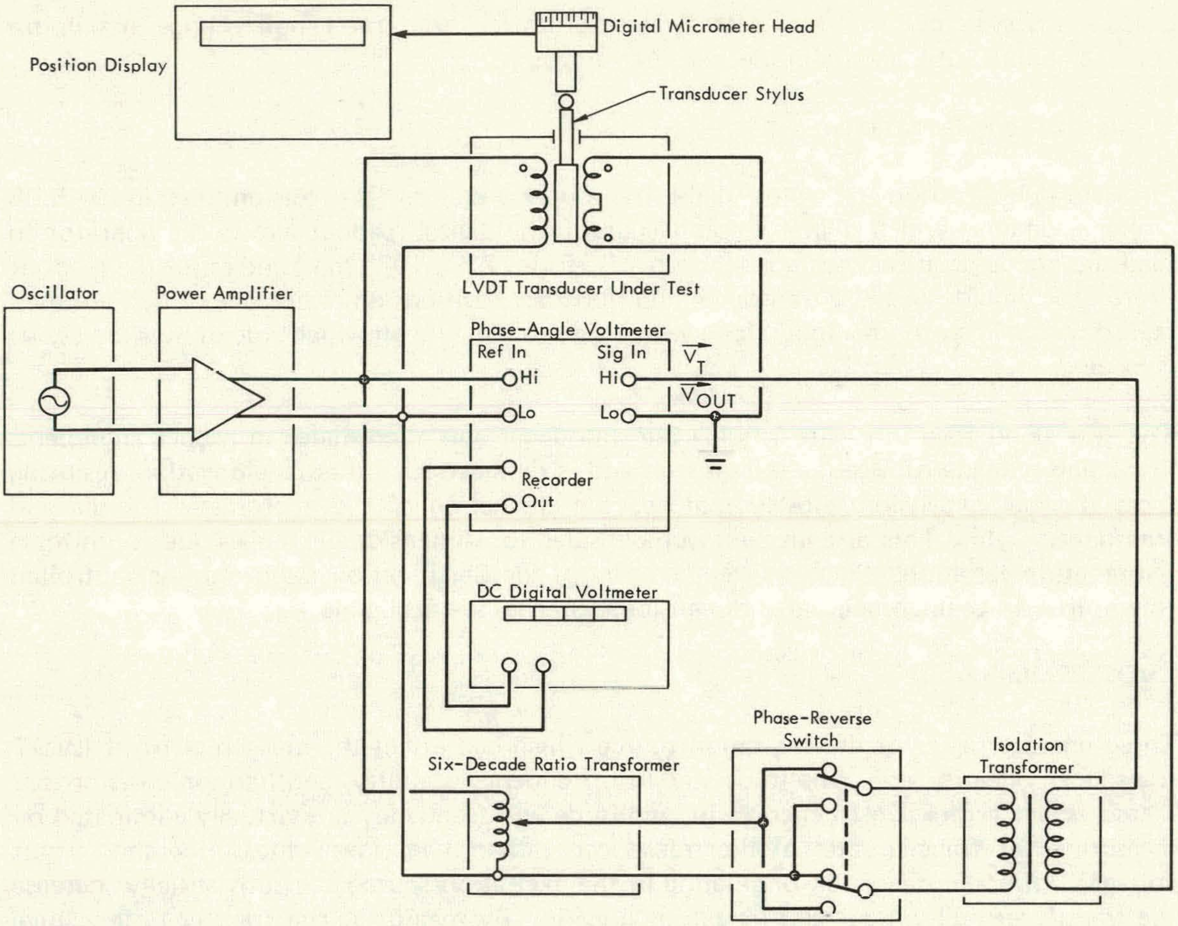

Figure 2. CIRCUIT ARRANGEMENT FOR THE PHASE-SENSITIVE LVDT TRANSDUCER TESTING SYSTEM.

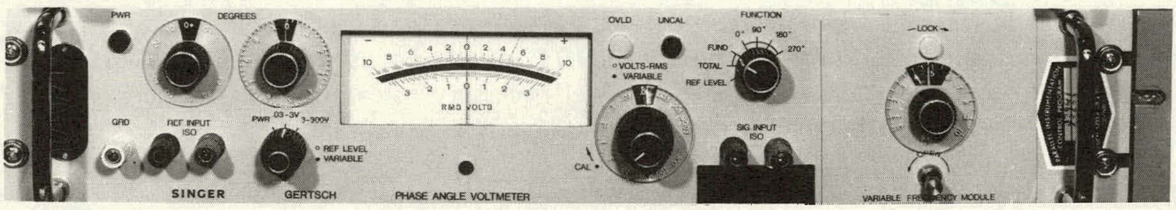

Figure 3. PHASE-ANGLE VOLTMETER USED IN THE TRANSFER-RATIO MEASURING CIRCUIT.

the isolation transformer (see Figure 2). $\vec{V}_{OUT}$ has two components: $\vec{V}_O$, which is in phase with $\vec{V}_{IN}$; and V_{90}, which is in quadrature (90^o out of phase) with $\vec{V}_{IN}$. Figure 2 shows $\vec{V}_T$ and $\vec{V}_{OUT}$ applied to the signal input terminals of the PAV. With the PAV set to measure in-phase voltage components, the voltage difference, $\vec{V}_O - \vec{V}_T$, is measured.(1) The PAV output voltage is given by:

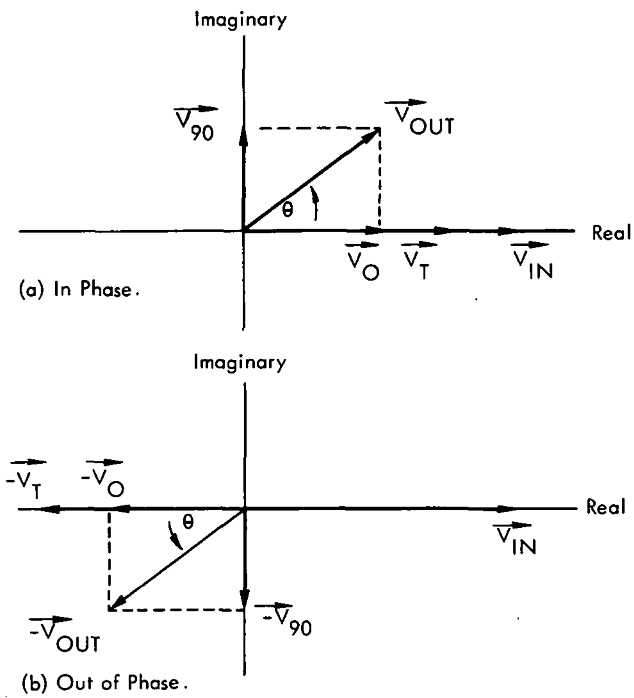

Figure 4. PHASOR DIAGRAMS FOR THE LVDT TRANSDUCER AND MEASURING CIRCUIT.

$$V_{PAV} = \frac{\sqrt{2}\,\pi}{4}\frac{2}{\Upsilon}\int_0^{\Upsilon/2} (\vec{V}_{OUT} - \vec{V}_T)\ dt \quad ,$$

$$= \frac{\sqrt{2}\,\pi}{4}\frac{2}{\Upsilon}\int_0^{\Upsilon/2} [V_{OUT} \sin(\omega t + \theta) - V_T \sin \omega t]\ dt \quad ,$$

$$= \frac{\sqrt{2}\,\pi}{4}\frac{1}{\pi}\ (2V_{OUT}\cos\theta - 2V_T) \quad ,$$

$$= \frac{\sqrt{2}}{2}\ (V_O - V_T) \quad , \text{or}$$

$$V_{PAV} = (V_O - V_T)_{rms} \quad ,$$

where:

V_{PAV} represents the output of PAV [volt (rms)] ,

$\frac{\sqrt{2}\,\pi}{4}$ the constant gain factor which converts the average value of a full-wave rectified sinusoid to the root-mean-square (rms) value (dimensionless), and

Υ the period of the sinusoid (second) ,

$\omega = \frac{2\pi}{\Upsilon}$ the radian frequency of the sinusoid $\left(\frac{\text{radian}}{\text{second}}\right)$, and

θ the phase angle between $\vec{V}_{OUT}$ and $\vec{V}_T$ (degrees).

$\vec{V}_{OUT}$, $\vec{V}_T$, and $\vec{V}_O$ are as previously defined (volt) and

V_{OUT}, V_T, and V_O are the magnitudes of $\vec{V}_{OUT}$, $\vec{V}_T$, and $\vec{V}_O$, respectively (volt).

Adjusting the ratio transformer dials varies the magnitude of $\vec{V}_T$. When the PAV output is zero (ie, when $\vec{V}_T$ equals $\vec{V}_O$), the ratio transformer dial setting indicates the transfer ratio, $\vec{V}_O/\vec{V}_{IN}$, corresponding to one position of the transducer stylus.

When the stylus is moved through the null position, a 180-degree phase change occurs in $\vec{V}_{OUT}$, as indicated in Figure 4(b). Switching the phase-reverse switch in the bridge reference element changes the phase of the isolation transformer output voltage, V_T, by 180 degrees. The PAV measures the resulting voltage difference, $(-\vec{V}_O) - (-\vec{V}_T)$. V_{PAV} now equals $-(V_O - V_T)_{rms}$. When the PAV output is brought to zero by adjusting the ratio transformer dials, as before, the transfer ratio, $-\vec{V}_O/\vec{V}_{IN}$, corresponding to the new transducer stylus position, is measured.

SYSTEM SPECIFICATIONS

Table 1 lists the electrical and mechanical specifications for the measuring system.

Table 1

LVDT TRANSDUCER MEASUREMENT SYSTEM SPECIFICATIONS

Electrical Specifications	
Excitation Voltage (maximum)	100 V_{rms} at 0.5 A
Excitation Frequency Range	300 Hz to 10 kHz
Transfer Ratio Measuring Range	0.000000 to 1.000000
Nonlinearity Introduced by Transfer Ratio Measuring Circuit	+ 0.0092% (FS)
Mechanical Specifications	
Transducer Stylus Travel Limit	2.00 in (5.08 cm)
Transducer Body Diameter Range	0.360 in (0.914 cm) to 0.376 in (0.955 cm)
Position Measuring Accuracy	± 43 µin (11 x 10^{-4} mm)
System Nonlinearity Measuring Accuracy	± 0.024% (FS) [for a 0.200-in (5.08-mm) transducer]

EVALUATION OF SYSTEM ACCURACY

General

For this system, two major components of error associated with measuring the maximum percent nonlinearity of a transducer are: (1) error in positioning the transducer stylus, and (2) linearity error introduced by the transfer ratio measuring circuitry.

To evaluate the total system accuracy, a test was designed to measure each of these components independently. In this way, each components's contribution to the total system accuracy was determined.

Stylus Position Measuring Accuracy

To determine position measuring accuracy, the digital micrometer head was compared to a laser interferometer standard in the Y-12 Gage Certification Laboratory. Twenty-two measurements were made at intervals of 0.100 in (2.54 mm), covering the total range of the micrometer [0 - 2 in (0 - 5.08 cm)]. From these data, an average bias of 19 μin (4.8×10^{-4} mm) with a precision (95% confidence limit) of ± 24 μin (6.1×10^{-4} mm) was calculated. In this report, accuracy is defined as the sum of the average bias plus precision. Therefore, the position measuring accuracy is ± 43 μin (11×10^{-4} mm), or ± 0.022% when stated as a percent of the full gaging range for a 0.200-in (5.08-mm) transducer.

Nonlinearity Introduced by the Transfer Ratio Measuring Circuit

A test was designed, with assistance from Y-12 Statistical Services, to determine the nonlinearity introduced by the transfer ratio measuring circuit.[2,3] To determine this system accuracy component, a set of 62 accurate voltage ratios from a "quasi-LVDT" was measured three times using the transfer-ratio measuring circuit.

To establish a set of accurate ratios for this evaluation, a quasi-LVDT was developed (Figure 5). A six-decade ratio transformer, a phase-reverse switch, and an isolation transformer are connected, as shown, with the input and output of the circuit wired into a typical LVDT transducer connector. Changes in the transfer ratio, produced by stylus positioning in an actual LVDT transducer, are produced by changes in the ratio transformer setting in the quasi-LVDT. Y-12's Physical and Electrical Standards Laboratory certified 62 ratios of the quasi-LVDT using a precision ratio transformer with traceability to the National Bureau of Standards. These certified ratios, ranging from -0.500000 to + 0.500000, were selected to include virtually all ratios that the measuring circuit should encounter during actual transducer certification.

A least-squares linear curve fit of the measured ratios versus the actual ratios was calculated for each run. For each measured ratio in each run, the difference from the fitted line was calculated and expressed as a percent of the full scale ratio. To estimate the worst-case bias of the nonlinearity, the six largest difference percentages were averaged, producing a value of 0.0051% (FS) with associated precision (95% confidence limit) of ± 0.0012% (FS). Precision of this test, ± 0.0029% (FS), was estimated from the within variation of the 62 difference percentages for each run. A worst-case nonlinearity of ± 0.0092% (FS) was obtained by summing the estimates for the worst-case bias, its associated precision, and testing precision.

System Accuracy

The maximum percent nonlinearity of an LVDT transducer can be determined from position and ratio data measured with this system with an estimated accuracy of ± 0.024% [for a 0.200-in (5.08-mm) transducer]. This estimate was determined by combining the position measuring accuracy (± 43 μin) and the worst-case nonlinearity (± 0.0092%) as follows:

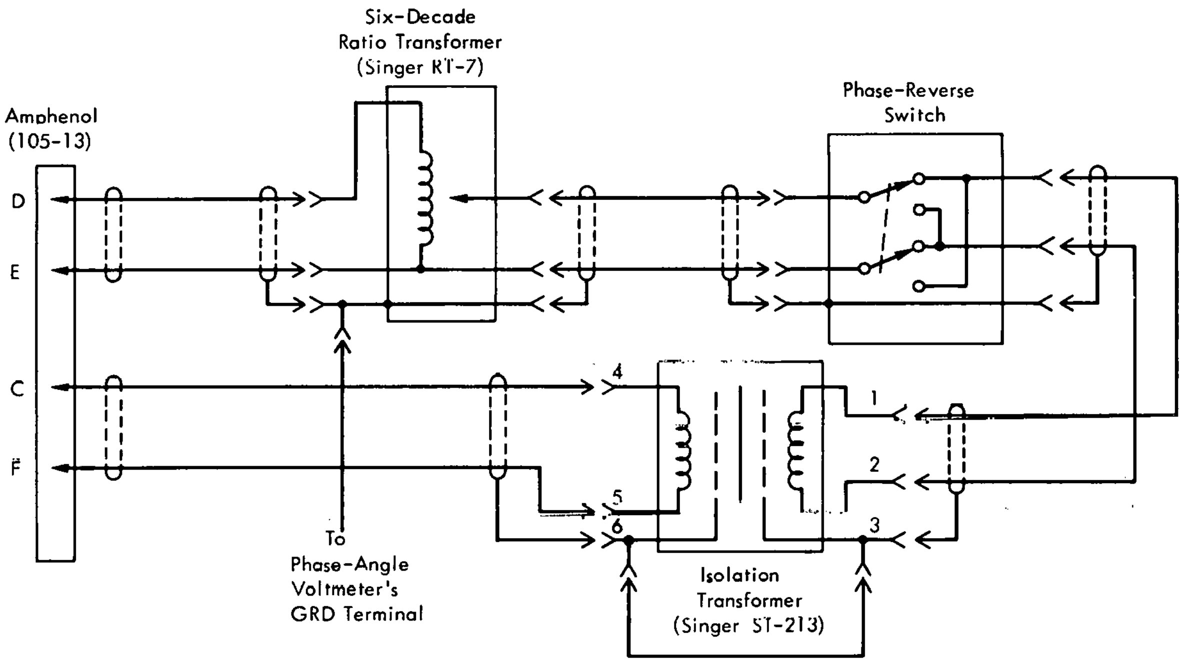

Figure 5. PRINCIPAL COMPONENTS OF THE QUASI-LVDT.

System Accuracy [in percent (FS)] =

$$\pm \sqrt{(0.0092)^2 + [(43 \times 10^{-6}/R) \times 100]^2} \ ,$$

where R represents the full gaging range, in inches, for the measured transducer.

REFERENCES

(1) *Instruction Manual, Phase Angle Voltmeter (PAV-4 Series)*, Manual 1-500782-152 (Rev A); The Singer Company, Electronic Products Division, Gertsch Corporation.

(2) Telford, J. L.; "Estimation of Bias and Precision of the LVDT Linearity Certification System", *Personal Communication*; February 9, 1973.

(3) Telford, J. L.; "Estimation of Accuracy of the LVDT Linearity Certification System", *Personal Communication*; February 27, 1973.

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APPENDIX

DEFINITIONS OF LVDT TERMINOLOGY

Output Voltage - The RMS secondary voltage as measured at the output cable plug. The measurement will be made with a rated excitation voltage. The secondary windings are connected series opposing.

Null - The position of the stylus, which gives zero or a minimum output voltage, is defined as the null position, and the corresponding output voltage is the null voltage.

Pretravel - The initial travel of the stylus, starting from a fully extended position and continuing to the gaging range, is called pretravel.

Over Travel - The initial travel of the stylus, starting from a fully retracted position of the stylus and extending to the gaging range, is defined as over travel.

Gaging Range - The useful portion of the transducer response to stylus measurement is the gaging range. It separates the pretravel and over-travel regions. Numerically, it is the sum of the absolute values of the plus and minus ranges.

Total Travel - Total travel is the sum of pretravel, gaging range, and over travel.

Linearity - Linearity is defined as the maximum deviation of the output voltage ratio curve from a straight line through the origin and lying parallel to the least squares best fit straight line. Linearity is expressed in percent (see Figure A-1) using the following equation:

$$\text{Percent Linearity} = [|Y_{imax} - mx_i| / mx_{full\ range}] \times 100 \ ,$$

where:

Line AB (Figure A-1)	represents a straight line through the origin and parallel to the best fit straight line,
mx_{max}	the calculated value on the straight line corresponding to the maximum displacement from null,
Y_{imax}	the output voltage ratio at the point of maximum deviation from the straight line, and
mx_i	the point on the straight line corresponding to maximum deviation point.
$mx_{full\ range}$	$= \|+ mx_{max}\| + \|- mx_{max}\|$

If the summation of the displacement values for a collection of data points is zero, then the slope (m) of the least-squares best fit straight line for that collection of data points is given by the following equation:

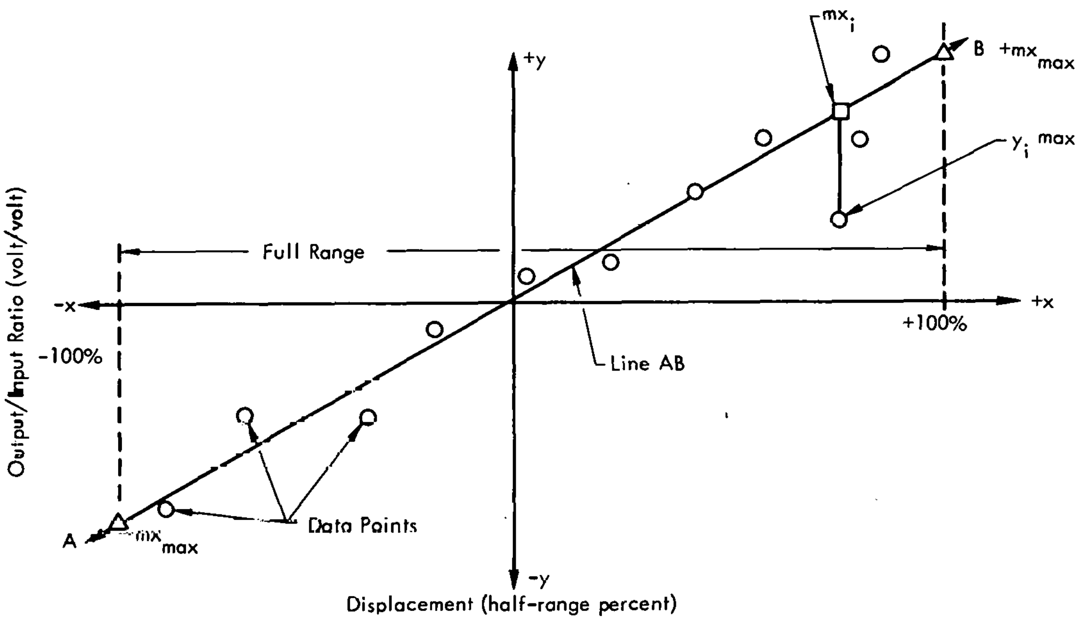

Figure A-1. TYPICAL LVDT TRANSDUCER LINEARITY CURVE FIT.

$$m = \overline{x_i y_i} / \overline{x_i^2} = [\sum_{i=1}^{n} (x_i y_i)] / \sum_{i=1}^{n} x_i^2 \ ,$$

where:

n represents the number of test data points,

x_i the displacement values of the data points,

y_i the output voltage ratio values of the data points,

$\overline{x_i^2}$ the average of the squared values of the x coordinates of all data points, and

$\overline{x_i y_i}$ the average product of the x and y coordinates of each data point.

Displacements on each side of null for determining linearity shall be 2, 5, 10, 20, 40, 60, 80, and 100% of the bilateral range.

Voltage Ratio - The output voltage ratio is defined as the ratio transformer setting which corresponds to the LVDT voltage output for a specific LVDT displacement.

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