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A PHASE-MEASURING SYSTEM FOR USE WITH DISTORTED, LOW-LEVEL WAVE--ETC(U)
JAN 61 D MUSTER, H B AVERY NOBSR72086

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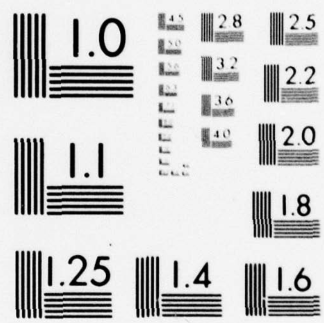

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A PHASE MEASURING SYSTEM FOR USE WITH DISTORTED, LOW-LEVEL WAVE SHAPES

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(6) A PHASE-MEASURING SYSTEM FOR USE WITH DISTORTED, LOW-LEVEL WAVE SHAPES

by

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A PHASE-MEASURING SYSTEM FOR USE WITH DISTORTED, LOW-LEVEL WAVE SHAPES[1]

1. Introduction

In the recent past, experimental studies of the dynamic response characteristics of large structures, such as ship's hulls, have been conducted for and by the technical divisions of the U. S. Naval establishment. The studies are an integral part of a larger program concerned with the reduction of underwater sound due to shipboard machinery. In such a study, it is vital to achieve clear understanding of the parameters that influence the path by which vibratory energy is transmitted from shipboard equipment to the water. For example, one set of such parameters is the mobility (or mechanical impedance) characteristics of the foundations to which the equipment is fastened, another the mobility spectra of the equipment looking into its footings.

A detailed discussion of measured mobility characteristics and the methods for their measurement is given elsewhere (1), (2), (3). In addition, the mobility method of vibration analysis (conceived originally by Firestone (4)) has undergone considerable refinement and extension and is currently enjoying wide application and acceptance in the analysis of lumped-parameter vibrating systems (5). Here we will confine ourselves to introducing the concept of mobility only in order to establish the framework within which the phase-measuring system described later is used.

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[1]The measuring system described here was developed and used on several measurement programs sponsored by Bureau of Ships, U.S. Navy, at General Engineering Laboratory, General Electric Company.

[2]Numbers in parentheses refer to identically numbered references in the Bibliography at the end of this report.

In its most general sense, mobility is defined as the complex ratio of velocity to force at the same or different points in a mechanical system (4). If the velocity and force are measured at the same point, their ratio is called "direct mobility"; if they are measured at different points, it is called "transfer mobility". As for all complex ratios, account is taken of the phase relationship that exists between velocity and force. In a qualitative sense, mobility is the measure of the ease with which a structure follows vibratory motion.

In matrix form, the response of a mechanical system (e.g., a foundation, machine, etc.) is characterized by the relationships

$$\left.\begin{aligned} V_i &= M_{ij} F_j \\ F_i &= Z_{ij} V_j \\ (i,j) &= (1, 2, \ldots, n) \end{aligned}\right\} \qquad [1]$$

where V and F are the velocity and force, respectively, at points "i" and "j" of the system and M_{ij} and Z_{ij} the corresponding mobility and mechanical impedance values, respectively. In order that the inverse relationship between the M and Z matrices of Equation [1] be meaningful and unique, a more restricted definition of mobility and impedance is required. The mobility M_{ij} is defined as the velocity at point "i" of a system due to the application of unit force at point "j" <u>with zero forces applied at all other points</u>. In contrast, mechanical impedance Z_{ij} is defined as the force which must be applied at point "i" of a system in order to cause unit velocity at point "j", <u>when all connection points of the system are constrained so as to have zero velocity (that is, are fixed)</u>.

Within the context of the above definitions, it is clear that the greater difficulty can be expected in the measurement of meaningful impedance spectra. Except for simple, lumped-mass systems or over only a limited frequency range for more complex systems, experimentalists always measure mobility, not impedance. However, it is equally clear that once the mobilities M_{ij} are known, the impedances Z_{ij} can be determined from the relationships given in Equation [1] .

The basic parameters that determine mobility or impedance are

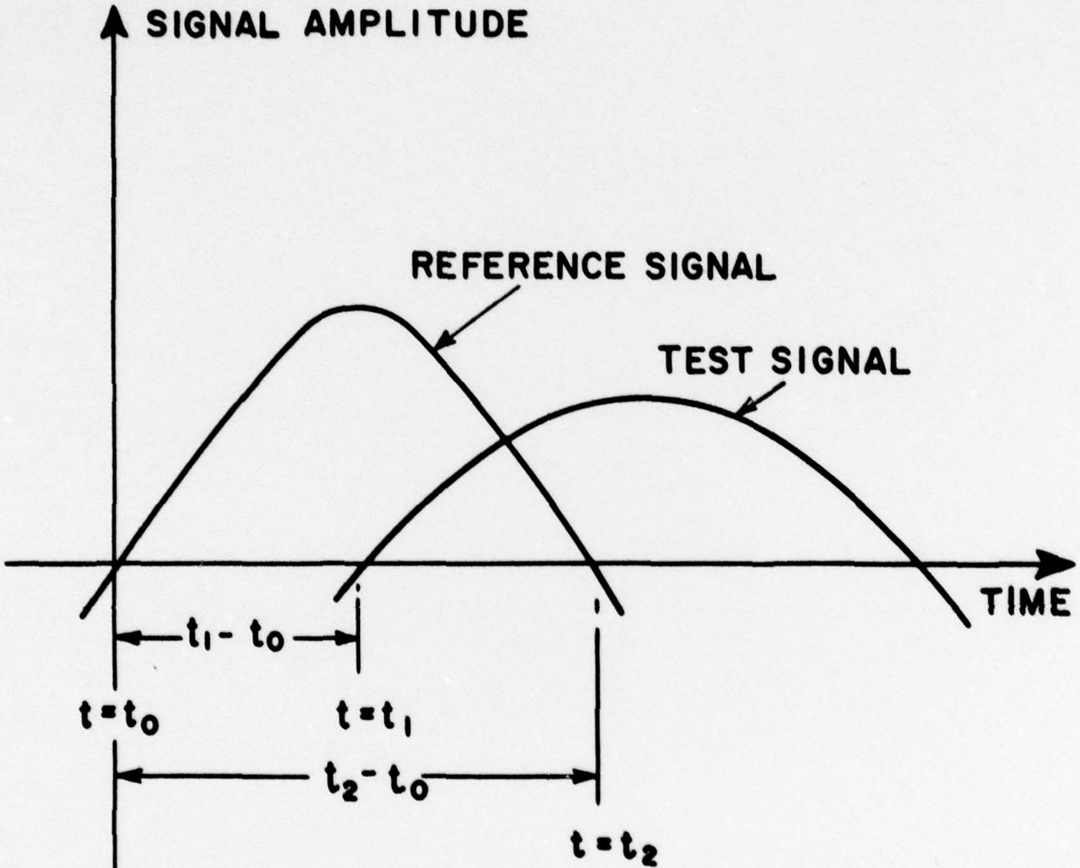
(1) force,
(2) velocity,
(3) frequency and
(4) phase (between the force and velocity).

In the remainder of the text here, we are concerned only with the measurement of the last, particularly for the case which occurs frequently in mobility measurement, when the force and/or velocity transducer signals are low-level and distorted.

-Contemporary methods and instruments for measuring phase.

The methods and instruments commonly used to measure phase between two electrical signals[3] are based on (1) axis-crossing, (2) vector-addition/or vector-subtraction and (3) voltage-multiplier circuits. In simple terms, the axis-crossing type measures the time interval between successive zero crossings of the reference and test signals (Figure 1) and translates this amplitude into angular measure by comparing it with that for the half-period of the reference signal (which is equivalent to 180°). The vector-

[3] For convenience, throughout this paper we will designate one signal as the reference signal, the other as the test signal. The choice of which signal is the reference is usually arbitrary.



$$\phi = \frac{t_1 - t_0}{t_2 - t_0} \cdot 180 \text{ (DEGREES)}$$

FIGURE 1
AXIS-CROSSING PHASE MEASUREMENT

addition type utilizes the trigonometric relationships that exist between the magnitudes of the sides and the angles of a triangle (e.g., the cosine law). If the magnitudes of the reference and test signals are made equal (by appropriate attenuation or amplification), then the amplitude of the vector sum is a measure of the phase between the two signals (Figure 2). Recently, Sykes (6) studied in detail the vector-addition and vector-subtraction methods of phase measurement and the sources and magnitudes of error encountered in their application. Within certain limiting assumptions, in (6) it is shown that for the greatest accuracy, different measurement techniques should be used, depending upon the magnitude of the phase angle. In the voltage-multiplier type the readout of a modified wattmeter and the product of the two signal amplitudes are related to the phase between them[4].

In the measurement of mobility[5], it is common for the signals from the force and velocity (or acceleration) transducers to

(1) differ greatly in magnitude (by as much as 1000 to 1),

(2) be affected significantly by noise (most frequently, a low signal-to-noise ratio occurs with respect to the motion, rather than force, signal) and

(3) be distorted by low-order harmonics (e.g., the force signal is affected occasionally by the internal characteristics of the driver).

Axis-crossing, vector-addition (6) and voltage-multiplier phase-measuring systems are sensitive to each of the above to a greater or lesser degree but, in each case, sufficiently that appreciable error is introduced when they are present. The phase-shifting measuring system described here was developed

[4] (Readout) $\sim$ RT cos ϕ . The phase is made a function of the readout alone by suitable adjustment of the amplitudes R and T.

[5] In other systems, similar effects are observed, although here we cite only the difficulties encountered in the measurement of mobility.

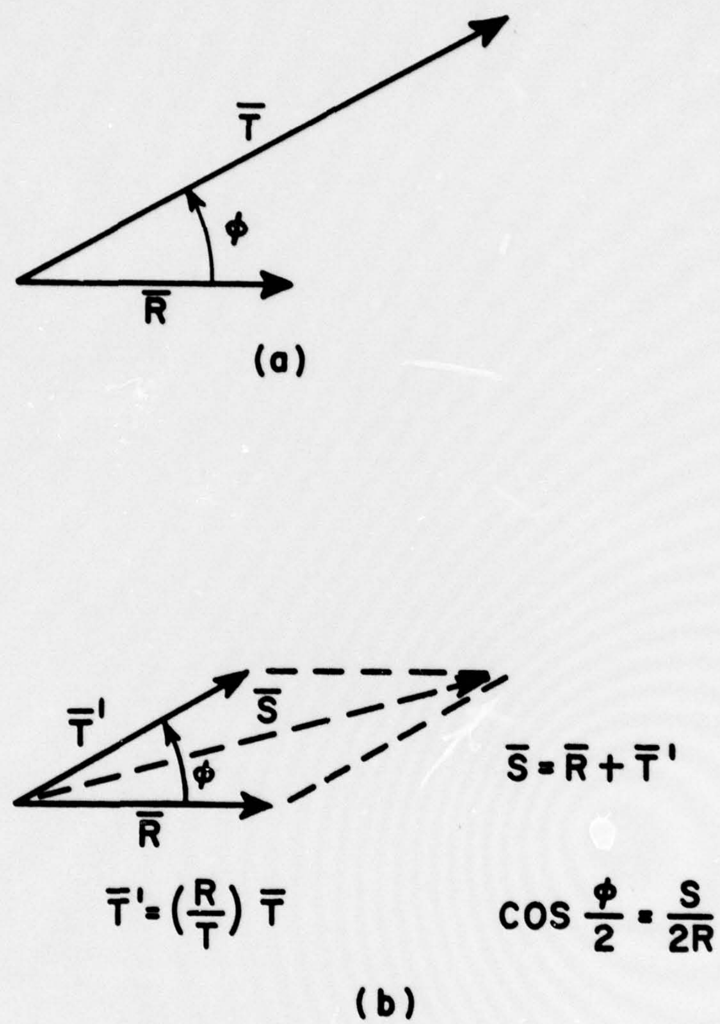


FIGURE 2
VECTOR-ADDITION PHASE MEASUREMENT

expressly to operate effectively under these difficult, but not unusual, conditions.

2. Requirements Placed on the Phase-measuring System

The requirements placed on the phase-measuring system described here are related specifically to the outputs and characteristics of the transducers and other components in a mobility-measuring system. The requirements for similar instrumentation used in conjunction with another task will probably be of the same kind but differ in magnitude.

In our case, the phase-measurement method should be relatively insensitive to the wave shape (harmonic and noise content) of the reference and test signals. The voltage magnitudes of either signal may be as low as 0.5 millivolt and the ratio of the magnitudes may be as high as 1000:1. The required precision of the measurement should be less than $\pm 1^\circ$. In order to cover all quadrants, the measuring system must be continuously variable and, preferably, the amplitudes of the reference and test signals should not be changed in the phase-measuring process.

3. Phase-shifting (Vector-rotation) Method of Measuring Phase

In this method, the phase between two signals is measured by indirect rather than direct means. The phase of the test signal is adjusted (without changing its amplitude) so as to be in phase with a reference signal, the magnitude of the adjustment giving the measure of the original phase. The phase adjustment is accomplished by using a resistance-capacitance circuit in which the impedances are so arranged as to produce a phase-altered output signal. The phase difference of the adjusted test signal and the reference signal is sensed and displayed on a cathode-ray oscilloscope.

Continuously variable phase adjusters have been designed using two methods, one in which the adjustment is accomplished by using a rotating magnetic field to induce a phase-altered voltage in a stationary coil inserted in the field (7) and a second in which the impedances of a resistance-capacitance circuit are arranged so as to cause a change in the phase of an input signal (8), (9), (10), (11). In our case, the large bulk and leakage fields associated with the first method are major disadvantages; in contrast, the compactness, versatility and stable operation of the second method recommend its use.

The circuit of the phase shifter is shown in Figure 3a. In order to adjust the phase of the test signal by more than 180°, two circuits are used in series. A cathode follower is inserted between the stages to match their impedances and prevent loading. Although using transformers in each stage permits grounding the input and output, they introduce an unwanted phase shift of the test signal. The effect of this is nullified by using a dummy circuit for the reference signal as shown in Figure 3b. The components (resistances, capacitances and transformers) of the two circuits are selected to have identical characteristics; thus, the reference and test signals are shifted equal amounts by the circuit characteristics. In addition, in order to insure that the reference and test signal circuits act simultaneously, the four variable resistances are ganged. The relationships between the electrical characteristics of the components and the phase angle are shown in Figure 3c.

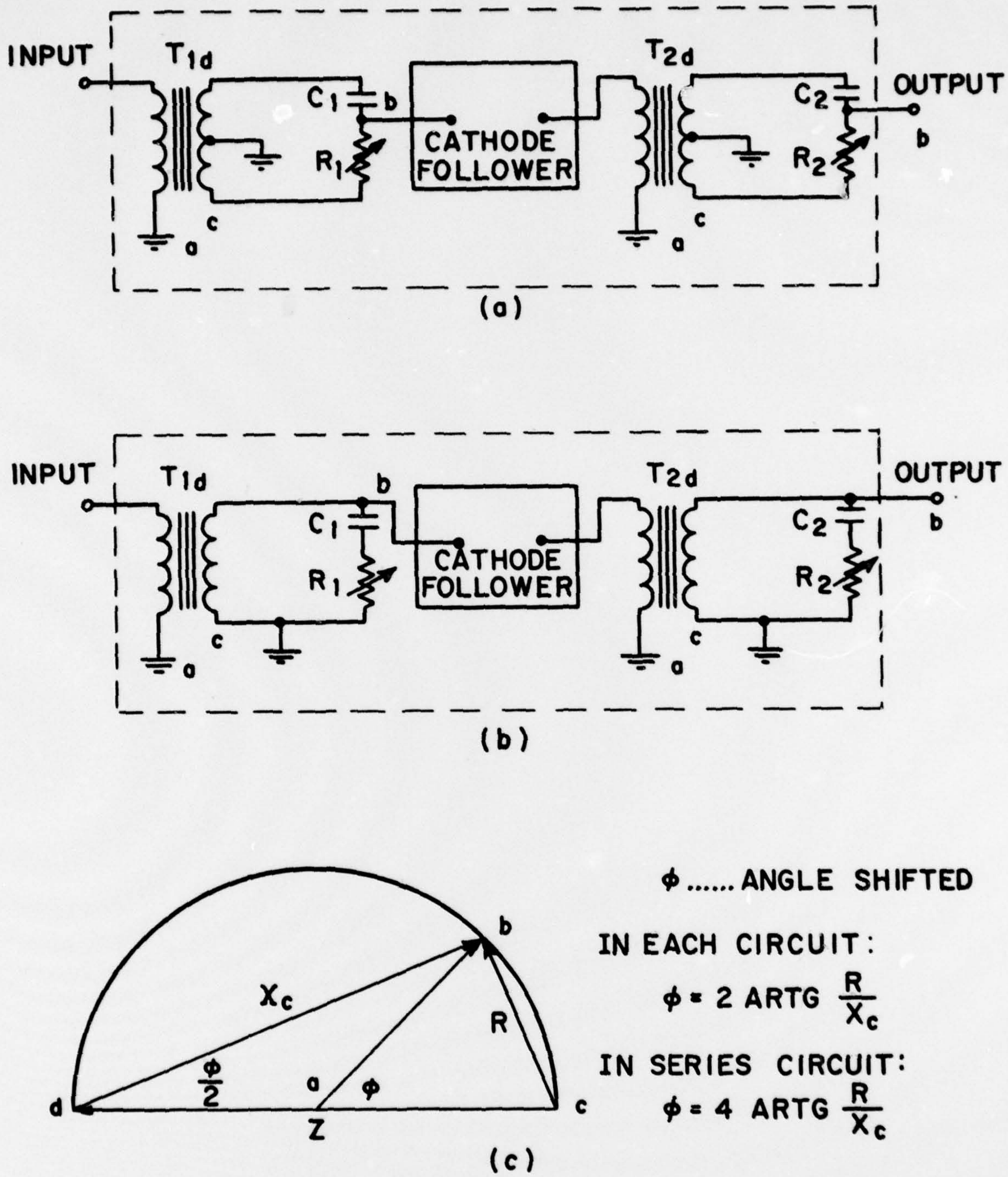


FIGURE 3
PHASE SHIFTER

A cathode-ray oscilloscope is used as a sensitive detector of the phase difference between the reference signal and the phase-altered test signal. When the signals applied to the plates of the oscilloscope tube are of the same frequency and are in phase or opposite phase, a straight-line trace is displayed on the tube face. The adjustment required in the phase of the test signal to produce the straight-line trace is then equal to the phase difference we seek to measure.

The complete phase-measuring system is shown in Figure 4. The readout of the shifter is the resistance of each of the ganged variable resistors (Figure 3). The use of this readout in determining the phase shift is given below.

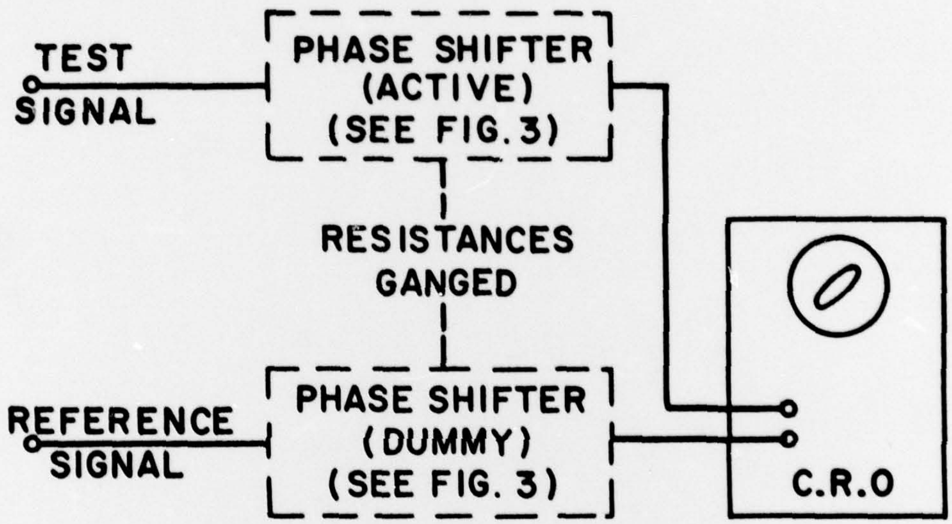
-<u>Electrical Characteristics of the Phase-Shifter Components</u>

For good resolution over the frequency range from 25 to 2000 cps, three capacitances are used:

(a) Scale A: 25 to 130 cps, 0.0663 μ fd
(b) Scale B: 100 to 500 cps, 0.0175 μ fd
(c) Scale C: 450 to 2000 cps, 0.00407 μ fd

The capacitances in each shifter circuit are gang-switched. For other frequency ranges the capacitance values can be changed accordingly.

The variable resistances are 100,000-Ohm, ten-turn precision wire-wound resistors (linearity tolerance $\pm$ 0.5%) coupled to a 1000-digit dial; thus, each digit is equivalent to a 100 ohm change ($\pm$ 0.5 ohm). At 50, 200, 1000 cps, it follows that one digit is equivalent to the following angle changes:



READOUT OF PHASE SHIFTER = $\frac{R}{100}$ (OHMS)

FIGURE 4
PHASE-MEASURING SYSTEM

Scale	Frequency (cps)	Equivalent Angle Change (Degrees) (1 digit 100 ohms)
A	50	0.5
B	200	0.5
C	1000	0.6

These values are well within the required precision of $\pm 1^{\circ}$.

Linear, audio driver transformers are used in the phase shifter circuit. In the frequency range from 20 to 20000 cps, they are characterized by a flat response ($\pm$ 1 db) and have a phase deviation of $\pm 0.2^{\circ}$. The amplifiers of the cathode-ray oscilloscope introduce a phase shift of less than 0.1°. By test it is estimated that a phase change of less then 0.2° can be sensed by using the straight-line trace on the tube face.

4. Phase Angle Computation and Chart

The pertinent relationships between the phase angle and the electrical characteristics of the phase shifter are shown on the chart of Figure 5. The chart is entered at the frequency and the readout of the phase shifter (R/100). At the reactance associated with the capacitance and frequency values, the phase angle is read as a function of the resistance readout.

For the fixed values of capacitance used in the phase shifter (0.0663, 0.0175 and 0.00407 μ fd, respectively), the ordinate can be scaled appropriately so that it reads directly in frequency for each capacitance. Such a chart is shown in Figure 6. It is entered at the frequency and resistance readout values and reads the phase angle directly. For a 2-inch, 10-division grid, the angle can be estimated readily within the required precision of $\pm 1^{\circ}$.

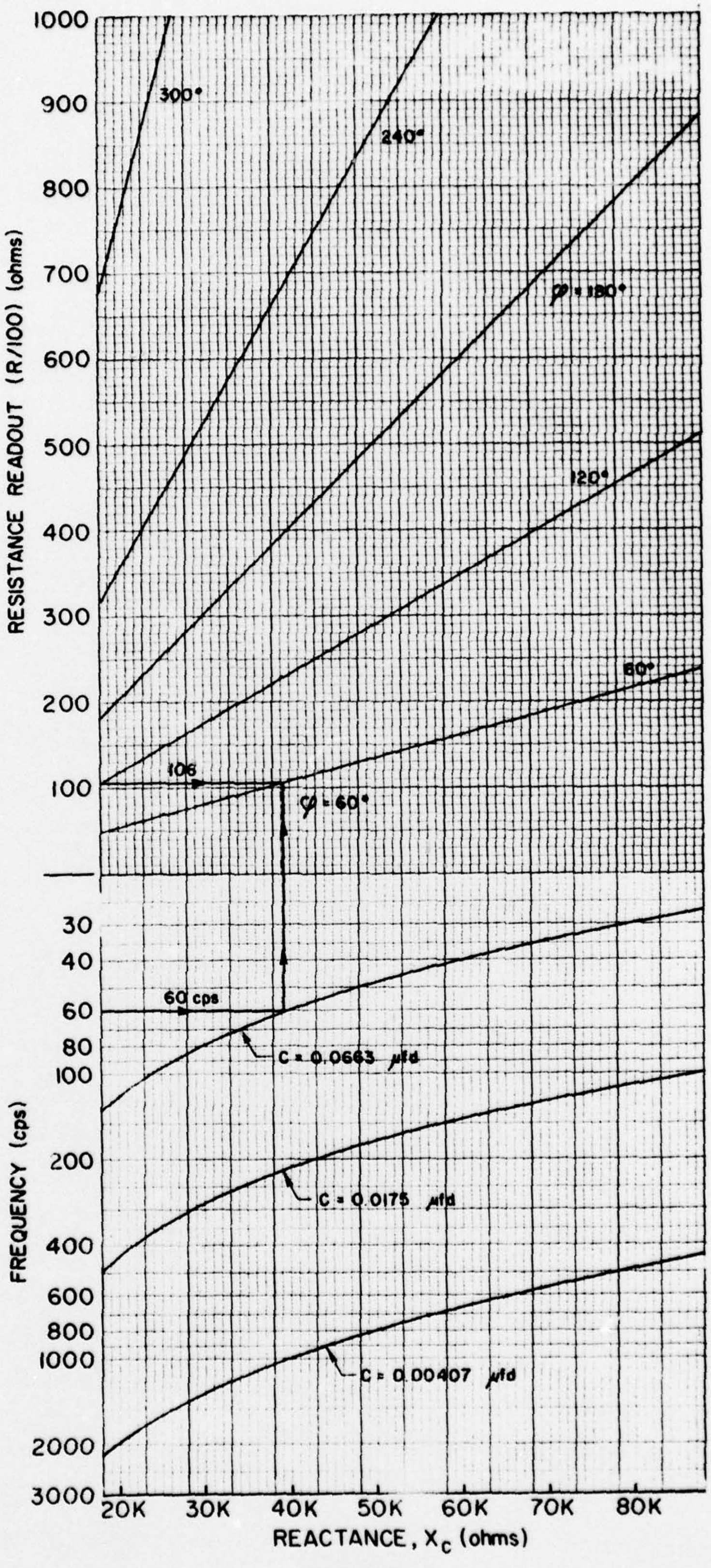


FIGURE 5
PHASE ANGLE GRAPHICAL COMPUTATION

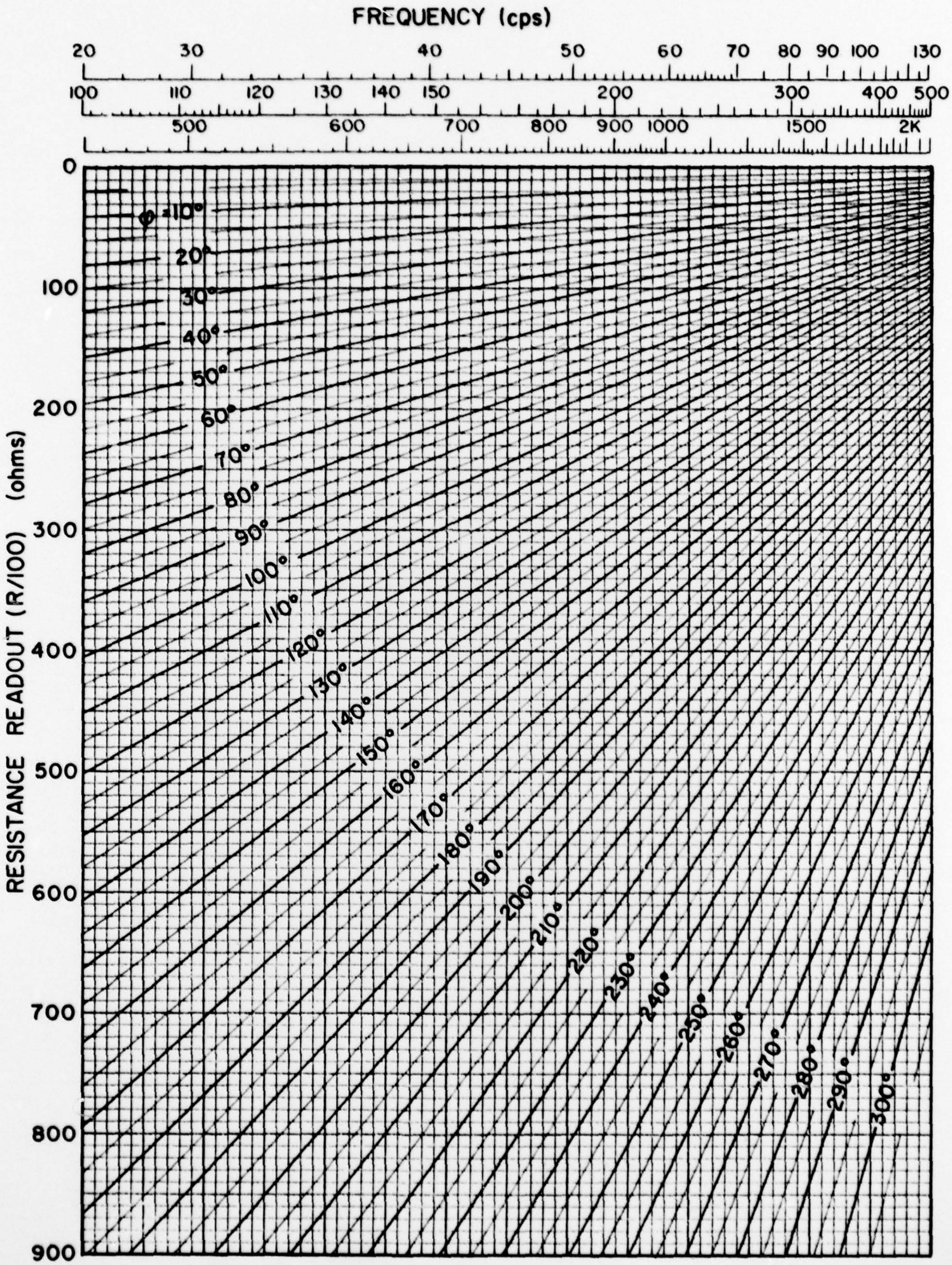


FIGURE 6 PHASE ANGLE CHART

-Effect of Noise and Distortion[6]

If one or both of two equal-frequency input signals are affected by noise, the associated out-of-phase and in-phase Lissajous figures displayed on the cathode-ray tube face are shown in Figure 7a, b, c. In each case, the phase indication of an axis-crossing, vector-addition or voltage-multiplier instrument would be affected significantly; particularly, if the phase difference were small. In contrast, the phase shift of the test signal (with respect to the reference signal) can be observed on the tube face almost as readily as that for two sinusoids unaffected by noise.

If the signal-to-noise ratio is low and the noise level varies widely the edges of the in-phase Lissajous figure also vary widely, making it difficult (if not impossible) to discern when the reference signal and phase-altered test signal are in phase. Under these conditions, accurate phase measurements are not possible by any method.[7] However, usually the noise level is significantly less than the level of either input signal (by, say, 20 db) and the relative variation in noise level is small. Thus, at the fundamental frequency, the Lissajous figure is clearly defined and any phase difference between the signals is as readily discernable as between noise-free sinusoids.

---

[6] Noise is defined as an erratic, intermittent, or statistically random oscillation. Distortion is an undesired change in wave form. Noise and certain desired changes in wave forms, such as those resulting from modulation or detection, are not usually classified as distortion.

[7] Under these circumstances, even filtering does not usually improve the signal-to-noise ratio significantly.

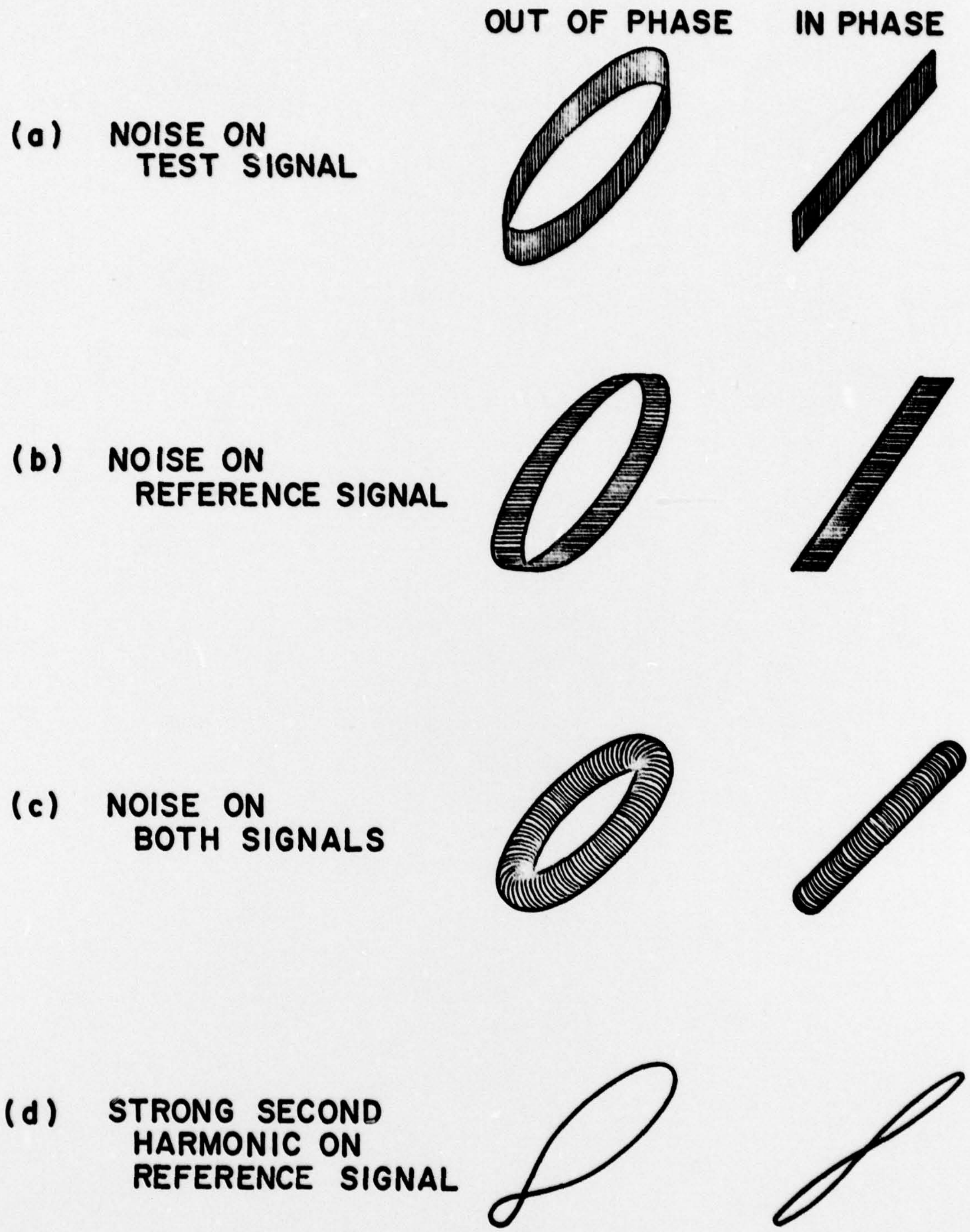


FIGURE 7
HARMONIC DISTORTION AND NOISE ON THE REFERENCE AND TEST SIGNALS

Within the context in which it is normally used, phase refers to the fractional part of a period through which the independent variable of a simple harmonic quantity (in our case, a voltage) has advanced, measured from an arbitrary reference. For example, in

$$e = E \sin(\omega t + \phi)$$

ϕ is the phase of an oscillating voltage of frequency ω $(= 2\pi f)$ and magnitude E. In more general terms, a periodic function composed of n components at harmonics of the fundamental frequency ω is given in the form

$$e = E_o + E_1 \sin(\omega t + \phi_1) + E_i \sin(2\omega t + \phi_2) + \ldots + E_n \sin(n\omega t + \phi_n)$$

where the E_i and ϕ_i $(i = 1,2,\ldots..n)$ are the amplitude and phase, respectively, of the components. Usually, for the cases we consider here, the signals can be represented by

-Reference signal: $e_R = E_R \sin \omega t$
-Test signal: $e_T = E_1 \sin(\omega t + \phi_1) + E_2 \sin(2\omega t + \phi_2)$

where $E_R = E_1 = 1$, $E_2 << E_R$, $0 \leq \phi_1 \leq 2\pi$, $\phi_2 = 0$ and the effect of all higher harmonics is negligible.

The in-phase Lissajous trace for the case cited immediately above is shown in Figure 7d. By extension, it is clear that the in-phase Lissajous of a sinusoidal reference signal and a test signal composed of n harmonic components is a symmetrically looped trace with (n-1) cross over points and its long axis inclined at 45^o to the horizontal. However, for significant distortion by harmonics greater than the second, it is probably better to introduce a zero-phase-shift, tuned-filter circuit before the phase shifter

(Figure 4) than to attempt to interpret the in-phase trace of the original distorted test signal.

The Lissajous figures for some cases where the test signal is distorted by the second harmonic or its frequency is an integral multiple of that of the reference signal are shown in Figure 8. The phase with respect to a reference signal ($e_R = E_R \sin \omega t$) can be determined for test signals characterized by

(1) $e_T = E_T \sin (\omega t + \phi)$

(2) $e_T = E_T \sin (2\omega t + \phi)$

(3) $e_T = E_1 \sin (\omega t + \phi_1) + E_2 \sin 2\omega t$

(4) $e_T = E_1 \sin \omega t + E_2 \sin (2 \omega t + \phi_2)$

$(0 \leq \phi \leq 2\pi)$

The first case above is the simplest and most common. The second occurs, for example, in the study of shaft dynamics where a once-per-revolution reference signal is associated with the motion caused by unbalance and a twice-per-revolution test signal is associated with a superposed motion due to shaft dissymmetry. The third case occurs in mobility studies where an interaction occurs between the driver and measurement-point characteristics. The last case occurs in the study of the steam turbine rotor dynamics. A twice-per-revolution motion of the rotor, out-of-phase with the once-per-revolution unbalance motion, occurs due to partial-arc admission of the steam.

The precision with which phase can be determined in each of the above cases is a function of the observer's ability to discriminate between the in-phase and out-of-phase Lissajous traces. In the first case (that of two sinusoids), the precision of the method has been demonstrated to be within $\pm 1^\circ$, even in the presence of noise. In the other cases, the precision is

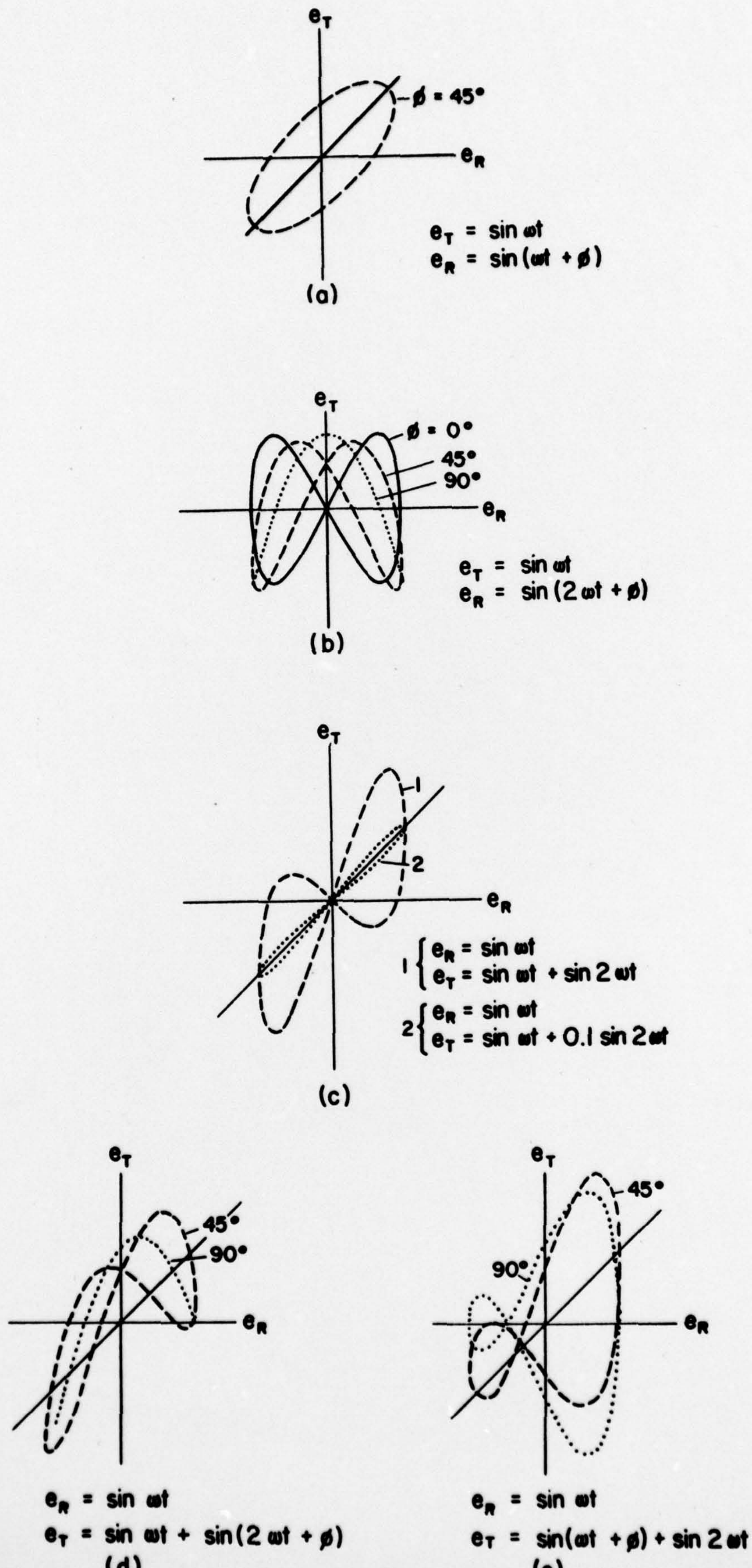


FIGURE 8

IN-PHASE AND OUT-OF-PHASE LISSAJOU TRACES determined by the ability of the observer to locate the crossover point exactly and sense the symmetry of the in-phase trace. By test the precision has been established as being less than $\pm 2^{\circ}$ for these cases.

Acknowledgement

The authors wish to express their appreciation to Mr. C. S. Duckwald (General Engineering Laboratory) for his valuable suggestions and advice in the design and use of the phase-measuring system described here.

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TITLE

A Phase-Measuring System for Use with Distorted, Low-Level Wave Shapes

ABSTRACT A phase-measuring system is described in which a simple R-C phase-shifter and an oscilloscope are used to measure the phase between two electrical signals. The required computation has been reduced to chart form which permits easy, accurate determination of phase (within ± 1°). The use of the phase-measuring system as an integral part of a mobility-measuring system is discussed.

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