C.P. No. 760

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Calibration Methods for the Accurate Assessment of the Static and Dynamic Performance of Some Flight Test Instruments

by

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LONDON: HER MAJESTY'S STATIONERY OFFICE

1964

NINE SHILLINGS NET

U.D.C. No.629.13.052:533.6.05

C.P. No.760

September, 1963

CALIBRATION METHODS FOR THE ACCURATE ASSESSMENT OF THE STATIC AND DYNAMIC PERFORMANCE OF SOME FLIGHT TEST INSTRUMENTS

by

I. McLaren

SUMMARY

Methods for measuring the static and dynamic performance of some flight test instruments are reviewed with special reference to calibrating equipment such as turntables, pendulums, shaking tables and special exciters.

The principles of frequency response tests are discussed in association with the theoretical characteristics of various, nominally, second order systems which are modified either by the method of testing or by the inherent, practical difficulties of instrument design.

Discussion is largely confined to the testing of sensing elements such as linear and angular accelerometers, rate gyroscopes, wind vanes, and ancillary devices such as filters and galvanometers.

A brief resume is also given of the characteristics and idiosyncrasies of measuring systems in general use.

Replaces R.A.E. Tech Note No. Aero 2914 - A.R.C. 25,592

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ILLUSTRATIONS

ILLUSTRATIONS (CONTD.)

1 INTRODUCTION

In recent years much emphasis has been placed on aircraft dynamic flight tests, mainly associated with the determination of the oscillatory modes of aircraft motion, with the measurement of dynamic loads on aircraft in turbulent air, and with the study of aircraft structural characteristics. The acquisition of reliable and accurate data from these tests requires a very high standard of instrumentation in the aircraft and interpretation on the ground.

For example, in the evaluation of aircraft transfer functions a normal accelerometer may have a specified requirement for the static performance of 0 to 2g for range with an accuracy of 1×10^{-3}g units. In the case of dynamic sensitivity the instrumentation is required to give 1% in modulus and 1° in phase angle over a frequency range of interest of 0 to 10 c.p.s. In addition, the modulus should be flat over this range and the system should be dynamically linear. Another typical dynamic investigation is the evaluation of stability derivatives using the time vector method of analysis. It has been found that an instrument error of 1° in phase angle measurement may represent an error of 10 to 15% in the modulus of the time vector representing the required force or moment which closes the vector polygon. Whilst it is comparatively easy to satisfy the static accuracy requirements the real difficulty is to obtain predictable response characteristics from the instruments in flight under dynamic conditions.

Ensuring that the system meets a stringent specification necessitates calibration techniques of a high standard. Even if the performance characteristics are available in published form or set forth in a theoretical analysis it is imperative to ensure that the assumed conditions really apply. In this field of work there is no substitute for test data.

2 INSTRUMENT CHARACTERISTICS

A perfect measuring system would have no errors under static or dynamic conditions and its output would be independent of all other factors such as temperature, pressure, humidity, vibration and unwanted inputs such as linear and angular displacements and their derivatives along and about the three axes. Furthermore, the system would be free of inherent defects such as Coulomb friction, hysteresis, non-linear springs and flexures, play in pivots and bearings, and damping that is not proportional to velocity.

Unfortunately, instruments of this calibre do not exist and it is necessary to select a type of system which will satisfy the particular requirements with regard to range, sensitivity, precision, linearity, resolution, weight and size. It is important, also, to keep components and devices simple and hence increase the reliability of the complete system. Essential ingredients of the system should also be examined carefully to determine the effects of the aforementioned extraneous variables and of dynamic conditions. Compatibility has to be considered from other aspects such as transmission, recording components, processing, computing and interpretation when selecting a transducer for use in a particular system.

A common-sense approach to this problem is to select the instrument which can best cope with the complete gamut of the varied requirements for the particular problem at hand, and devise test methods and special artifices to obtain a precise knowledge of its characteristics.

Physical quantities such as acceleration, velocity, displacement, pressure, force, strain, vibration and temperature comprise some of the more important parameters measured in flight test work. To obtain information on a particular set of data, specialised instruments are used in conjunction with recording systems such as multi-channel galvanometer recorders, magnetic-tape recorders, and telemetry systems.

This paper deals only with devices for the measurement of acceleration, angular velocity, incidence and sideslip, as information on one or more of these quantities is desired in most flight tests. No attempt is made to present a full treatment of procedures involving their installation in aircraft.

2.1 Acceleration

The acceleration of an aircraft can be determined, without reference to the external environment, by measuring the inertia force or torque experienced by a mass attached to the accelerating body. Typically, the acceleration is detected by measuring:

(a) the linear or angular displacement of an elastically suspended mass

(b) the strain or twist in a resilient member supporting the mass

(c) the flow of current in a coil situated in a magnetic field from which is derived an equal and opposite force to hold the mass in a null position

(d) the change in natural frequency of a vibrating wire whose tension is being altered

(e) the charge produced by piezoelectric materials subjected to a mechanical force.

Since devices such as those under (e) attenuate low frequency inputs they tend to be used more for the measurement of local structural vibrations than for the study of the motion of the aircraft and hence will not be dealt with further.

2.2 Angular velocity

The single degree of freedom rate gyroscope is widely used for the direct measurement of the angular velocity of an aircraft about one or more of its axes. In general, it includes an electrically driven rotor or wheel so mounted that its case can rotate about an axis perpendicular to its shaft. Movement about this axis is spring restrained and is detected by a displacement pick-off. The measurement of this output axis torque can be used as a measure of the magnitude of the input angular velocity which produced it.

An associated development is the force-balance type of rate gyroscope in which the signal from the pick-off is amplified and fed to coils, situated in magnetic fields, to hold the gyro in equilibrium. The mechanical springs are dispensed with in this configuration.

New developments, important in flight test work, use a vibrating device[1]. Examples are the tuning fork and torsional gyroscopes, which produce high sensitivities, have long life characteristics, and eliminate uncertainties due to gimbal bearing irregularities, wear of rotor bearings, and unbalance.

2.3 Airflow direction sensors

The angles of incidence and sideslip define the direction of the airflow with respect to the aircraft. The measurement of airflow direction can be made by employing a free-floating wind vane which aligns itself with the local free air stream. A displacement pick-off senses deflection of the vane with respect to a reference line on the aircraft. To avoid unacceptable position errors the vane must be mounted ahead of the fuselage nose on a pole at least $1\frac{1}{2}$ fuselage diameters in length and this imposes severe limitations on the size and weight of the sensing head[2].

Another class of instrument used for the measurement of the free stream direction with respect to the aircraft utilises the pressure difference set up between a pair of holes oriented at equal angles on either side of the longitudinal axis of a probe which is inclined to the airflow. A differential pressure pick-up provides a signal for recording purposes. The sensitivity of this type of sensor may be dependent on Mach No. and the ambient atmospheric pressure and hence may require more extensive wind tunnel and in-flight tests than those required for vane type sensors. This is probably one of the reasons why they have not been used extensively in flight test work.

From the safety aspect alone pressure sensors should be adopted where there is a possibility that the detachment of a vane could endanger the aircraft, e.g. by entering the engine.

The discussion of calibrating techniques involving airflow direction sensors is mainly confined to vane types although many of the techniques discussed apply equally well to both types.

3 STEADY-STATE CALIBRATING TESTS

3.1 Linear accelerometer tests

Calibrations of linear accelerometers are usually expressed in g units, 1g being the acceleration in terms of the local terrestrial gravity. Two calibration procedures for imposing convenient g increments on the instrument are the added weight and tilting tests.

The former test consists of adding weights to the sensitive element to simulate acceleration forces. However, the weights should be hung from the centre of gravity of the moving system to avoid improper loading of the springs or link assembly. For this, the centre of gravity of the moving system must be known precisely. Furthermore, the sensing element is exposed to a concentrated rather than a distributed load. For these reasons it is considered that the added weight test does not provide acceptable accuracy for initial calibration purposes, although it can be of great value for calibration checks in the field.

The tilting test is one in which the accelerometer is calibrated against the earth's gravitational acceleration by rotating it about a horizontal axis to selected angular positions. This method is suitable for low range instruments as they can be inclined through +1g, zero and -1g positions to obtain any fractional increment in this range.

However, there are two important sources of errors. First, the principal axis may not be parallel or perpendicular to some reference face of the instrument case because of manufacturing tolerances. Such misalignment between the measuring axis and the reference surface may give rise to calibration errors of considerable magnitude. In certain instances small misalignments of the order of 30' of arc may introduce errors of the order of 1×10^{-2}g units at a scale reading of zero g. The error is a non-linear function of the applied g, being a maximum at zero g and a minimum at the ±1g points for 360° rotation. A typical calibration curve representing conditions where the misalignment between a base, used as a reference face, and the measuring axis is α is shown in Fig.1. It is seen that although it resembles a hysteresis loop in that upscale deflections come to rest at a different point to downscale deflections for the same applied g it may in no way be related to hysteresis. Therein may lie a trap for the unwary. By conducting a few preliminary tests it is possible not only to determine the origin of this loop but to eliminate it if it is caused by improper alignment. These tests are sufficiently well known and so elementary in nature that they need not be described here. Suffice it to say that any misalignments between the measuring system and the appropriate mounting faces should be carefully noted to avoid faulty positioning of the installed instrument in the aircraft.

The other important general factor is the problem of ensuring that cross-coupling errors are correctly accounted for, particularly on an accelerometer which relies on the displacement of a mass. Cross-coupling is a change in output due to a component of acceleration perpendicular to the measuring axis. The effect of this interfering variable is illustrated by a damped mass-spring system mounted on a tilting table as shown diagrammatically in Fig.2. It is clearly seen that the mass swings in a small arc when the system is subjected to acceleration forces. It can be shown that the output is of the form $g \sin(\theta \pm \alpha)$, to a high degree of approximation, where the sign of α is dependent on the direction of the cross component along the arm, and its magnitude is equal to $\varphi \sin \theta$, φ being the full scale movement of the mass in degrees. The calibration curve resulting from tilting through 360° is distinguishable, in this case, by two loops instead of one, since if the instrument is precision engineered cross-effects are seen to be negligible at the zero and ±1g positions.

As the design of the majority of instruments of this type is a compromise between a system having large displacements per g for ease and stability of measurement and one having small displacements per g to obtain high frequency characteristics it is inevitable that the mechanical deflection of the instrument's mass has well defined limits. In some practical arrangements this has resulted in the term α being highly significant, and in one particular instance, produced an error of the order of 5×10^{-2}g units at 0.5g.

If the test had been carried out with the instrument positioned so that the two non-measuring axes were interchanged, cross-effects would have been considerably reduced. However, even with this configuration, cross-axis sensitivity may be important if the accelerometer is operating in the presence of cross-accelerations of the order of 2 or 3 times the rated range. This may be particularly noticeable in accelerometers employing inductance pick-ups in such a manner that they are susceptible to mechanical deflections, perpendicular to the sensitive axis, and to torsional displacements of the armature. In units of this type errors have been observed which were not linear functions of the applied accelerations and the impressed cross-accelerations. The r.m.s. value of the cross-axis sensitivity was of the order of 0·02 g/g for inputs ranging from $\frac{1}{2}$ to 2 times the rated range of the instrument. From these considerations it is seen that accurate calibration is required to ensure that test results are traceable to known standards of measurement. Moreover, judicious placement of the accelerometer on the tilting table and in the aircraft is required in order to minimise cross-coupling effects.

High quality test equipment is needed as in some instances, the measurement of angles to seconds of arc may be required for the tilting test. For these measurements, methods such as digital readout systems employing light sources, optical systems, and photocells have to be used to determine the angular position of the tilting table.

Steady-state accelerations higher than 1g can be obtained by the use of a rotating arm. Predetermined increments of steady centrifugal forces can be imposed on the accelerometer by varying either the speed or the radius of rotation. Variation of the radius of rotation is not recommended since extreme care is necessary to realign the instrument at the differing radii for each calibrating step.

Also, since the test is performed in the earth's gravitational field, judicious placement of the instrument is necessary to reduce cross-coupling effects to the minimum.

Points worthy of special attention to achieve the necessary accuracy in the centrifuge test are as follows:

(a) Since the acceleration varies as the square of the angular velocity, speed measurement and regulation must be precise.

(b) The radius of rotation should be large enough so that no correction is required for any changes that may occur in mass position due to changes in centrifugal forces.

(c) The axis of the rotating arm should be truly vertical so that a cyclic component of the earth's gravitational acceleration is not superimposed on the steady-state acceleration generated by the rotating arm.

3.2 Angular accelerometer tests

It is difficult to devise experimental techniques for the production of precise steady-state angular accelerations. Two possible alternative methods for calibrating angular accelerometers are discussed.

One method is the added weight test for applying known moments to the sensing element to produce a deflection equivalent to that normally caused by angular acceleration forces. Some drawbacks associated with this technique are:

(a) Precise knowledge of the moment of inertia of the sensing element is required.

(b) The magnitude and the point of application of the applied moment must be known exactly.

(c) It imposes a concentrated rather than a distributed load on the sensing element.

(d) Similar conditions are difficult to simulate if the instrument is oil-filled for damping purposes.

For these reasons this type of test can only be recommended for field checks.

Probably the most satisfactory method for calibrating angular accelerometers is to subject the instrument to sinusoidal angular accelerations. The ranges of angular accelerometers commonly required for aircraft flight test work can be separated into two classes; namely ±2 rads sec^{-2} and ±5 rads sec^{-2} with discriminations in the regions of ±15 minutes of arc sec^{-2} and ±1° sec^{-2} respectively. As it is fundamentally difficult to combine high sensitivity with high undamped natural frequency without resort to force-balance types, it is found that many low range instruments have low natural frequencies in the region of 3 c.p.s. to 7 c.p.s. To avoid the results being influenced by dynamic conditions the frequency of the input should be at least ten to fifteen times lower than the undamped natural frequency of the instrument under test.

Electro-mechanical exciters or oscillatory tables employing such methods as cross-heads or cams fail to produce sinusoidal outputs at the large amplitudes, in the region of ±30°, and low frequencies of the order of 0·3 c.p.s., needed to calibrate a low range instrument. One of the solutions to this problem is to employ a device similar in principle to an angular accelerometer but having little or no damping. The system is essentially a compound pendulum or a gravity controlled inertia which, when released from an initial angular displacement, executes free oscillations.

Referring to Fig.3, it is seen that the pendulum consists of a massive rigid beam suspended at a short distance from its mid-point on a shaft which is housed on low friction roller bearings. The system should be so large that reaction forces or torques from the instrument under test are of minor significance. Various pairs of weights can be attached to the beam at selected positions to change its moment of inertia and frequency, and a pair of springs can be fitted to connect the beam to the rigid frame to supply additional restoring torque. The combination of weights and springs must be selected to avoid unwanted frequency vibrations from the two arms of the beam.

Before mounting the instrument on the test rig platform it is imperative to evaluate the effects of unwanted inputs such as linear accelerations and angular velocities along and about all axes. The familiar technique of the 2g turnover in the earth's gravitational field can be extended to cover all 3 axes for the linear acceleration case. Angular velocity errors can be determined by rotating the instrument about its 3 axes in succession on a turntable. Accurate vertical alignment of the turntable axis and a constant speed are essential to avoid extraneous angular accelerations.

These tests are helpful in placing the instrument in the aircraft so that the effects of the interfering inputs are minimised. During calibration, alignment of the axis of the instrument with the axis of the pendulum shaft is important.

The test run is started by releasing the beam from a deflected position without imparting any motion to it whatsoever, a surprisingly difficult task. Of many methods, two of the more successful were to hold the beam in its selected position either by a fuse wire, disintegrated by a large current, or by a weight with a polished base, resting against one end of the beam and pulled away smartly on a highly polished surface.

Angular position and angular velocity pick-offs are fitted to the test rig and their outputs together with that of the instrument are recorded over several cycles on a multi-channel oscillograph recorder. This procedure is repeated with suitable initial deflections so that range, calibration factor, and linearity of the instrument may be inspected. The peak applied angular acceleration is obtained from the product of the initial angular displacement and the square of the frequency. The required accurate knowledge of time or frequency is obtained by recording the output of a master tuning fork.

Two factors which can contribute errors to the test results are the transient input (complementary function) and the amount of damping present in the test rig.

Assuming that the instrument constitutes a second order system, as many of them are, and that it is being subjected to sinusoidal angular accelerations then the conditions existing at the moment of release of the deflected oscillating beam are shown in Fig.4 where it is seen that its angular acceleration is at a maximum. At this time, i.e. $t = 0$, the steady state output of the instrument should have a value corresponding to point A, lagging the input by α, because of the damping force. This resisting force coupled with the inertia of the system results in the instrument needing time to catch up before it can swing into regular phase relationship with the applied angular acceleration. If the dynamics of the system are linear and the impressed frequency is less than the natural frequency and $\xi < 1$ it can be shown that the output is of the form

$$\cos(\omega_i t - \alpha) - \frac{\cos\alpha}{\sin\varphi} e^{-\omega_n \xi t} \sin(\omega_n \sqrt{1 - \xi^2}\, t + \varphi)$$

where ξ = damping factor relative to critical

ω_i = impressed frequency (rads per sec)

ω_n = undamped natural frequency (rads per sec)

$$N = \frac{\omega_i}{\omega_n}$$

$$\alpha = \tan^{-1} \frac{2\xi N}{1 - N^2}$$

$$\varphi = \tan^{-1} \sqrt{\frac{1}{\xi^2} - 1} \left(\frac{\omega_n^2 - \omega_i^2}{\omega_n^2 + \omega_i^2}\right)$$

From the above expression it was found that a linear second-order system with a $\xi = 0{\cdot}6$ achieves perfect correspondence to within a tolerance of 2% in modulus in approximately $2\pi/\omega_N$ sec. In other words, with this damping the error becomes negligible at the beginning of the first recorded negative half-wave if the undamped natural frequency of the instrument is ten times higher than the impressed frequency.

So far it has been assumed that the oscillating beam executes simple harmonic motion. Since frictional forces are always present the free vibrations decay and the mechanical motion takes the form of a damped sinusoid. It has been found from experience that if the bearings on the test rig are of first class quality and suitably lubricated and if the beam is of large inertia the damping forces present are predominantly of the viscous rather than the coulomb friction type. Thus the damping force is approximately proportional to velocity and of the form $- \beta\, d\theta/dt$.

In many practical test set-ups the value of ξ was of the order of 0·01 or less. It can be shown that if ξ is << 1, a convenient rule of thumb method to correct the calculated angular acceleration input derived from the initial displacement and the recorded frequency consists of multiplying it by $(1 - \xi^2)\, e^{-2\xi^2}$. With damping factors of the order quoted the errors are insignificant. For frequency response purposes it should be also noted that the phase shift of the output should be retarded by 2ξ radians.

However, in circumstances where both the transient input and damping factor appreciably affect the results a practical and accurate method has been evolved to give final corrected results. The method is based on the fact that the wave forms, after the transient has died out, are exponentially attenuated sine waves. A rough estimate is made of the time when the transient ceases to be of consequence and subsequent peak values are plotted as ordinates and cycles as abscissae on log-normal graph paper. The resultant graph should be a straight line and from extrapolation of this line the true first peak value can be determined as if no transient existed. Alternatively, a French curve, having an exponentially shaped edge, can be superimposed on the recorded traces to achieve the same purpose.

3.3 Rate gyroscope tests

A spring restrained rate gyroscope depends on the detection, by a pick-off, of the angular displacement about the gimbal bearings. The angular displacement is proportional to the angular velocity and the magnitude of this displacement for full scale input largely determines the sensitivity to the effect of cross-coupling due to angular velocities about other axes. The sine of the maximum deflection is a measure of the error due to perpendicular angular velocity so that, for example, a deflection of 2° gives an error of about 3% of the applied perpendicular angular velocity.

Small values of precession for full scale input are thus essential if decoupling from the input axis is to be confined to a negligible amount. The R.A.E. - Aero Flight force-balance type of rate gyro does not suffer from this effect since the gyro assembly virtually does not require to move about the gimbal axis to produce an output.

Again, it is important to evaluate the effects of linear accelerations along all axes by inclining the instrument through various positions in the earth's gravitational field. If the instrument is of good design and properly mass balanced the error due to a linear acceleration of 1g in any direction should be less than 1% of full scale deflection. A point worth noting is that unless stated otherwise it is taken for granted that the rotor is running for all these tests.

The measuring axis can be located with respect to a reference axis by rotating the instrument at constant speed on a turntable in two positions so that no outputs are produced from the two non-sensitive axes. The measuring axis is then mutually perpendicular to these two axes.

Rate gyroscopes which have large inertias about their gimbal axes and low spring restraints may be susceptible to angular acceleration effects about these axes. This feature can be investigated at various values of angular acceleration by mounting the instrument on an oscillatory beam, similar to that previously mentioned, with the gimbal axis aligned with the shaft.

Full scale deflections of rate gyroscopes for general flight test work are confined within the ranges ±5°/sec to ±100°/sec with further extension to ±250°/sec for the special case of spinning tests. This section of the note deals primarily with the low range type as they are fundamentally more difficult to design and require more sophisticated testing techniques.

Static calibration of the instrument is performed by placing it on a turntable which rotates around a vertical axis at various constant speeds. The input axis is aligned with the turntable axis and this is not critical since the output to input ratio is a cosine function of the angle of misalignment.

For the low range instrument it is seen that angular velocities in the region of 2 to 3 minutes of arc per second are required for calibration purposes. It has been found from experience that the levels of mechanical vibrations and noise associated with some conventional turntables employing motors and gears are unacceptable. These difficulties can be overcome by a turntable of novel design, as shown in Fig.5.

The turntable consists of an aluminium disc mounted on a vertical shaft contained in oilite bearings for horizontal loads and incorporating an air bearing for axial loads. Current is passed through coils, which are wound on a laminated magnetic core positioned so that the disc cuts all the magnetic flux flowing between the pole pieces. Movement of the disc between the pole pieces sets up circulating eddy currents in it which oppose the motion. A weight attached to the end of a string, which is wound round a pulley on the disc imparts a driving torque. The asymptotic value of the final velocity of the disc occurs when the total resistance to motion, which includes eddy current damping and friction, is equal to the torque imparted by the weight.

The equation of motion of the system is:

$$a \frac{d^2 \theta}{dt^2} + b \frac{d\theta}{dt} = T_o$$

where a = total moment of inertia of moving system

θ = angular displacement in radians

b = the damping constant

T_o = impressed torque.

When the asymptotic value of final velocity is reached then

$$a \frac{d^2 \theta}{dt^2} = 0$$

and

$$b \frac{d\theta}{dt} = T_o$$

or

$$\frac{d\theta}{dt} = \frac{T_o}{b} .$$

The damping constant b is proportional to the square of the current flowing in the coil and to the thickness of the disc. The disc was carefully machined from a forging to produce a high degree of homogeneity. As the coulomb friction in the system is of small magnitude the damping constant b is almost entirely due to eddy currents and hence the damping torque is proportional to velocity. If the current is kept constant b is a constant and since T_o is determined by the weight W the disc rotates at constant speed after the transient has subsided. A thin sheet of high permeability material is placed around the magnetic circuit to prevent the magnetic field from reaching instruments under test.

The edge of the disc is engraved in degrees to give angular displacement and with the aid of a stop watch the angular velocity is obtained. By varying the weight or the current, various speeds of rotation are attained. The vibration and noise levels at low speeds on the turntable are negligible.

Instead of altering the speed of the turntable the rate gyroscope can be tilted on the table to give incremental steps at constant angular velocity. A value of the latter is chosen so that the instrument deflects full scale in the conventional position. This technique also allows the effects of the precession angle and coupling errors on the instrument to be experimentally determined.

Fig.6 illustrates, schematically, the physical situation. The instrument is tilted through a known angle keeping the gimbal axis horizontal. Clearly the output is proportional to cos $(\theta \pm \alpha)$ where θ is the angle of tilt from the horizontal and α is the precession angle, the latter's magnitude being equal to $\varphi \sin \theta$, where φ is the full scale deflection of the gyro in degrees, and its sign depends on the direction of rotation of the gyro wheel with respect to that of the turntable. These errors are difficult to determine experimentally if the gyro is not tilted, as $\cos \alpha$, if α is $2\frac{1}{2}^{\circ}$, is negligible.

Gyroscopes employing potentiometric pick-offs should be particularly inspected in this manner as they usually have large precession angles so as to obtain sufficient resolution.

Pendulums and shaking tables are occasionally used to calibrate rate gyroscopes under so-called steady state conditions by producing essentially pure sinusoidal excitations. These tests are carried out under dynamic conditions at very low frequencies and they can be helpful to the extent that calibrations can be effected at likely flight test frequencies.

However, to be classed as static calibrations, the tests must be performed at frequencies at least ten times lower than the natural frequency of the instrument, avoiding a detectable change due to frequency response characteristics. With self-oscillating devices the inherent damping and transient inputs at the moment of release must be considered. Mechanical shaking tables and exciters seldom produce simple harmonic motion at large amplitudes and low frequencies without evidence of distortion due to back-lash, coulomb friction, and the second harmonic.

3.4 Airflow direction sensor tests

Fig.7 shows a photograph of the R.A.E., Aero Flight windvane which incorporates an a.c. pick-off for measuring purposes.

In a good windvane the following electro-mechanical design features must be avoided:-

(a) lack of mass balance of the moving element

(b) significant coulomb friction or play produced by bearings, links, and potentiometric types of pick-offs, and

(c) parasitic torques generated either by inductive pick-offs or spring ligaments.

Aerodynamic sources of error are related to such factors as;

(a) locating the moving element too near the body or boom so that the effect of upwash becomes significant

(b) lack of robustness of the windvane so that airloads and vibration cause malfunctioning

(c) the weight of the unit is of such a magnitude to produce the required robustness that bending of the boom assembly is appreciably increased when it is subjected to air loads and aircraft accelerations. This feature may also lower the natural frequency of the boom assembly, and

(d) asymmetry of the vane due to poor workmanship.

The errors produced by the features listed in the first group should be assessed in the laboratory. Errors associated with the second group are usually determined by wind tunnel tests and by tests conducted on the completed installation on the aircraft.

Static calibration tests are made in a wind tunnel by rotating the instrument body to predetermined angular positions at suitable values of $q(= \rho/2\ V^2)$. Hysteresis is examined by noting the difference between upscale and downscale deflections for the same angle of incidence and should be examined at various speeds as the misalignment torque varies with q. The vane must be mounted on the probe to include the effect of its interference on the airflow.

At subsonic speeds the vane is usually in the region of a disturbed pressure field created by the aircraft. At supersonic speeds it is hoped that the vane is relatively unaffected by the presence of this field and that the shock waves which form ahead of the aircraft do not extend to the region where the vane is located. However, Schlieren photographs of the shock pattern obtained from a vane and probe assembly in a supersonic tunnel at $M = 1{\cdot}6$ revealed that this was not so[3]. It was also found that a symmetrical distribution of vanes about the supporting probe produced a smaller and more consistent zero error at high speeds than the single vane installation. It is thought that the production of this good feature involving a more bulky protuberance of the boom assembly than usual may have contributed strongly to the creation of the shock wave.

For some flight test work the above calibration methods are adequate. For absolute calibration, further tests are required in flight on the particular aircraft.

Satisfactory flight calibrations are difficult, tedious, and time consuming and many methods have been attempted. A precise knowledge of aircraft angles of attack or yaw and flight path is of paramount importance in most tests.

A few possible methods are:-

(a) Photographing the horizon or the sun to provide a stable reference for aircraft attitude.

(b) Measuring aircraft attitude with an inclinometer in combination with a longitudinal accelerometer to verify that unaccelerated flight is achieved or, if this is not so, to correct for longitudinal acceleration.

(c) Measuring aircraft attitude with an accurate free gyroscope having a pendulous erection system, and obtaining rate of descent by measuring height and time.

Despite its complexity and potential unreliability, one of the best methods is by the use of an inertial platform employing a velocity-damped Schuler vertical system. Two stage integrations of the outputs of three mutually perpendicular accelerometers mounted on the platform produce three linear velocities and three linear displacements, thus providing direction and magnitude of both aircraft velocity and distance flown. Pitch and azimuth can be determined very accurately as the drift rates of most platforms are in the region of 0·1 degrees per hour.

Although the stable platform accurately predicts the motion of the aircraft in space, corrections would still have to be applied for bending of the boom due to inertial and aerodynamic loading and for air velocity components produced by pitching, rolling, and yawing velocities about the flight path.

Gusts may produce noise in the steady state results, making interpretation difficult and suggesting that tests be conducted at dawn in calm air, preferably over the sea or at high altitude over land.

4 DYNAMIC CALIBRATION

During flight testing it is frequently necessary to measure the oscillatory behaviour of an aircraft. The oscillations may be pilot induced, or may result from flying through turbulent air.

In order to measure these oscillations successfully and accurately, instrumentation systems based on sound dynamics in the characteristics and relations of the transducer, intermediate circuitry, and recording medium are required. Such systems must have predictable transfer functions under various input amplitudes and frequencies and environmental conditions of temperature and pressure.

Many conventional transducers for measuring accelerations and angular velocities can be represented by mass, spring, and velocity damped systems. If these second-order systems are linear they can be completely characterised by two fundamental parameters; the undamped natural frequency and the damping factor relative to critical. By referring to the well-known family of response curves Figs.8 and 9, the moduli and phase shifts of linear second-order systems can be determined for sinusoidal excitation at any frequency.

From dynamic considerations alone, paying no attention to other requirements, two methods are favoured for selecting a transducer on the basis of its natural frequency and damping factor. The first is the selecting of a damping factor which endeavours to combine the widest bandwidth, consistent with an error not greater than say 1% in the modulus, with a phase shift increasing linearly with frequency so as to avoid destroying the time relationship existing between the fundamental and its harmonics. To meet the condition for the modulus requires a damping factor of 0·64 critical and the phase shift case requires 0·75 critical. However, as a damping factor of 0·64 introduces very little harmonic distortion this value is usually chosen.

The second is that which comprises a natural frequency many times higher than any signal to be recorded and a damping factor of sufficient value to prevent mechanical damage being inflicted on the transducer due to resonance or shock. An electrical low pass filter can now be inserted between the instrument and the recording medium to dominate the system's dynamic performance.

Tailoring the transfer functions in this manner so that the outputs of all the quantities being measured have practically the same dynamic characteristics is useful in flight tests, particularly where cross-spectra are to be computed.

Many measuring systems suffer from the effects of coulomb friction, non-linear springs and suspensions, and damping that is not proportional to velocity. Consequently these systems are seldom linear over large ranges of amplitudes and frequencies.

The actual characteristics of any system can only be determined in the laboratory by dynamic tests. Two types of test are commonly used for this purpose. They are the analysis of the response to a step function input and the analysis of the response of the system to a sinusoidal input at differing frequencies.

The former method may be relatively simple and straightforward. It consists of determining the natural frequency of the instrument with zero damping. When damping has been added the damping factor is readily interpreted by observing the overshoot after a step function has been applied.

The method is applicable only to systems which are under-critically damped (oscillatory), as they usually are; the percentage overshoot is a function only of the damping factor and is given by $100\, e^{(-\xi\pi/\sqrt{1 - \xi^2})}$ where ξ is the damping factor relative to critical, Fig.10. By referring to response curves, Figs.8 and 9, the modulus and phase shift of the instrument at any given frequency can be determined. Strictly, this technique can only be used if it is known, a priori, that the system can be described by a linear second-order differential equation with constant coefficients. However, valuable information can sometimes be obtained on individual units of higher order systems; for example, to test the linear second-order portion of a system containing a low pass filter which has been included to shape the frequency spectrum. When used on these higher order systems great care is needed in the interpretation of the results, particularly where overall performance characteristics, e.g. change of phase shift and modulus with frequency, are to be derived.

The main advantages of the sinusoidal response method are:

(a) The sinusoid is the only periodic waveform in which the amplitudes of the components of all frequencies except the fundamental are zero. Naturally, a sine wave has only one bar in its spectrum. This feature eliminates the frequency distortion which could arise from an excitation consisting of a number of sinusoidal variations at different frequencies. This distortion of the composite output signal arises when the characteristics of the instrument are such that each component is displaced along the time axis by a different amount. Some flight testing techniques, of course, may require tests to obtain a knowledge of the dynamic response properties of the instrument when subjected to excitation with complex waveforms.

(b) The system's response to sinusoidal excitation yields information on the effects of Coulomb friction, backlash, and damping that is not proportional to velocity, if these features are present in the system.

(c) A basic property of the sinusoid is that any derivative with respect to time is the shape of a sine wave. Clearly, this is a distinct advantage as the test measurements include amplitudes and their time derivatives. If the parameters of the systems are linear then sinusoidal inputs will always produce sine wave types of output.

(d) It allows a precise comparison between the response at very low frequencies and the steady state response, thus providing a criterion of the reliability of the dynamic test data.

(e) It can test the system for multiple resonances by covering a wide frequency bandwidth.

The criticisms normally levelled at the sinusoidal response method are:

(a) Electro-mechanical shaking tables and exciters seldom produce sinusoidal displacements of large enough amplitudes, both linearly and angularly, at low frequencies unless they are relatively large and heavy.

(b) More than one of these devices will be required to cope with all types of instruments.

(c) Devices such as compound and torsional pendulums and cantilever springs executing free oscillations seldom produce mechanical displacements of sinusoidal form to the necessary degree of symmetry unless the inherent damping forces are negligible and restrictions are placed on amplitudes.

Force-balance systems are sometimes dynamically calibrated by inserting into the system an electrical signal which simulates a mechanical excitation. These closed loop response tests are potentially very accurate, and they are also very convenient for periodic checks and field use.

Many of the machines for dynamic response testing presented here are free-oscillating devices. The procedure for evaluating the transfer function of the instrument consists of recording on a galvo-recorder the displacement or amplitude of the input motion together with the test specimen's output. The output of an accurate tuning fork is also recorded so that displacements can be converted into rates or accelerations. Peak values of input and output are compared to find the variation in the modulus of the system with frequency.

Phase shift is derived from simple measurements of the recorded traces of input and output.

Transfer function analysers, while expediting the analysis, do not provide pictures of input and output waveforms for examination and it may also be difficult to include all components in the system, e.g. the galvanometer.

4.1 Forms of dynamic calibrating devices

4.1.1 Shaking table Fig.11

This machine is used to calibrate linear and angular accelerometers and rate gyroscopes dynamically.

It consists of a variable speed drive stabilised by a high inertia flywheel to which a crank pin is attached. A rod connects the crank pin, which is radially adjustable on the flywheel, to the crosshead on which instruments can be mounted for linear reciprocating motion. For oscillatory angular motion a sliding rod connects a pin on the crosshead to a shaft which is suitably housed in bearings. To eliminate mechanical noise the drive connecting the motor to the main shaft is performed by belts and pulley wheels; ball-races used on the assembly are specially selected and fitted.

A potentiometer measures amplitude and a speed meter is attached to the main shaft to indicate frequency.

The advantages of this system are:

(a) Precise and steady values of amplitudes and frequencies can be imposed on the instrument.

(b) A wide frequency range of 0·5 to 25 c.p.s. is obtainable.

(c) No corrections are required for decaying free vibrations or transients.

The disadvantages of this system are:

(a) At large values of crank radii corrections must be applied for harmonic distortion.

(b) At the minimum frequency of 0·5 c.p.s. the maximum value of linear acceleration obtainable is approximately 0·1g. The limiting factor here is space requirement.

(c) The complete elimination of mechanical noise and vibration is seldom achieved.

4.1.2 Cantilever leaf spring assembly Fig.12

This unit comprises a pair of leaf springs which are rigidly attached at one end to a fixed housing and a mass is attached to the free ends. This shaker is, in fact, similar in principle to an accelerometer without a damping mechanism. The springs have a linear load-deflection characteristic over the working range and have a high transverse stiffness.

A wide range of accelerations at various frequencies can be obtained by varying the mass or the length of the springs. The amplitude of the shaker can be measured by photo-electric cells, an a.c. pick-off, and a potentiometer.

This device can be used for calibrating horizontal and normal linear accelerometers dynamically. For the latter case the springs are biased so that they are straight throughout their entire length when the mass and spring assembly is subjected to an acceleration of 1g in the middle of its range.

The shaker executes damped free oscillations when released from a selected deflected position. The unit's inherent damping factor, ξ, is of the order of 0·006 so that the required corrections to the modulus and phase shift of the test instrument's output are of the order of 0·01% and 0·7° respectively.

The advantages of this system are:

(a) No mechanical noise or vibrations are present.

(b) High frequencies are easily obtainable.

(c) Provided the springs are working well within their linear load-deflection characteristics, harmonic distortion is negligible.

The disadvantages of the system are:

(a) To obtain reasonable values of acceleration at low frequencies e.g. 0·25g at 0·1 c.p.s., with negligible waveform distortion, the springs become excessively long.

(b) Excessive static deflection of the mass when calibrating normal accelerometers at low frequency makes biassing of the springs difficult. For instance when the shaker is set for a natural frequency of 0·5 c.p.s. the mass has, fundamentally, a static deflection of approximately 40".

(c) Time must be allowed for the transient to subside completely or corrections for this factor must be applied.

4.1.3 Vertical rotating machine Fig.14

This unit makes use of the earth's gravitational field to provide a sinusoidal forcing function for linear accelerometers.

It consists of a flywheel mounted on a horizontal shaft which is driven by a velodyne motor through pulley wheels and belts to give various controlled speeds without mechanical noise and vibration. Steel slip-rings running in troughs of mercury allow connections to be made to the instrument which is mounted on a plate near the centre of the flywheel. ±1g or any intermediate value of the earth's gravitational field can be imposed on the instrument by rotating it in a vertical or inclined plane. The precise value selected can be checked by a static turnover before commencing the tests.

Frequency and phasing are determined by recording an appropriate point e.g. top dead centre, on the flywheel by a photo-electric cell arrangement.

The advantages of this method are:

(a) Any frequency down to zero frequency can be obtained.

(b) Sinusoidal excitation is assured under constant speed condition.

(c) No cams, eccentrics, gears or links are incorporated to produce unwanted noise or vibration.

The disadvantages of this method are:

(a) Due to the centrifugal force, the dynamic response properties of accelerometers, which require movement of the mass to produce an output, are considerably modified at all but the lowest frequency ratios. The equation of motion for a conventional mass, spring, and velocity damped system subjected to this test is

$$\ddot{X} + \frac{\beta}{m}\dot{X} + (\omega_N^2 - \omega_i^2)\,X = g \sin \omega_i t + \omega_i^2 R$$

where R is the radius of the effective centre of the mass and spring assembly from the axis of rotation.

Amplitude ratio and phase shift curves shown in Figs.15 and 16, display the actual behaviour of the instrument undergoing this test. It will be seen that standard frequency response curves no longer apply. The physical interpretation of this phenomenon is that the centrifugal force causes an apparent reduction in the spring force of the instrument as frequency increases.

(b) Positioning of the effective centre of the mass-spring system with respect to the axis of rotation must be accurately known.

(c) The instrument must be of the type which is negligibly affected by cross-effects.

(d) The results are very sensitive to speed variation.

4.1.4 Compound pendulum Fig.13

One of the most versatile of dynamic test rigs is the compound pendulum, which is capable of calibrating linear as well as angular accelerometers and rate gyroscopes dynamically.

The test rig consists of a rigid beam suspended at its mid-point on a shaft suitably housed in low friction roller bearings. A long arm is attached to the beam in such a manner that it resists torsional stresses and twisting actions.

With various combinations of springs and of weights, arranged so as to keep the centre of oscillation below the axis of rotation, a wide frequency range can be covered.

Displacement and velocity pick-offs are incorporated to provide recorded input information and a Moiré Fringe device is installed to give a precise measure of static amplitude. A table is provided on the shaft for angular devices such as rate gyroscopes and angular accelerometers. Linear accelerometers are accommodated on a platform at the end of the arm.

The pendulum executes damped free oscillations when released from a selected deflected angular position. To avoid tedious corrections to the results it is imperative to reduce bearing friction to a minimum.

With the configuration as depicted only accelerometers suitable for measuring normal acceleration can be calibrated.

However, horizontally measuring accelerometers can be accommodated by turning the pendulum on its side so that its shaft is vertical.

The advantages of this system are:

(a) No mechanical noise or vibrations from motors, gears, and cams are present.

(b) A wide range of frequencies is covered, extending to a frequency as low as 0·01 c.p.s.

(c) With restricted amplitudes and negligible friction in the system, angular oscillations are produced with very little distortion.

The disadvantages of the system are:

(a) To obtain reasonable values of linear acceleration at low frequency, the displacement of the end of the arm must be large. As the motion follows a circular arc corrections must be applied to account for the tilting of the accelerometer in the earth's gravitational field.

(b) Care must be exercised to ensure that instruments with poor transverse characteristics are not influenced by centrifugal forces.

(c) Transients may have to be considered.

4.2 Future developments

Future developments are being directed at improving dynamic calibrating gear by employing force motors of the permanent magnet moving coil type. No cams, links, or gears will be used, and the coils will be excited with selected values of alternating current at various frequencies; power being derived from a low frequency oscillator and power amplifier.

4.3 Dynamic calibrating techniques for airflow direction sensors

(a) Dynamic properties of windvanes

Friedman[4], has shown that the frequency response characteristics of vane-type instruments may be quite different from those of the classical second order systems. As a simple classical demonstration, suppose that a windvane is mounted on a probe protruding from an aircraft's nose to measure angle of yaw. Assume that the aircraft is executing sustained sinusoidal lateral oscillations about an axis defined by the shaft of the windvane and that the shaft follows a nearly straight path in space. If the vane has negligible friction and its damping is aerodynamic then it is reasonable to suppose that the vane will align itself with the direction of the free airstream and also follow a nearly straight path in space. In the absence of external disturbing moments the output from the vane will correspond to the input under static and dynamic conditions.

However, if internal damping is interposed between the vane and its body then this is no longer so. If aerodynamic damping can be ignored, then at low impressed frequencies the viscous link between the vane and its body tends to move the vane with respect to the direction of the airflow. This tendency increases with the impressed frequency, until, at frequencies approaching the undamped natural frequency of the vane, it is almost moving in unison with the body. When the impressed frequency equals the natural frequency no output is observed. Fig.17 shows the essential quantities of an electrical analogy, with which it is possible to study the characteristics of the system in the familiar realm of electrical circuits.

It will be seen from the illustration that a windvane, having no internal damping and no friction in its bearings, can be represented by the electrical circuit with R_1 omitted. Thus the output achieves perfect correspondence with the input under static and dynamic conditions.

If the problem is idealized by the absence of aerodynamic damping (R_2), then the amplitude ratio and phase shift are given by

$$|A| = \left(1 + \left[\frac{2\xi_1 N}{1 - N^2}\right]^2\right)^{-\frac{1}{2}}$$

and

$$\varphi = \tan^{-1} \frac{2\xi_1 N}{(1 - N^2)}$$

where $|A|$ = the ratio of the amplitudes of the output to the input

$$\xi_1 = \frac{R_1}{2w_n L} = \text{damping factor relative to critical}$$

and $$N = \frac{w_i}{w_n}.$$

The dynamic amplitude ratio and phase shift are plotted against N for different values of ξ_1 in Figs.18 and 19.

In practice, these curves are considerably modified by the presence of aerodynamic damping. Two representative conditions are displayed in Figs.20 and 21. In both cases a realistic aerodynamic damping factor of 0·2 relative to critical is chosen, while the two arbitrary values of 0·1 and 0·6 are selected to represent internal damping.

An internal damping factor of 0·1 represents the value of damping which might be inherent in the windvane due to viscous friction and air-loads on the bearings. The second value of damping might be that which is incorporated to control the response of the instrument to dynamic inputs.

From these considerations, it will be seen that, even if the vane employs a much higher value of natural frequency than the impressed frequencies resulting from aircraft rigid body motions that are required to be investigated, then the modulus and phase shift may be different from those based on elementary theory if appreciable internal damping is present. Another factor that must be considered is that the internal damping ratio, unlike the aerodynamic damping ratio, is not independent of indicated airspeed[5].

It must be remembered that this particular case was selected as being the most significant for the demonstration of certain dynamic peculiarities. In actual practice, it would indeed be fortuitous if the aforesaid assumptions were fulfilled.

So far nothing has been said about aircraft angular velocities causing air stream direction measurement errors. These require kinematic corrections to be made to the results.

Windvanes are also used in flight tests for gust response measurements. In this instance, measurements of gust velocities are required. Two approaches to this problem are examined.

Firstly, the windvane can have response characteristics featuring a reasonably high natural frequency and a damping factor 0·6 relative to critical. As it is difficult to combine the requirements of high natural frequency and high aerodynamic damping, resort will have to be made to some form of internal damping to achieve this value. The system can be treated as a conventional second order system whose modulus is relatively flat up to 80% of the vane's natural frequency, on the assumption that there is little or no aircraft rotation.

Secondly, the windvane can have a natural frequency, very much higher than the top frequency of importance in the test, and aerodynamic damping which is inherently low. A filter can now be inserted into the system and be so designed that it dominates the system performance under dynamic conditions.

A point worthy of consideration is that airflow direction sensors of the differential pressure tube type can be designed to have very high frequencies. For these, the range of natural frequencies extends into the hundreds of cycles per second region. In these circumstances it may well be that the instrument's transfer function can be neglected over modest frequency bandwidths such as 0-20 c.p.s.

A complete statement of the case concerning dynamic flow direction sensing techniques in flight test work is beyond the scope of this Note. However, it is hoped that this brief discussion has highlighted some of the problems encountered in the use of windvanes under dynamic conditions. Many of these problems may turn out to be far from trivial and Ref.6 should be consulted for more detailed information.

Suffice it to say that it behoves the technician to choose instruments with characteristics compatible with the basic aerodynamic requirements demanded from the investigation in hand so that the task of interpretation is reduced as much as possible.

It may be of interest to point out that the windvane illustrated in Fig.7 has an undamped natural frequency of approximately 45 c.p.s. at 150 kts E.A.S. The aerodynamic damping factor ξ_2 is of the order of 0·2 at ground level conditions. The vane incorporates an a.c. pick-off and special bearings, thereby reducing friction and giving infinite resolution.

(b) Frequency response tests on windvanes

One method for determining the frequency response characteristics of a windvane is to oscillate the vane body sinusoidally in a wind tunnel at various amplitudes and frequencies at selected wind speeds.

This technique can be accomplished by a motor-driven cam and eccentric arrangement or by a compound pendulous device capable of being fitted with various springs to cover the required frequency band. A pick-off is embodied on the calibrator to record the input amplitude.

To facilitate interpretation of the results and to ensure freedom from kinematic effects, the axes of rotation of the exciting device and windvane shaft should coincide. The instrument, of course, while undergoing these tests can be located at predetermined distances from the axis of rotation to simulate and assess the effects of angular velocities.

These tests are excellent for determining what type of system the windvane represents. For instance, what is thought to be an aerodynamically damped vane with conventional dynamic characteristics may contain enough viscous or coulomb friction in the bearings and pick-off to substantially change its frequency response characteristics.

If the level of turbulence in the wind tunnel is not excessive subsonic dynamic calibrations are relatively straightforward. Supersonic tests of this nature have never been attempted by the author, but one or two points are worthy of consideration.

(i) If a wind tunnel with a large working section is chosen for the test so as to accommodate the rather bulky oscillatory mechanism, then care must be exercised in ensuring that its presence does not unduly increase the level of turbulence. From this point of view, a tunnel with a small working section might be more suitable for this purpose. This would permit the oscillating device to be located externally with possibly only a shaft protruding into the working section.

(ii) As the misalignment torque of the windvane is proportional to q, i.e. $\rho/2\ V^2$, it may be considered that its undamped natural frequency under these conditions is so high that step input tests will suffice.

Step input tests have been carried out in wind tunnels and in flight at selected conditions of air speed and atmospheric pressure. For this purpose a remotely controlled electrical solenoid is embodied in the body of the windvane. When the solenoid is operated it subjects the vane to a step input of a predetermined amplitude. These tests are helpful to the extent that they can be performed at particular conditions of air speeds and altitudes likely to be encountered in the flight tests.

5 CONCLUDING REMARKS

The object of this Note is to present the results of the author's practical experience in the static and dynamic calibration of some sensing elements for flight test work. To keep the Note within a reasonable size the scope of topics has been limited, and a selection made which it is thought will be of practical value to potential users in this wide field.

Two general observations can be made. Firstly, sinusoidal oscillating techniques provide a more comprehensive and quantitative assessment of the dynamic properties of the instrument than transient techniques. Secondly, force-balance types of accelerometers and rate gyroscopes offer advantages over their conventional mass-spring counterparts by virtue of their inherent high stability and lack of cross effects and also because large machines may not be required for their dynamic calibration.

If machines or exciters are used to evaluate the dynamic performance of instruments then sustained rather than free oscillatory motion would remove some of the uncertainties, such as transient effects and damped sine-waves, associated with the latter.

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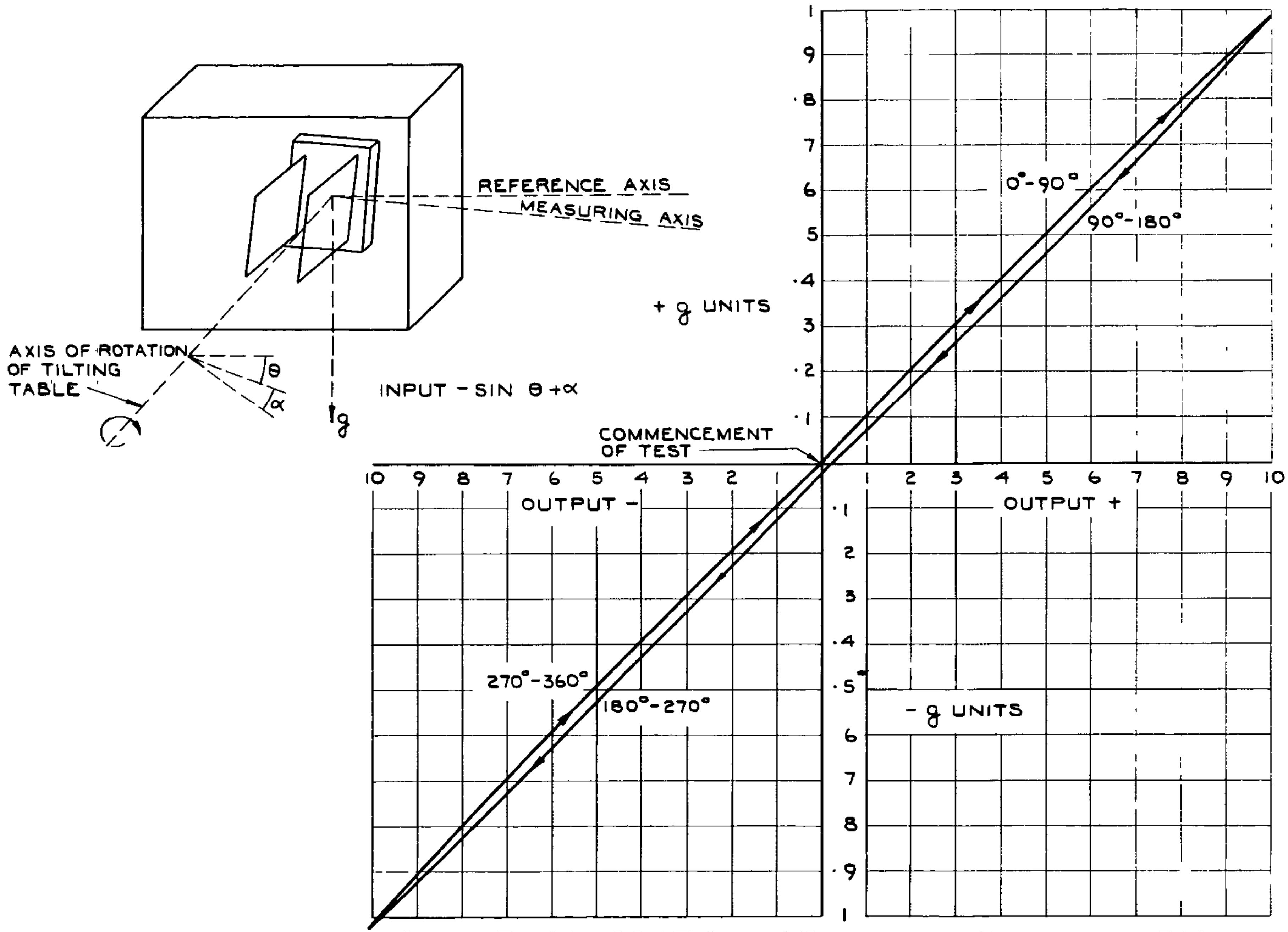


FIG. 1. TILTING TEST CALIBRATION OF AN OTHERWISE LINEAR ACCELEROMETER SHOWING THE EFFECT OF AN UNCORRECTED 1° MISALIGNMENT BETWEEN THE MEASURING AND REFERENCE AXES.

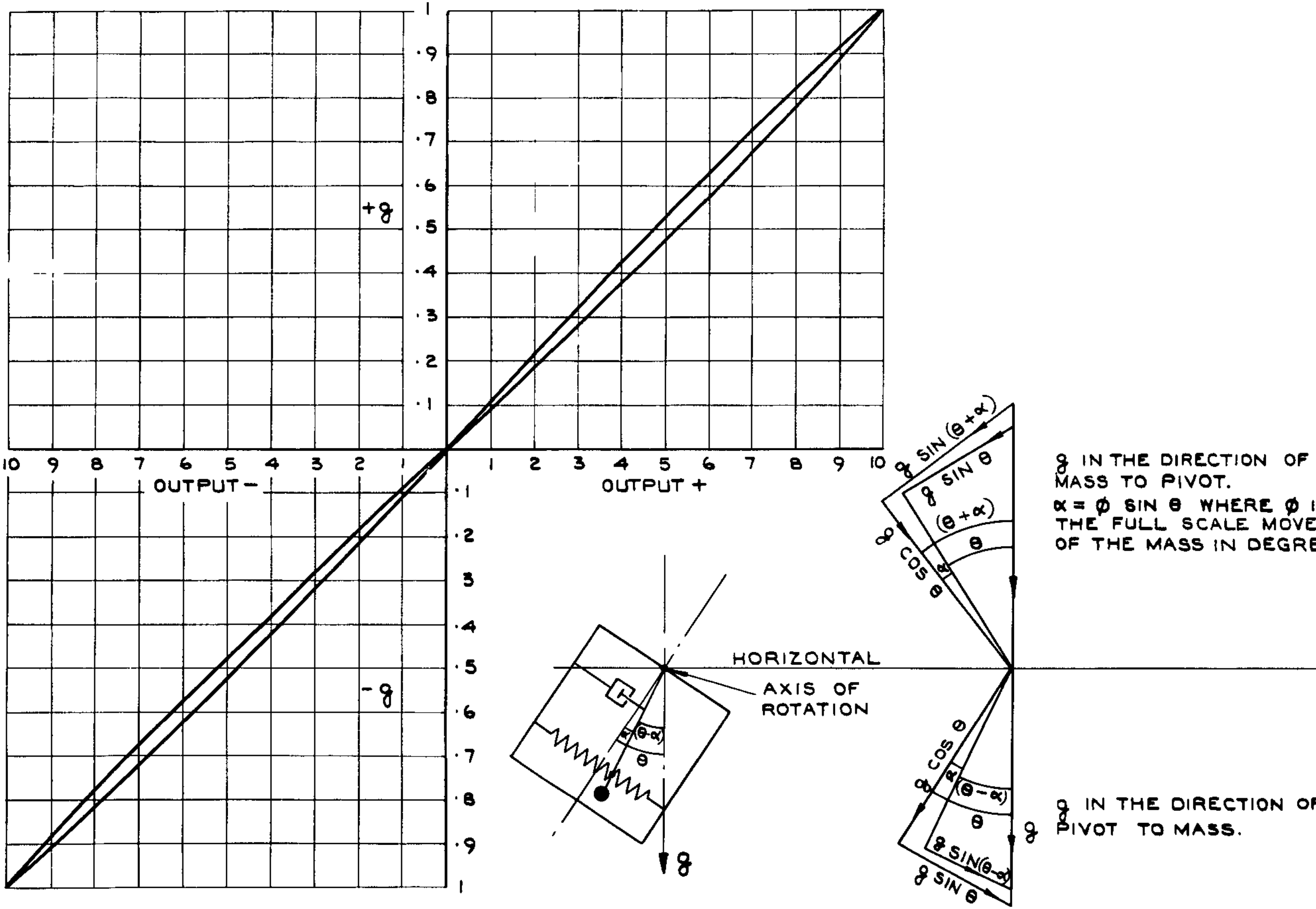


FIG. 2. TILTING TEST CALIBRATION OF AN OTHERWISE LINEAR ACCELEROMETER WITH g ACTING LENGTHWISE ALONG THE ARM AND THE RESULTS UNCORRECTED FOR a $\pm 2\frac{1}{2}^{\circ}$ F.S.D. OF THE MASS.

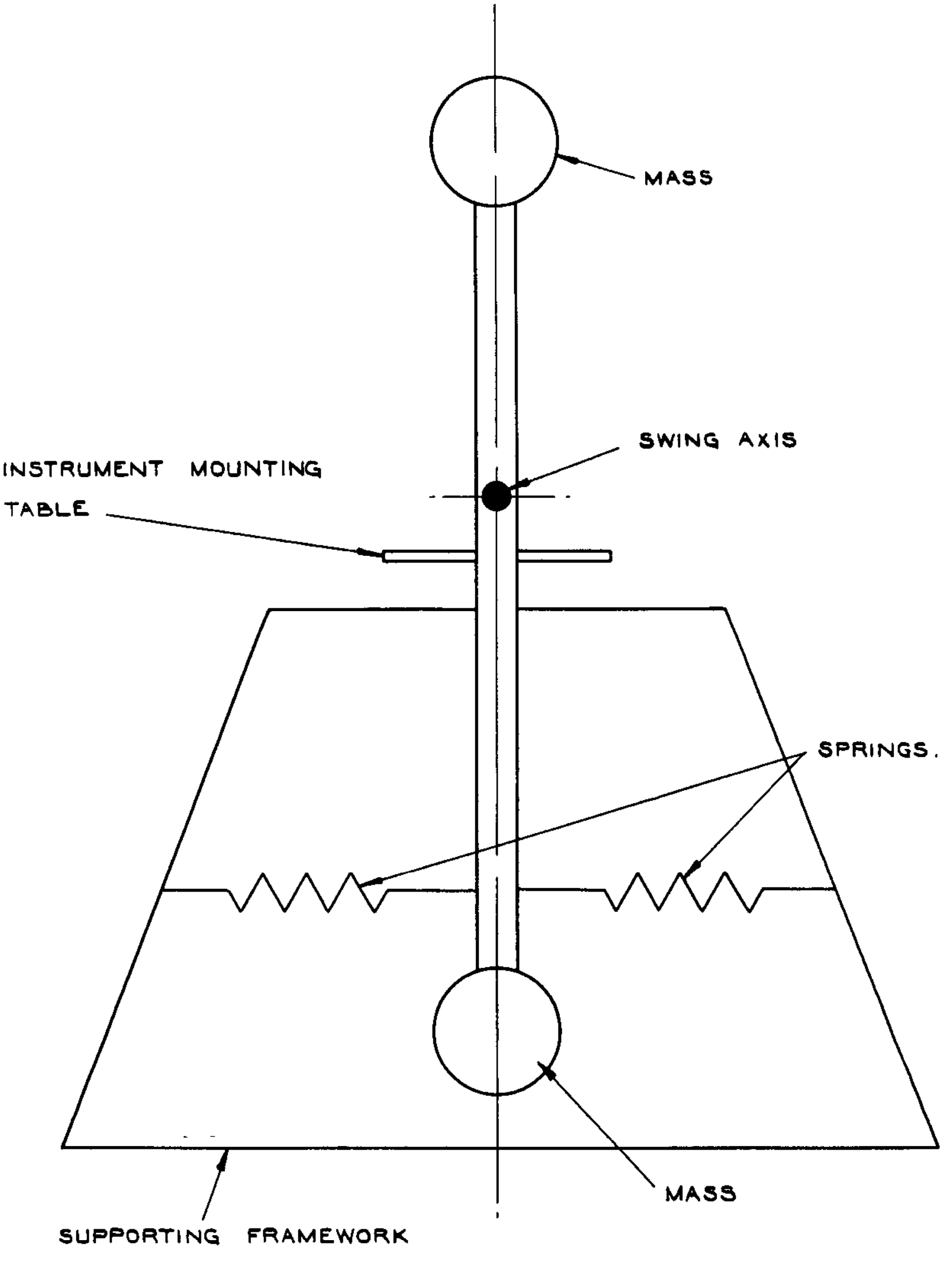


FIG. 3. COMPOUND PENDULUM.

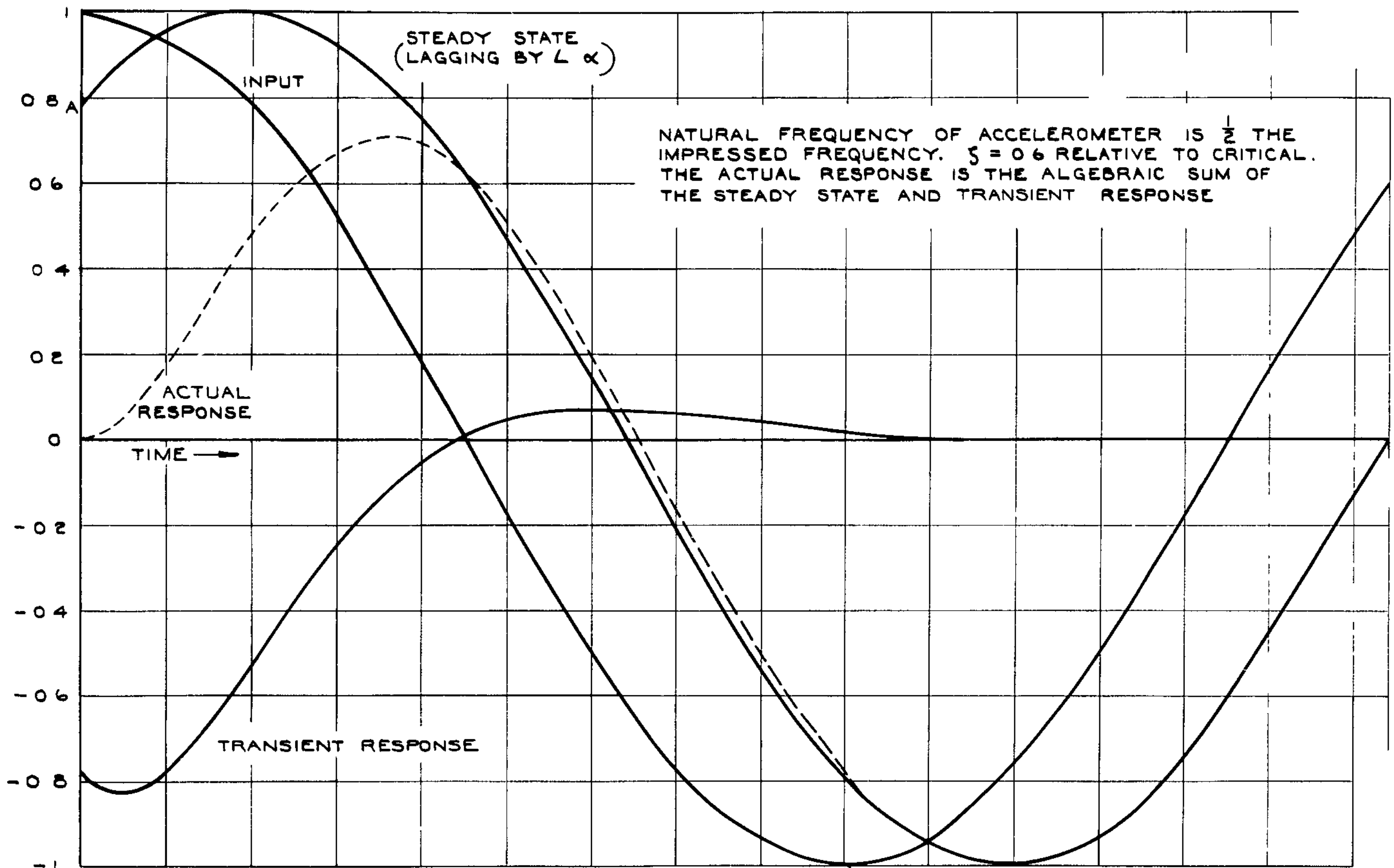


FIG. 4. THE TRANSIENT RESPONSE OF AN ANGULAR ACCELEROMETER WHEN IT IS SUDDENLY SUBJECTED TO A SINUSOIDAL ANGULAR ACCELERATION AT ITS PEAK VALUE

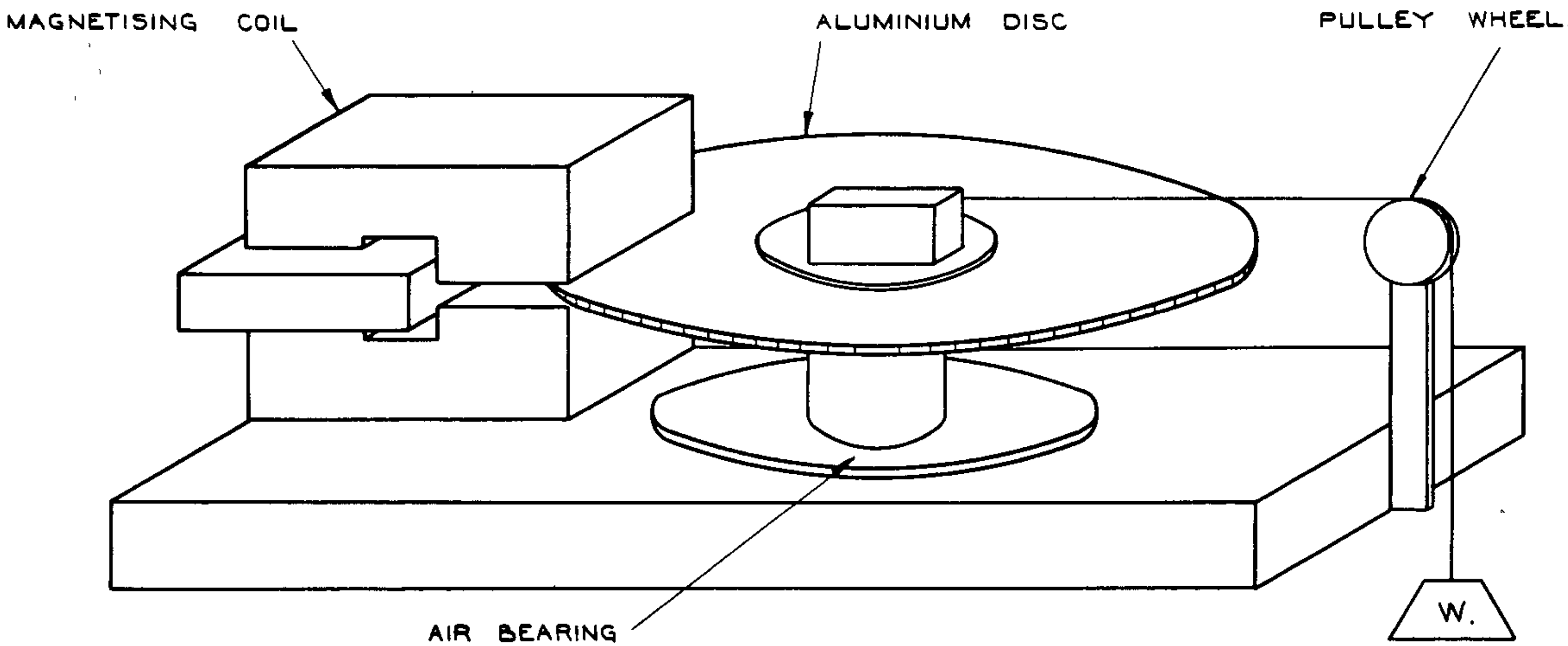


FIG. 5. EDDY CURRENT DAMPED TURNTABLE FOR LOW RATES.

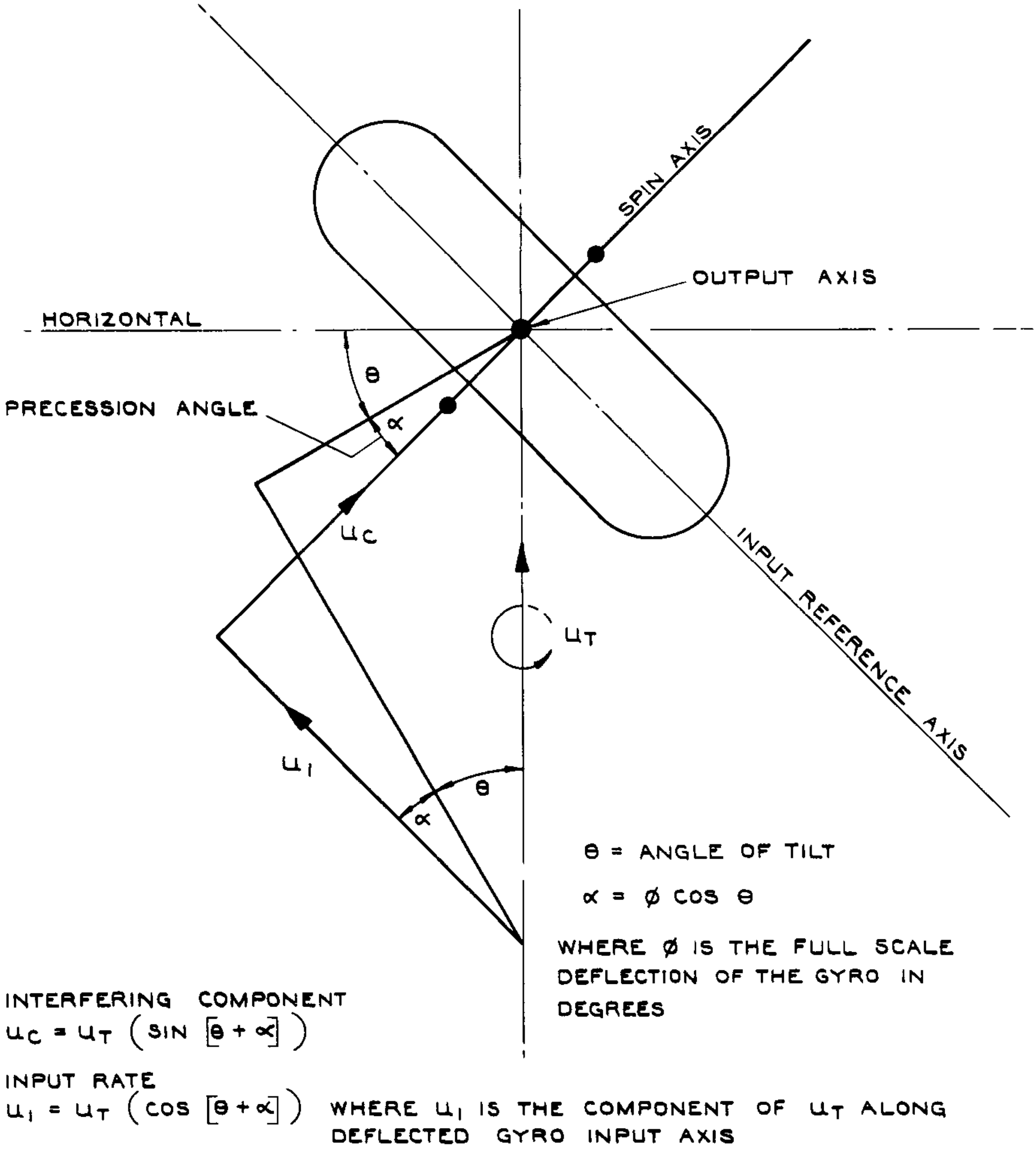


FIG. 6. GEOMETRY OF THE INPUTS TO A RATE GYROSCOPE WHICH RELIES ON ANGULAR DISPLACEMENT ABOUT THE GIMBAL BEARINGS FOR MEASURING PURPOSES WHEN UNDERGOING TILTING TESTS ON A TURNTABLE REVOLVING AT CONSTANT SPEED.

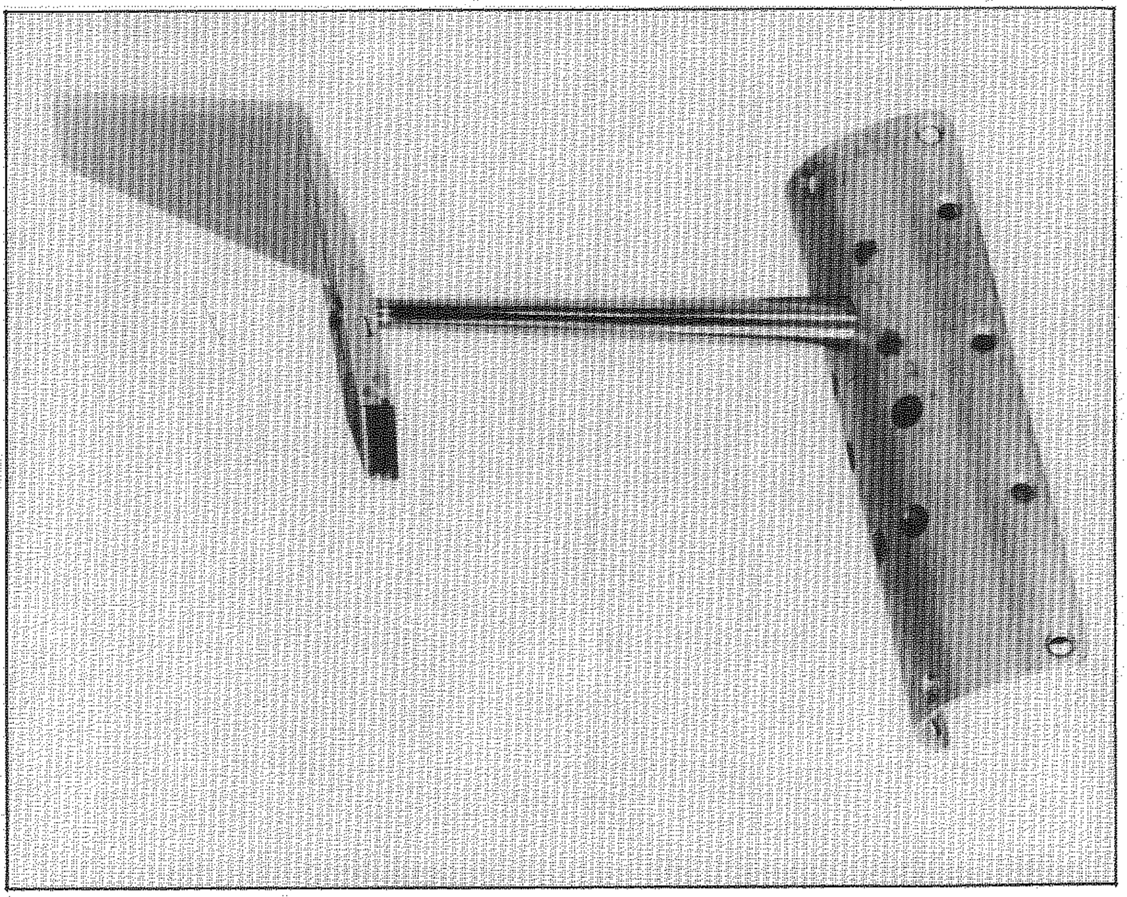


FIG.7. WIND VANE

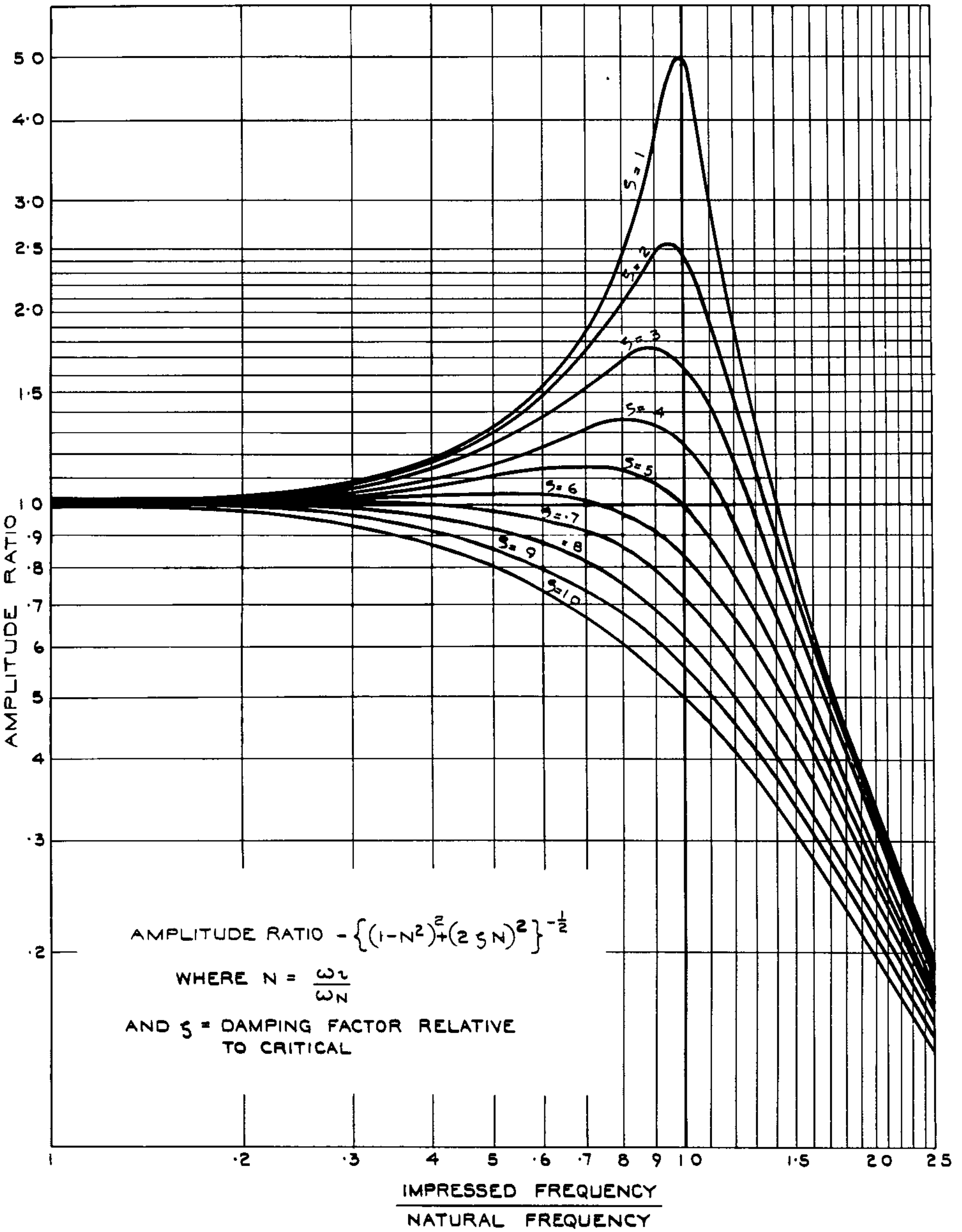


FIG. 8. DIMENSIONLESS FREQUENCY RESPONSE CURVES OF CONVENTIONAL SECOND ORDER SYSTEM.

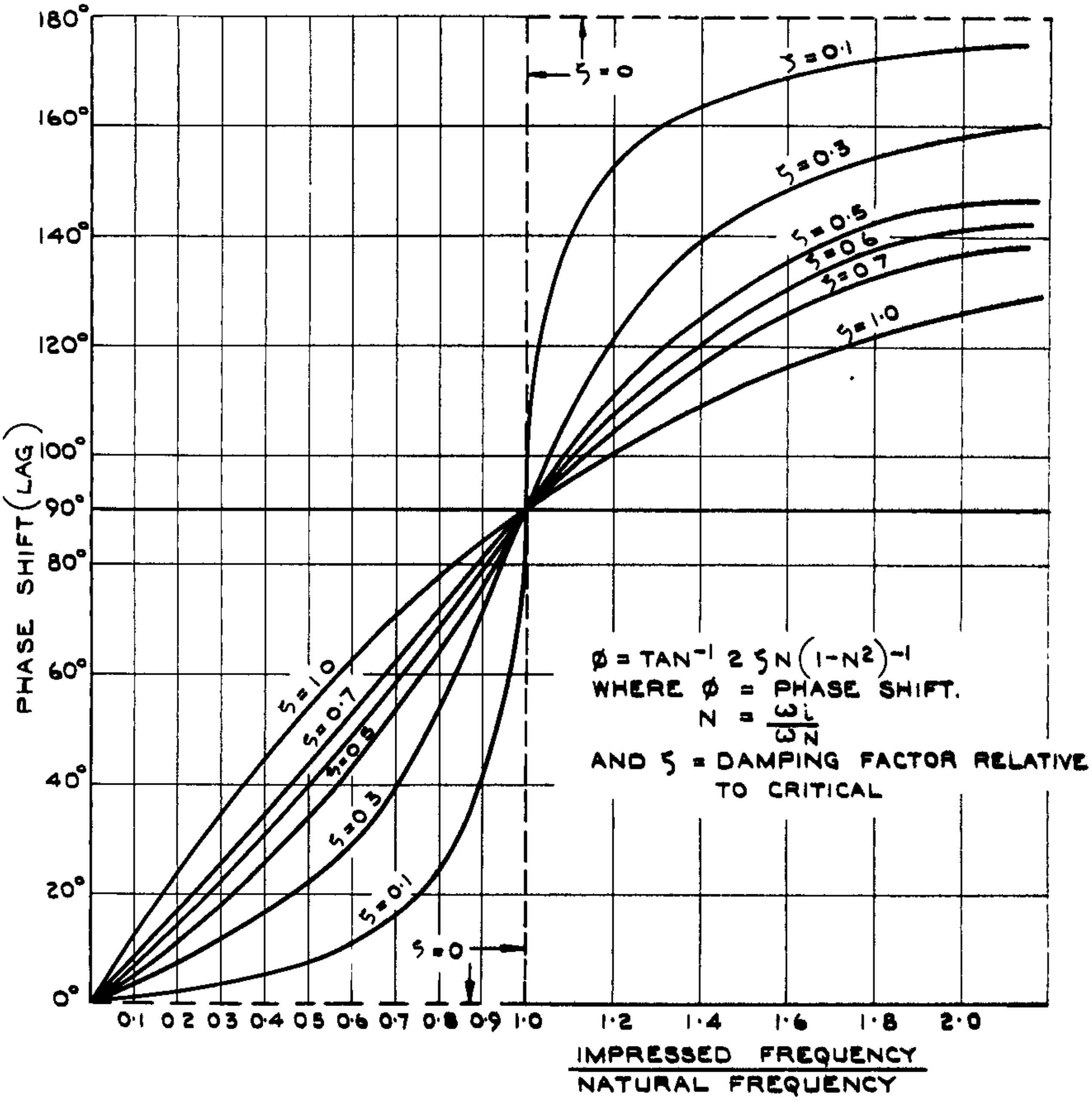


FIG. 9. VARIATION OF PHASE ANGLE WITH DAMPING OF CONVENTIONAL SECOND ORDER SYSTEM.

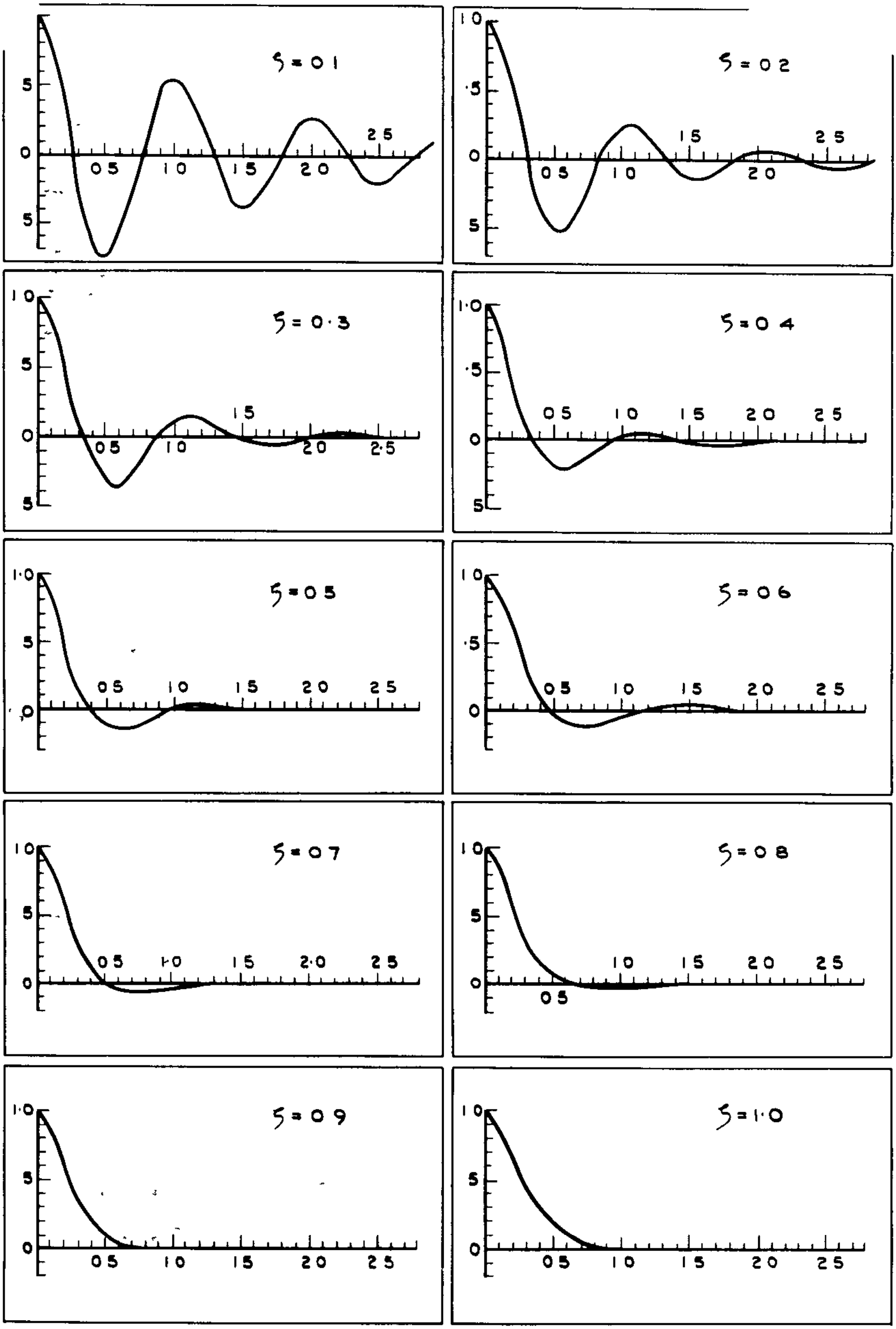
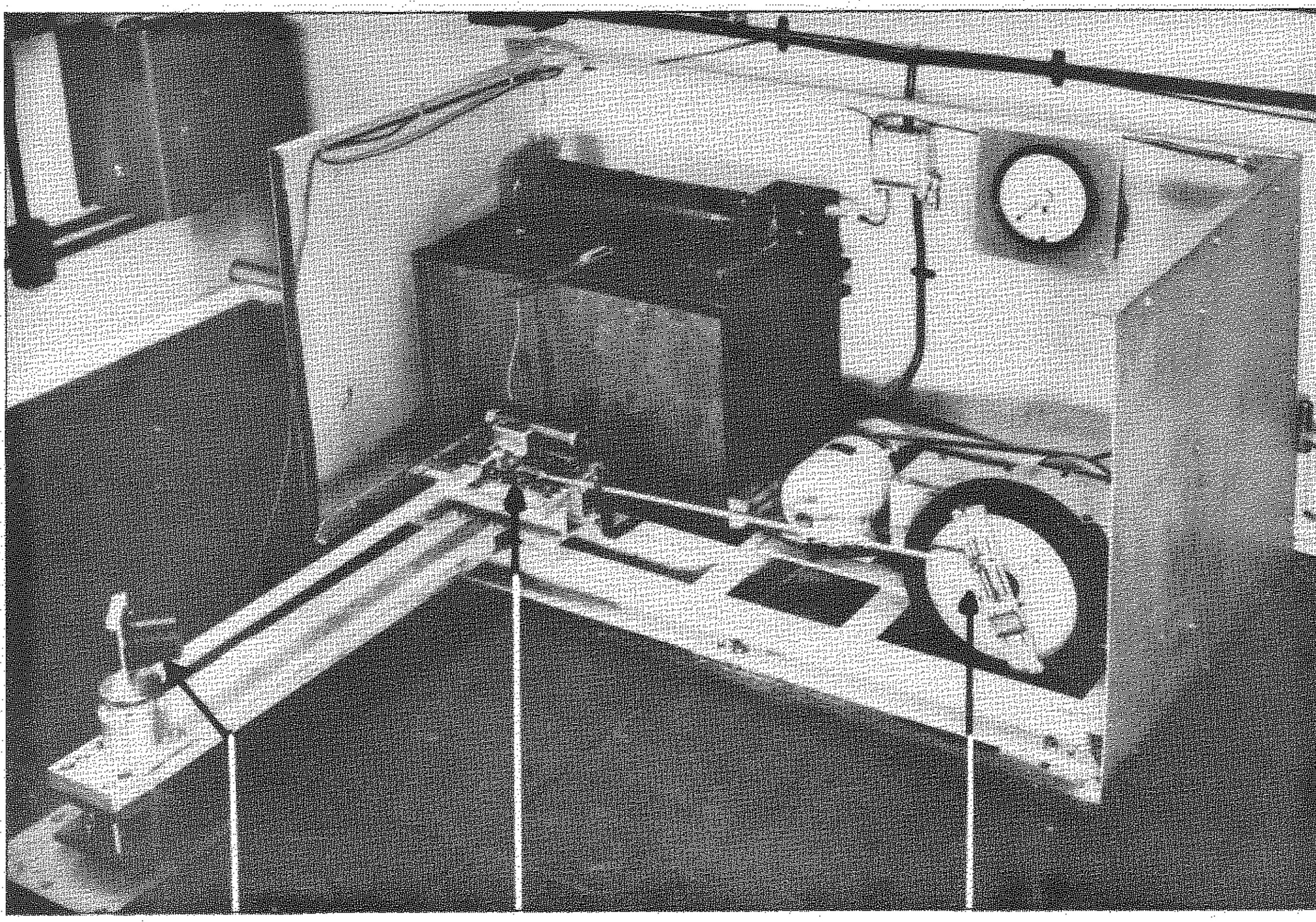


FIG. 10. THE OVERSHOOT ENCOUNTERED FOR VARIOUS DEGREES OF DAMPING WHEN A STEP-FUNCTION IS APPLIED TO CONVENTIONAL SECOND ORDER SYSTEM.



GYRO MOUNTED ABOVE PIVOT

CROSSHEAD WITH POTENTIOMETER TO INDICATE DISPLACEMENT

ADJUSTABLE THROW FOR CRANK ARM

FIG.11. SHAKING TABLE

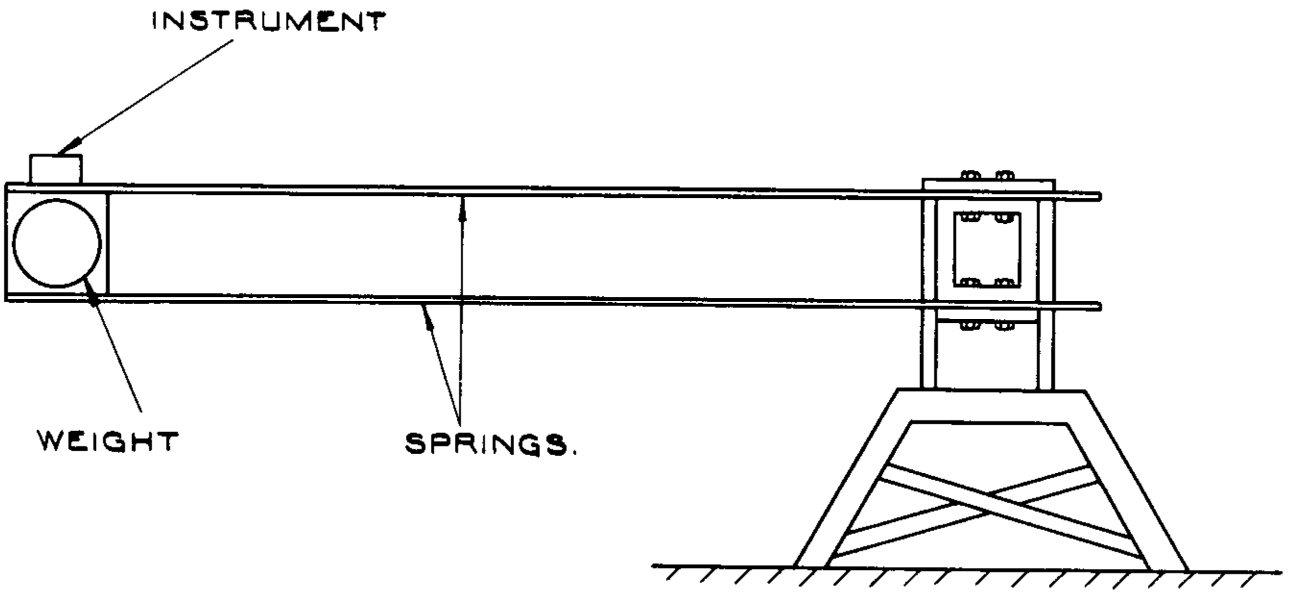


FIG. 12. CANTILEVER LEAF SPRING ASSEMBLY.

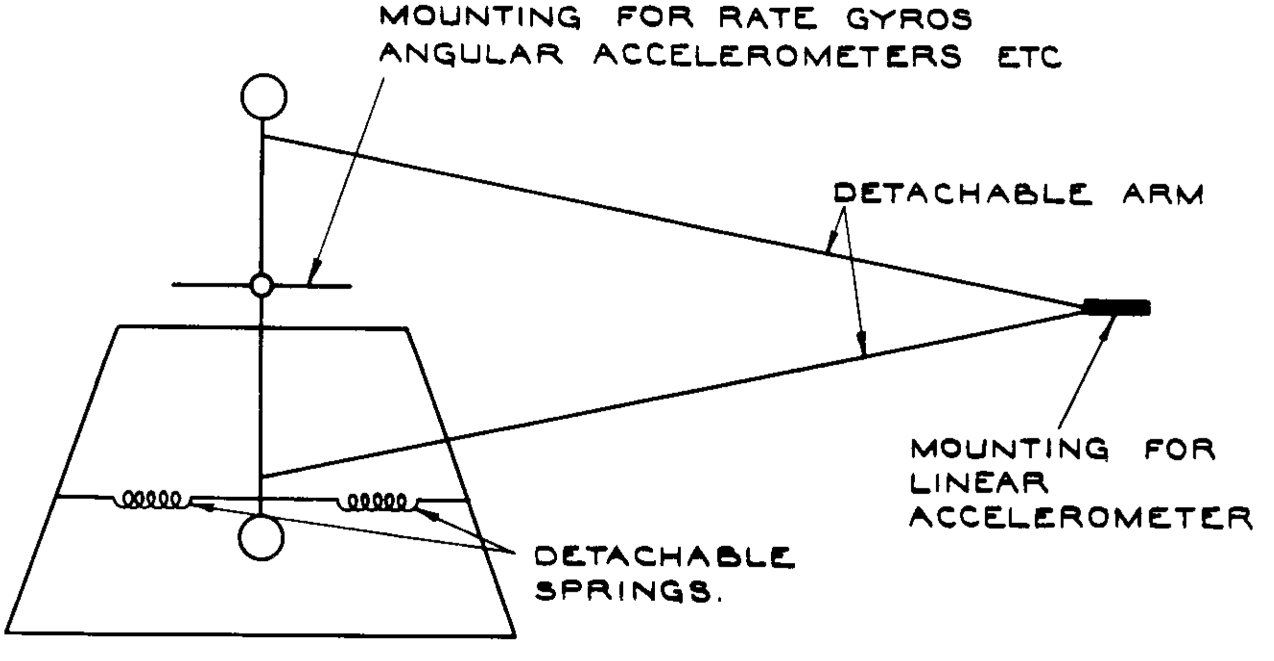


FIG. 13. COMPOUND PENDULUM WITH FACILITY FOR CALIBRATING LINEAR ACCELEROMETERS.

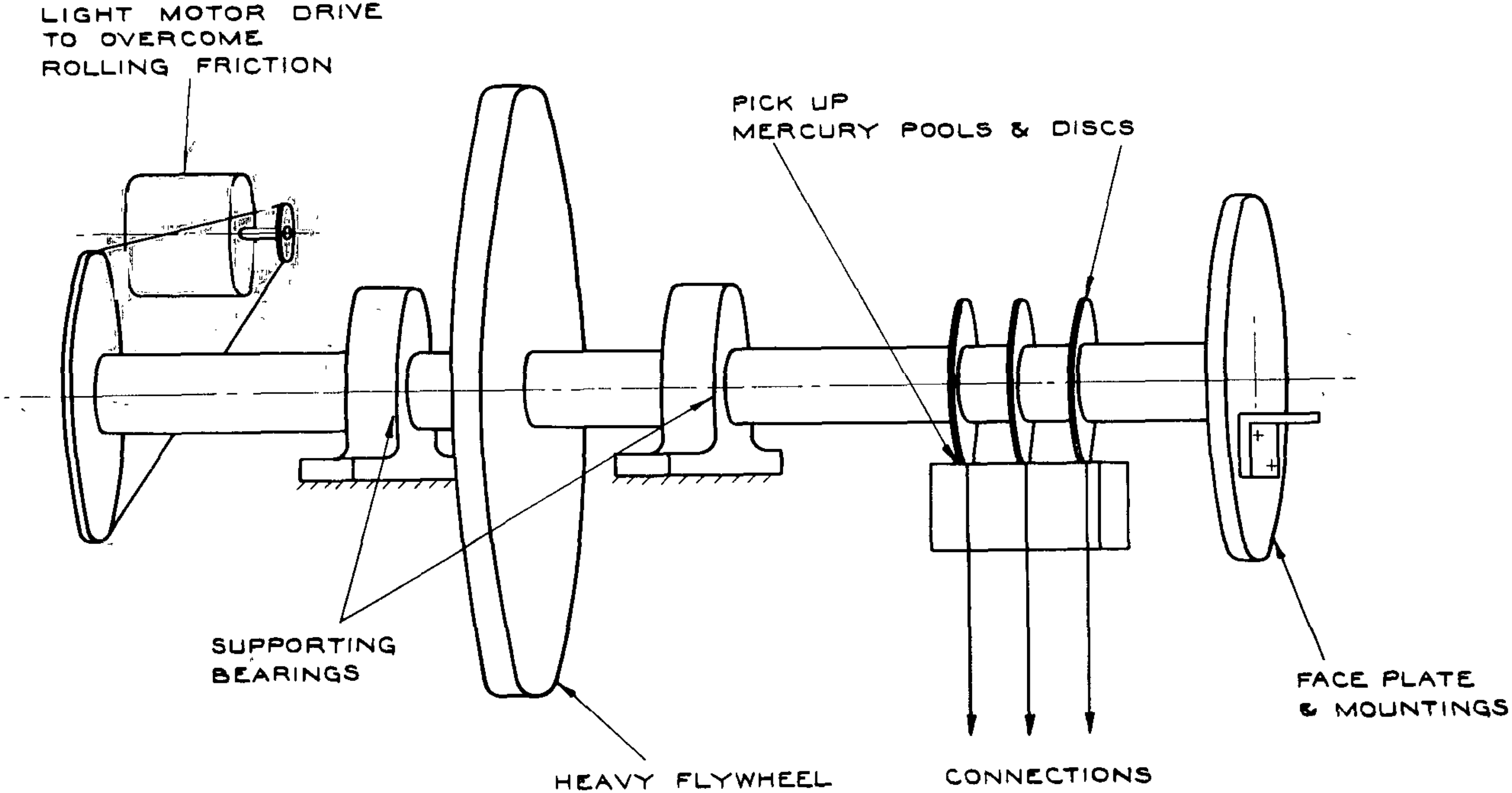


FIG 14. ROTATING MACHINE FOR DYNAMIC CALIBRATION
OF LINEAR ACCELEROMETERS.

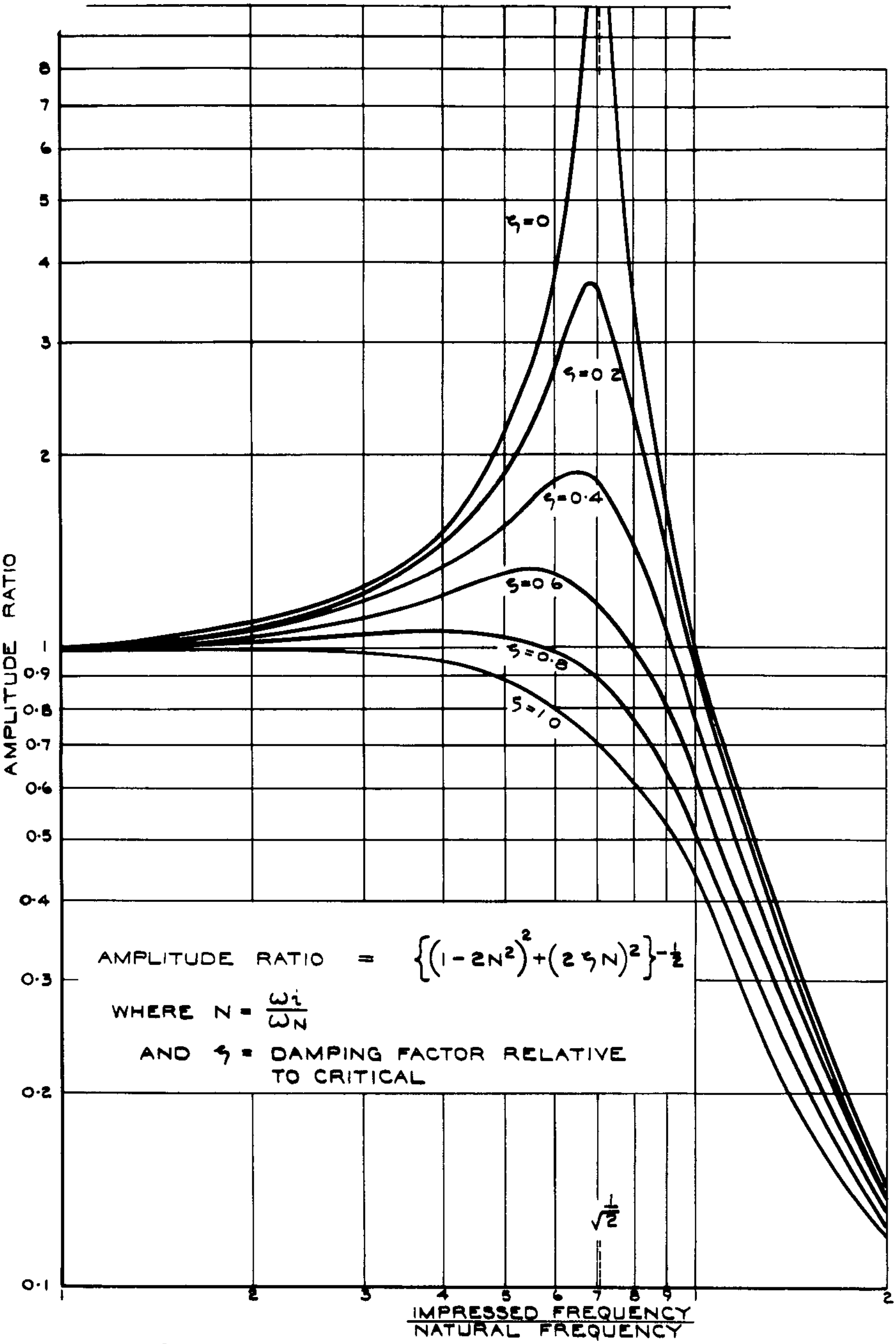


FIG.15. DIMENSIONLESS FREQUENCY RESPONSE CURVES OF AN ACCELEROMETER SUBJECTED TO A DYNAMIC ROTATIONAL TEST.

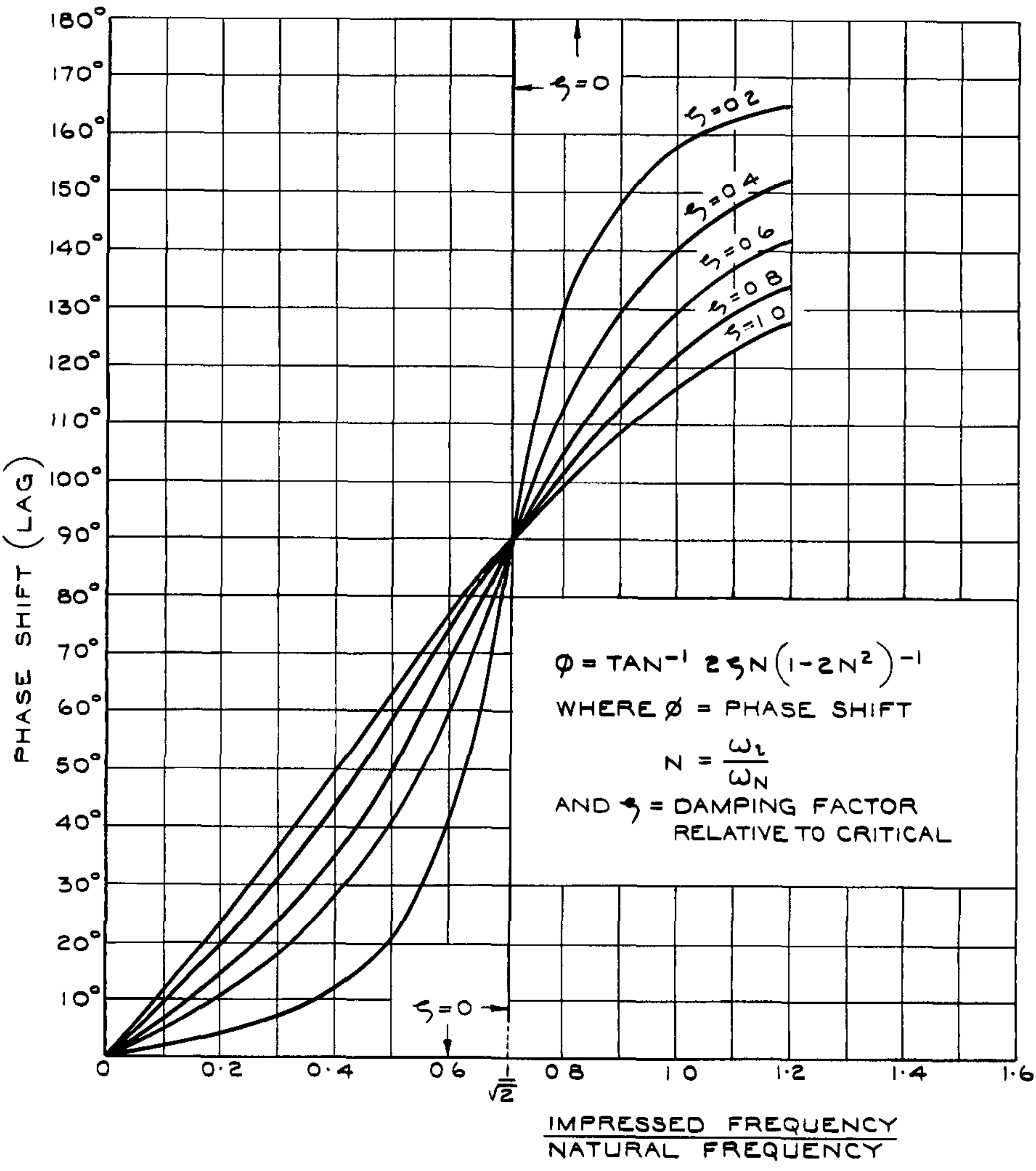
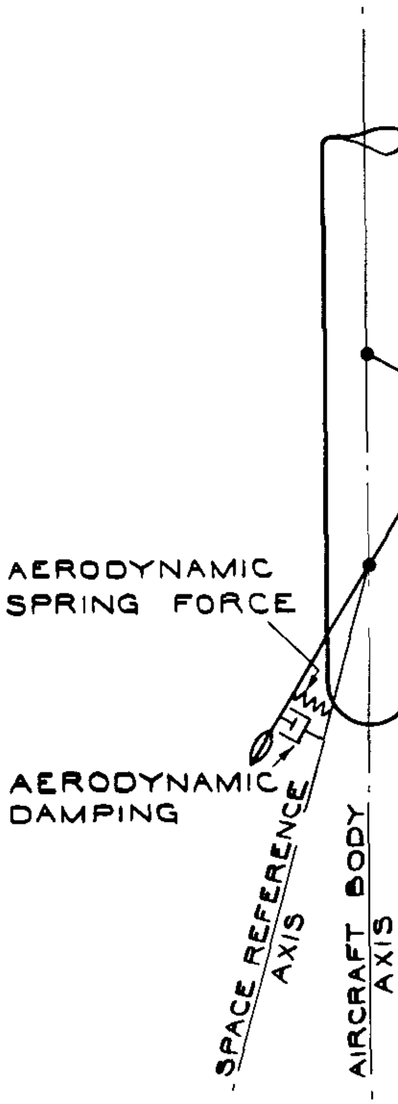
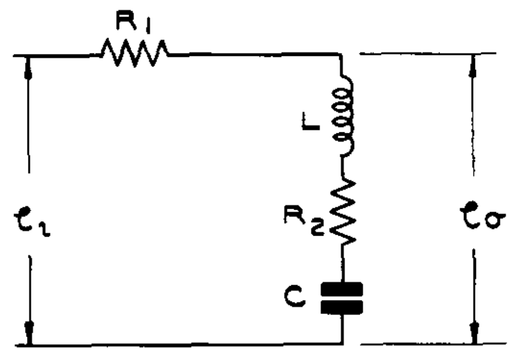


FIG. 16. VARIATION OF PHASE ANGLE WITH DAMPING OF AN ACCELEROMETER SUBJECTED TO A DYNAMIC ROTATIONAL TEST.





CORRESPONDING QUANTITIES

I	INERTIA OF VANE	– L	INDUCTANCE
B_1	INTERNAL DAMPING CONSTANT	– R_1	RESISTANCE
B_2	AERODYNAMIC DAMPING CONSTANT	– R_2	RESISTANCE
K	AERODYNAMIC SPRING CONSTANT	– C^{-1}	CAPACITANCE^{-1}

FIG. 17. THE ELECTRICAL EQUIVALENT OF THE WINDVANE

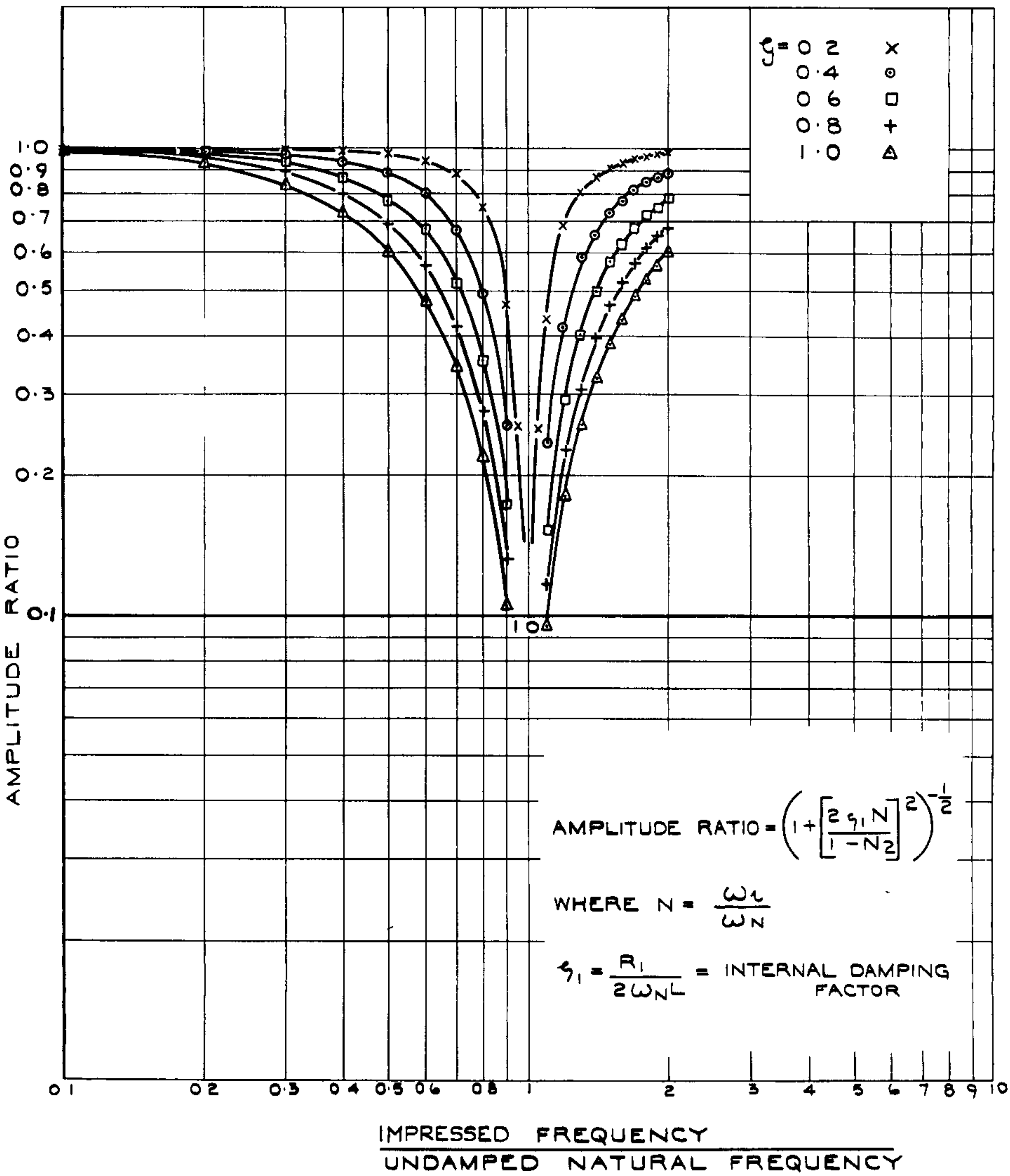


FIG. 18. RESPONSE OF A WINDVANE, WITH VARIOUS VALUES OF INTERNAL DAMPING, TO SINUSOIDAL INPUTS APPLIED TO ITS BODY.

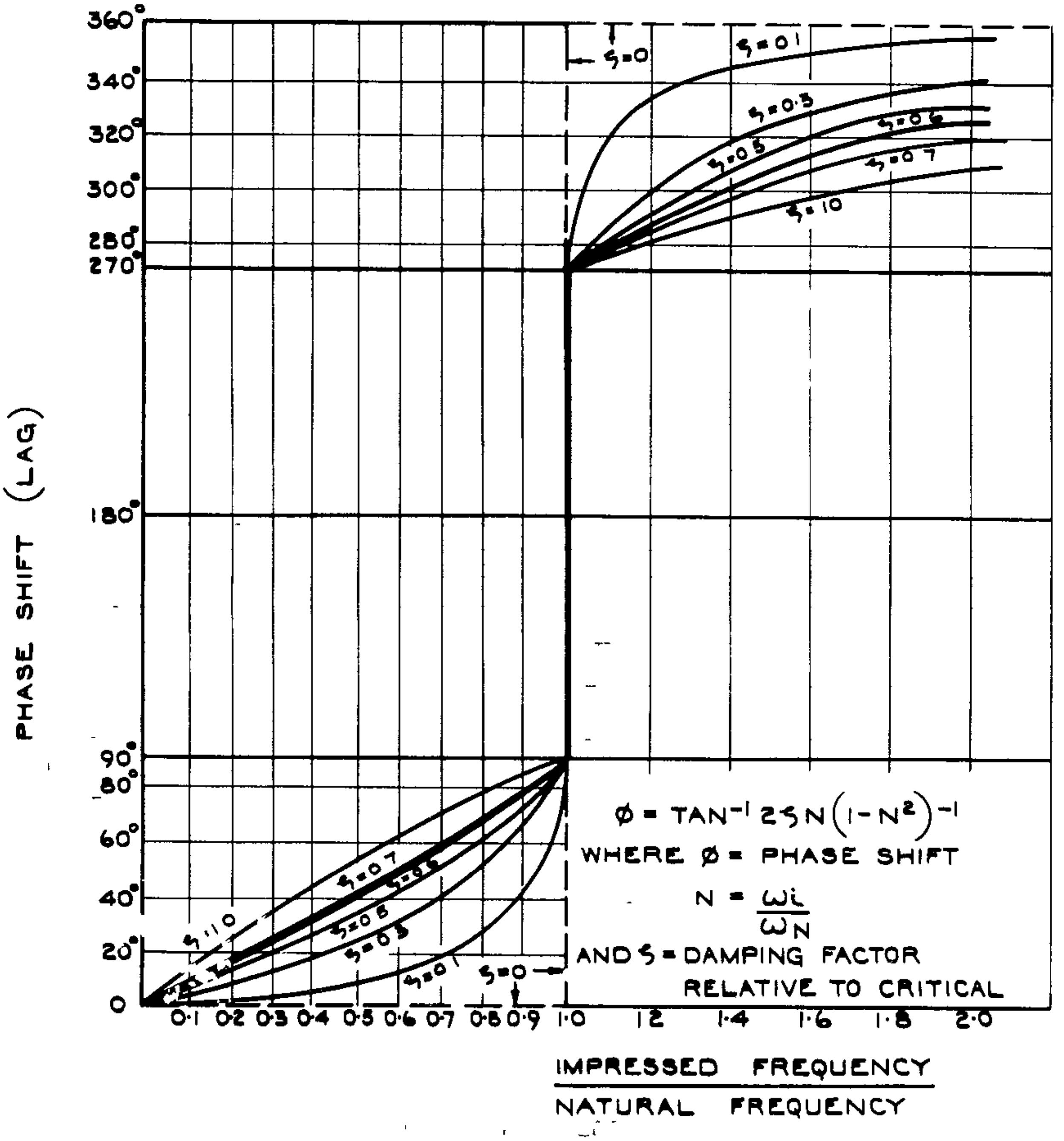


FIG. 19. VARIATION OF PHASE ANGLE WITH INTERNAL DAMPING OF A WINDVANE SUBJECTED TO SINUSOIDAL INPUTS ABOUT ITS BODY.

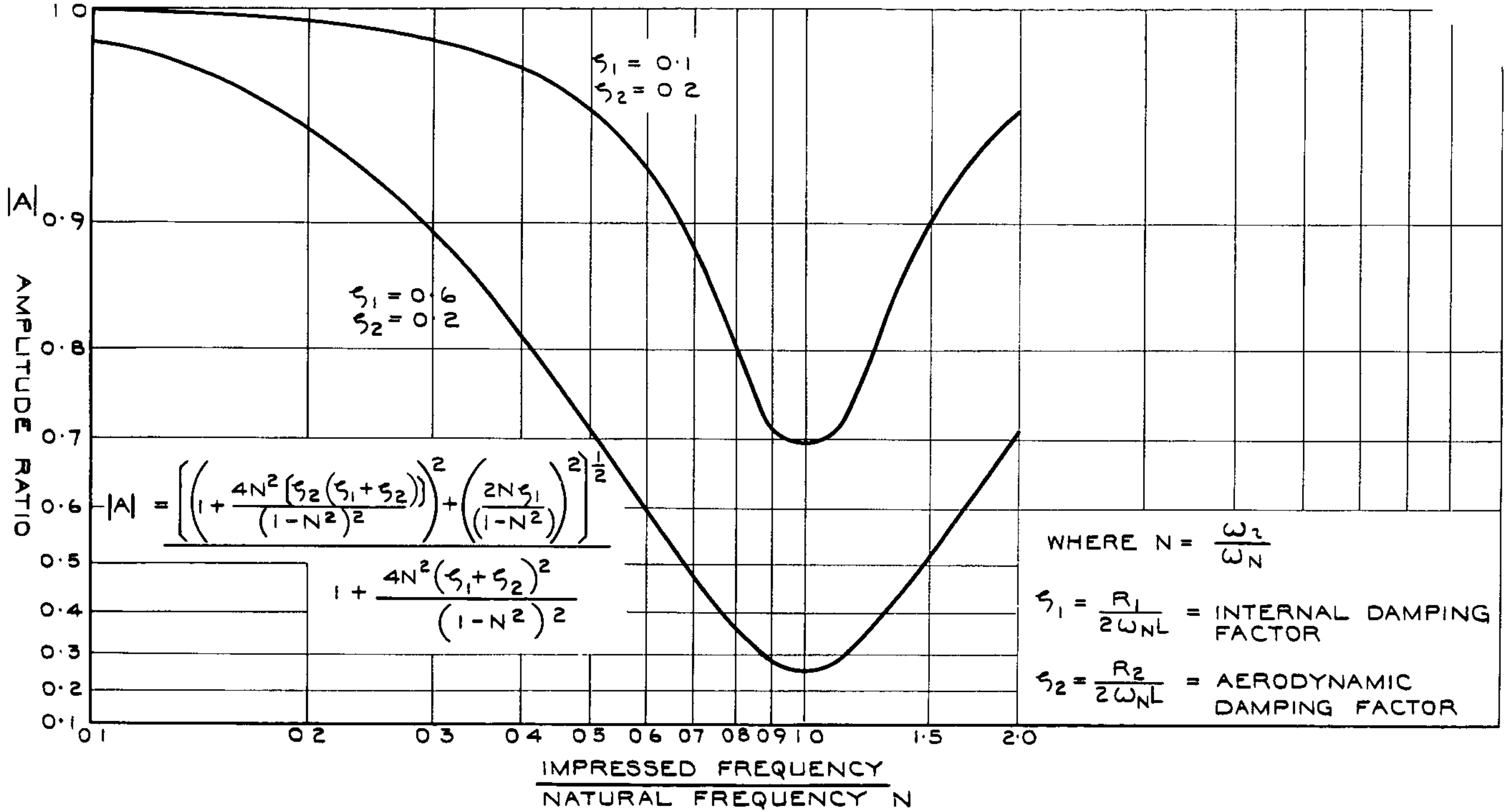


FIG 20. RESPONSES OF A WINDVANE, WITH CONSTANT AERODYNAMIC DAMPING OF 0·2 AND INTERNAL DAMPING OF 0·1 AND 0·6, TO SINUSOIDAL INPUTS APPLIED TO ITS BODY.

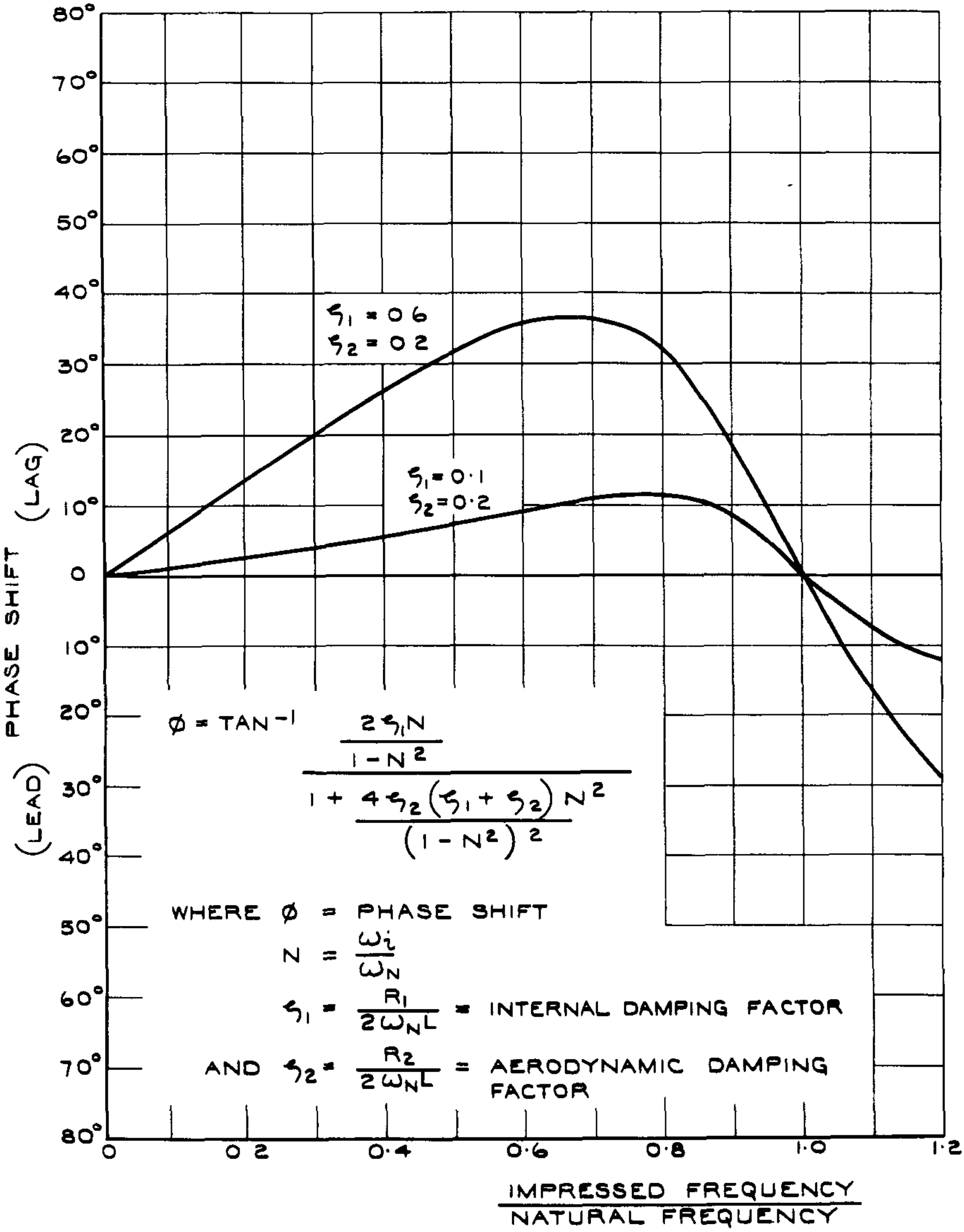


FIG. 21. VARIATIONS OF PHASE ANGLE OF A WINDVANE, HAVING CONSTANT AERODYNAMIC. DAMPING OF 0·2 AND INTERNAL DAMPING OF 0·1 AND 0·6, SUBJECTED TO SINUSOIDAL INPUTS ABOUT ITS BODY.

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