C.P. No. 652 C.P. No. 652 (1)

MINISTRY OF AVIATION

AERONAUTICAL RESEARCH COUNCIL

CURRENT PAPERS

The Static and Dynamic Response Properties of Incidence Vanes with Aerodynamic and Internal Viscous Damping

by

W. J. G. Pinsker

LONDON: HER MAJESTY'S STATIONERY OFFICE

1963

PRICE 3s 6d NET

U.D.C. No. 629.13.052.42 : 533.6.013.423 : 533.6.013.6

C.P. No.652

August, 1962

THE STATIC AND DYNAMIC RESPONSE PROPERTIES OF INCIDENCE VANES WITH AERODYNAMIC AND INTERNAL VISCOUS DAMPING

by

W. J. G. Pinsker

SUMMARY

The various contributions to the static position error of practical incidence vanes are briefly reviewed. The dynamic response of a windvane is shown to depend critically on the aerodynamic damping and viscous friction acting on the vane. It is also shown that the vane responds differently to incidences generated by gusts, aircraft plunging and by aircraft rotary motion. Frequency response formulae and graphs are given to illustrate some typical cases.

Replaces R.A.E. Tech. Note No. Aero 2833 - A.R.C. 24,245.

LIST OF CONTENTS

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS (CONTD.)

1 INTRODUCTION

The instrument most frequently used to measure the aerodynamic incidence (angles of attack and sideslip) of aircraft is the windvane. Designed to align itself with the local airflow, the vane in principle allows the incidence to be read directly as an angle and in this sense it may be considered as the ideal sensing element for the measurement of flow direction.

In practice, however, this ideal is much more difficult to achieve than one could suspect from such elementary considerations. Even for static measurements a number of "position errors" will unavoidably distort the actual readings of practical windvanes. Although primarily concerned with the dynamic response characteristics of incidence vanes, this paper will first briefly discuss the principal sources of static and quasi-static errors.

However even when full allowance is made for these static errors, the dynamic response of the vane may further distort the results, if dynamic phenomena are to be recorded. The vanes used in flight testing are usually so designed that their natural frequency is an order of magnitude greater than the frequencies of the stability modes of the aircraft so that these will be faithfully recorded. This may no longer be true, however, if the same vane is used to record gusts of much higher frequency or perhaps if it is installed on a relatively small flying object, such as a free flight model with relatively high frequencies of its natural responses.

In a recent publication G. J. Friedman[1] has pointed out some unexpected dynamic response characteristics of vanes with internal viscous damping. In the present investigation both internal damping and the aerodynamic damping supplied by the vane itself are considered.

Furthermore a distinction is made between incidence generated by rotary motion of the aircraft (say pitching or yawing), by translatory aircraft motion (heaving or plunging) and by gusts.

2 THE PRINCIPAL SOURCES OF STATIC AND QUASI-STATIC ERROR

In this section the principal contributions of the aircraft and of the vane support to the local incidence as sensed in practice by a windvane are briefly reviewed. Although it is generally realised that such errors are present, their potential magnitude is often not fully appreciated. As virtually all factors contributing to the so called position error normally are additive in the sense to make the vane over-read, the resulting total error has been known to reach values of almost 100% in not unduly careless installations.

2.1 The isolated vane assembly

The windvane as understood here is the complete vane assembly which comprises the actual vane with its mass-balance and the support, generally a cylindrical body, containing the bearings for the vane shaft and an electrical pick-up as illustrated in Fig. 1.

When at an incidence, i.e. in a cross flow $w = \alpha V$, the potential flow round the body of the instrument will increase the local cross flow velocity by an amount w_i which will be equal to w close to the cylinder and decrease rapidly as the distance from the body increases. This effect can be reduced by minimising the diameter of the instrument body and by increasing the distance of the vane from the support. As the magnitude of the above contribution to the position error can be readily determined in a wind tunnel it would appear unwise to compromise the vane design for this particular consideration.

The effects of flow interference induced by the vane support are, however, more embarrassing in supersonic flow, where the calibration of the vane must be expected to vary with Mach number. In Ref.2, a wind tunnel calibration is given of a supersonic incidence vane in current use. The principal results are reproduced in Fig.2. It should be noted that in this particular case, the vanes were mounted approximately halfway along the existing noseboom of an aircraft, which was relatively bulky and therefore may have contributed strongly to this position error. It has been suggested that these shortcomings of conventional incidence vanes in supersonic flow could be overcome by using, instead of a windvane, a cone freely pivoted at the head of a support sting.

As well as these aerodynamic sources of vane error, it is equally important to consider the effects of friction on the vane shaft. Although vanes are usually free from objectionable friction under laboratory conditions, flight test results invariably indicate the presence (for reasons which so far have not been adequately explored) of substantial friction. It is not uncommon to observe, apparently because of friction, lags in the response of vanes of up to 0.05 sec, clearly a prohibitive amount, even if relatively slow aircraft responses are recorded. It has frequently been found that static measurements fail to show an equivalent amount of friction-caused hysteresis. A possible explanation of this apparent inconsistency is as follows:

In steady conditions the level of vibrations in the aircraft may permit the vane to overcome the friction in jerks and finally reach the correct position. This same behaviour (also e.g. observed in the trailing motion of a rudder with circuit friction) would convert a basically solid type friction force into an apparent viscous type in dynamic measurements.

Although great improvements are being made at present to reduce or eliminate potentiometer friction, it must be emphasised that such refinements may be wasted if no corresponding attention is paid to bearing friction caused by aerodynamic loads.

2.2 The effects of the support boom on the vane

Another source of "position error" which is frequently overlooked is the aeroelastic distortion of the boom supporting the actual vane. At high indicated speeds this phenomenon has been estimated to contribute alone 20% to the overall position error. More complex still is the position if the inertia of the boom + vane assembly is considered as well so that we have to treat it as an oscillatory system. Further one must remember that the aircraft itself is an elastic structure, so that the vane will measure the incidence of the particular part of the airframe, to which it is attached and not strictly the quantity that is normally described as "incidence" or "sideslip".

2.3 Position error due to flow induced by aircraft

Whereas it should be possible to predict or calibrate on the ground the contributions to the position error discussed so far, the effect most commonly understood as the aerodynamic position error may be much more difficult to estimate. There are essentially three methods available to account for this position error. They are listed below in order of increasing reliability:

(i) theoretical estimate of the induced flow field in the vicinity of the vane location

(ii) flow survey on a wind tunnel model of the aircraft

(iii) static calibration in flight.

It is obvious that the latter technique can give by far the most accurate calibration not only of the aircraft induced position error but of all the errors discussed so far.

2.4 Kinematic position error

As windvanes cannot normally be mounted at the C.G. of the aircraft they sense in addition to the incidence proper (which is normally referred to the C.G. of the aircraft) flow components generated by the rotary motion of the aircraft. A full table of all the possible corrections that may be applicable to a particular vane - location is given in the A.G.A.R.D. Flight Test manual Vol.II Chapter 11:4(e). For instance an angle of attack vane, if mounted at a distance x feet ahead of the C.G. within the plane of symmetry, records pitching q as an incremental incidence,

$$\Delta\alpha = -\frac{qx}{V}, \qquad (1)$$

similarly, it senses rate of roll p if mounted outside the plane of symmetry, say y feet out on the starboard wing, as:

$$\Delta\alpha = \frac{py}{V}. \qquad (2)$$

These kinematic corrections can be fully eliminated from a flight record if the relevant aircraft rates of rotation are measured.

3 THE EQUATIONS OF MOTION OF A WINDVANE ATTACHED TO AN AIRCRAFT

In the following analysis we shall be investigating the dynamic response of a windvane to the various components of aerodynamic incidence which the aircraft experiences in flight. For simplicity of analysis the vane is assumed here to be free from position errors although it would be easy to take the static position error contributions into account when interpreting actual dynamic flight tests. May it suffice here to indicate that:

(i) aerodynamic position errors induced by the instrument body, and by the aircraft, and the kinematic position errors discussed in Section 2.4, are equivalent to what shall now be termed incidence generated by translatory motion (α_γ or β_χ)

(ii) quasi-steady position errors due to boom and aircraft elasticity are equivalent to incidences generated by aircraft rotary motion (α_θ or β_ψ).

Restricting the discussion now to the idealised case of a vane subject to no position error, and taking first angle of attack the vane senses incidences which may be generated in flight (Fig.3) by three distinct phenomena:

(i) angular rotation of the aircraft to give an incidence equivalent to angle of pitch

$$\alpha_\theta = \theta \qquad (3)$$

(ii) translatory motion of the aircraft $\dot{z}$ to give

$$\alpha_\gamma = -\gamma = -\frac{\dot{z}}{V} \qquad (4)$$

where γ is the angle of climb

(iii) gust with components normal to the surface of the vane, i.e.

$$\alpha_g = \frac{w_g}{V} . \qquad (5)$$

The total incidence sensed by the vane in the longitudinal plane is therefore

$$\alpha = \alpha_\theta + \alpha_\gamma + \alpha_g . \qquad (6)$$

In the lateral plane as illustrated in Fig.4 we get similarly:

$$\left.\begin{aligned} \beta_\psi &\equiv \psi \\ \beta_\chi &\equiv \chi = \frac{\dot{y}}{V} \\ \beta_g &\equiv \frac{v_g}{V} \end{aligned}\right\} \qquad (7)$$

and

$$\beta = \beta_\psi + \beta_\chi + \beta_g . \qquad (8)$$

These two cases are obviously identical and any results obtained for the longitudinal case can be applied to the lateral motion if we substitute

$$\left.\begin{aligned} -\beta_\psi &\text{ for } \alpha_\theta \\ -\beta_\chi &\text{ for } \alpha_\gamma \\ -\beta_g &\text{ for } \alpha_g . \end{aligned}\right\} \qquad (9)$$

Considering now the longitudinal case only, the response of a windvane with mass balance exposed to the airflow as shown in Fig.1 is described by the equation (Fig.5)

$$I(\ddot{\alpha}_\theta+\ddot{\delta}) - d_a(\dot{\alpha}_\theta+\dot{\delta}) - d_i\dot{\delta} - k(\alpha_\gamma+\alpha_g+\delta) = 0 \tag{10}$$

where δ = deflection of vane

$I = i_o^2 \frac{W}{g}$, vane inertia about pivot

$d_a = \frac{\partial M_a}{\partial \dot{\delta}}$, aerodynamic vane damping

$d_i = \frac{\partial M_i}{\partial \dot{\delta}}$, internal vane damping

$k = \frac{\partial M}{\partial \delta}$, weathercock stability of vane.

As the incidence due to aircraft translation α_γ and due to gust α_g are additive, they may be combined into the plunging incidence:

$$\alpha_z = \alpha_\gamma + \alpha_g \tag{11}$$

Equation (10) can be nondimensionalised to read

$$\ddot{\alpha}_\theta + \ddot{\delta} + 2\zeta_a\omega_n(\dot{\alpha}_\theta+\dot{\delta}) + 2\zeta_i\omega_n\dot{\delta} + \omega_n^2(\alpha_z+\alpha_\theta+\delta) = 0\,. \tag{12}$$

The aerodynamic and damping parameters can be obtained from the following expressions.

(i) The undamped natural frequency of the vane in rad/sec is,

$$\omega_n = \sqrt{-\frac{\partial M/\partial\delta}{I}} = 0.196\,\frac{V_i}{i_o/\ell}\sqrt{\frac{S}{W}\,\frac{a_1}{\ell}}\,. \tag{13}$$

(ii) The contribution to the damping due to the aerodynamic effect of the vane is,

$$\zeta_a = -\frac{\partial M_a/\partial\dot{\delta}}{2\,I\,\omega_n} = \frac{0.098}{i_o/\ell}\sqrt{\frac{\ell\,a_1\,\sigma}{W/S}}\,. \tag{14}$$

(iii) The contribution to the damping provided by viscous friction in the instrument:

$$\zeta_i = -82.1 \frac{\partial M_i/\partial \dot{\delta}}{V_i \ell^2} \left(\frac{\ell}{i_o}\right) \sqrt{\frac{\ell}{W a_1 S}} \tag{15}$$

where W = weight of vane

S = area of vane surface

ℓ = distance of centre of pressure of the vane from pivot

a_1 = lift slope of vane surface

i_o = inertia radius of vane

σ = relative density.

The natural frequency of the vane ω_n is proportional to equivalent air speed. It can be shown that this is also true over a wide range of flight conditions of the high frequency modes of the aircraft oscillation in yaw and in pitch. Consequently a windvane will tend to work at a fixed frequency ratio when recording these aircraft modes.

The inherent aerodynamic damping when expressed as a damping ratio of the vane is independent of speed but reduces with increasing altitude.

The relative damping provided by a mechanical damper is inversely proportional to equivalent air speed.

4 FREQUENCY RESPONSE OF WINDVANE TO AIRCRAFT INCIDENCE

It has been shown that the aerodynamic incidence, which a windvane senses, can be separated into two kinematically distinct components. α_θ or (β_ψ) results from angular displacement of the aircraft and α_z or (β_y) can be generated by either aircraft plunging or by normal gusts or by a combination of both. The response of the vane of these two different types of input differs, so they are treated separately.

4.1 Aircraft rotary motion

Assuming α_z to be zero in equation (12) and assuming

$$\alpha_\theta = \alpha_{\theta_o} e^{i\omega t} \tag{16}$$

the response of the vane δ to α_θ can be obtained by substituting

$$\delta = \delta_o e^{i\omega t} \tag{17}$$

into equation (12). This gives the frequency response expression,

$$\frac{\delta_o}{\alpha_{\theta_o}} = - \frac{1 + \dfrac{4\zeta_a(\zeta_a+\zeta_i)\left(\dfrac{\omega}{\omega_n}\right)^2}{(1-(\omega/\omega_n)^2)^2} - i\,\dfrac{2\zeta_i\,\dfrac{\omega}{\omega_n}}{1-\left(\dfrac{\omega}{\omega_n}\right)^2}}{1 + \left\{\dfrac{2(\zeta_a+\zeta_i)\,\dfrac{\omega}{\omega_n}}{1-\left(\dfrac{\omega}{\omega_n}\right)^2}\right\}^2} . \tag{18}$$

The modulus of this complex expression gives the amplitude ratio,

$$\left|\frac{\delta_o}{\alpha_{\theta_o}}\right| = \frac{\sqrt{\left\{1 + \dfrac{4\zeta_a(\zeta_a+\zeta_i)\left(\dfrac{\omega}{\omega_n}\right)^2}{\left[1-\left(\dfrac{\omega}{\omega_n}\right)^2\right]^2}\right\}^2 + \left\{\dfrac{2\zeta_i\,\dfrac{\omega}{\omega_n}}{1-\left(\dfrac{\omega}{\omega_n}\right)^2}\right\}^2}}{1 + \left\{\dfrac{2(\zeta_a+\zeta_i)\;\omega/\omega_n}{1-\left(\dfrac{\omega}{\omega_n}\right)^2}\right\}^2} , \tag{19}$$

and the phase angle between δ and α_θ is given by

$$\tan \varepsilon_{\delta\to\alpha_\theta} = - \frac{\dfrac{2\zeta_i\left(\dfrac{\omega}{\omega_n}\right)}{1-\left(\dfrac{\omega}{\omega_n}\right)^2}}{1 + \dfrac{4\zeta_a(\zeta_a+\zeta_i)\left(\dfrac{\omega}{\omega_n}\right)^2}{\left(1-\left(\dfrac{\omega}{\omega_n}\right)^2\right)^2}} . \tag{20}$$

With aerodynamic damping only, $\zeta_i = 0$ and equations (19) and (20) reduce to

$$\left|\frac{\delta}{\alpha_\theta}\right| = 1.0 \tag{21}$$

and

$$\varepsilon_{\delta\to\alpha_\theta} = 0 . \tag{22}$$

The windvane without mechanical damping therefore indicates the correct value of α_θ over the full frequency range.

For the other extreme with instrument damping only ($\zeta_a = 0$) equations (19) and (20) have been computed for the range of the parameters $0 < \omega/\omega_n < 2$ and $0 < \zeta_i < 1$. The resulting frequency response diagram is shown in Fig. 6. Although, as pointed out elsewhere, windvanes are normally used only to record aerodynamic phenomena at frequencies well below the natural frequency of the vane, the frequency response diagrams presented in this note cover the range up to 2 ω_n, i.e. for most applications a quite unrealistic range.

In Fig. 7 the results are given for a vane with fixed internal damping ($\zeta_i = 0.5$) and a range of values of aerodynamic damping. In Fig. 8 a case is considered where aerodynamic damping is fixed ($\zeta_a = 0.2$) and mechanical instrument damping is varied.

4.2 Aircraft plunging motion or gusts

Assuming no aircraft rotation ($\alpha_\theta = 0$) the response of a vane to incidence created either by a translatory motion of the aircraft or by normal gusts, α_z, is obtained by assuming

$$\alpha_z = \alpha_{z_o} e^{i\omega t} \tag{23}$$

and substituting also in equation (12),

$$\delta = \delta_o e^{i\omega t}. \tag{24}$$

This gives the frequency response equation

$$\frac{\delta_o}{\alpha_{z_o}} = - \frac{1 - i \dfrac{2(\zeta_a+\zeta_i) \frac{\omega}{\omega_n}}{1 - \left(\frac{\omega}{\omega_n}\right)^2}}{\left(1 - \left(\frac{\omega}{\omega_n}\right)^2\right)\left(1 + \left\{\dfrac{2(\zeta_a+\zeta_i) \frac{\omega}{\omega_n}}{1 - \left(\frac{\omega}{\omega_n}\right)^2}\right\}^2\right)} \tag{25}$$

or in terms of amplitude ratio and phase angle

$$\left|\frac{\delta_o}{\alpha_{z_o}}\right| = \frac{1}{\sqrt{\left\{1 - \left(\frac{\omega}{\omega_n}\right)^2\right\}^2 + \left\{2(\zeta_a+\zeta_i) \frac{\omega}{\omega_n}\right\}^2}} \tag{26}$$

and

$$\tan \varepsilon_{\delta \to \alpha_z} = - \frac{2(\zeta_a + \zeta_i) \frac{\omega}{\omega_n}}{1 - \left(\frac{\omega}{\omega_n}\right)^2} . \qquad (27)$$

Equations (25)-(27) are identical to those for a conventional second order system if $(\zeta_a + \zeta_i) = \zeta$ is taken as the total damping. The corresponding response diagrams are given in Fig. 9.

5 NUMERICAL EXAMPLE

As a typical example, the incidence vane used at present for high speed testing at the R.A.E. is considered. The approximate principal dimensions for this instrument are:

S	=	$0.007\ ft^2$	vane area
W	=	0.035 lb	weight of vane assembly
i_o/ℓ	=	0.8	relative inertia radius
ℓ	=	0.14 ft	vane arm
a_1	=	2.0	vane lift slope

internal damping is not provided.

From equations (13) and (14) the natural frequency and the aerodynamic damping are obtained as:

$$\omega_n = 0.40\ V_i \text{ rad/sec}$$

or the period

$$T = \frac{2\pi}{\omega_n} = \frac{15.6}{V_i} \text{ sec}$$

and

$$\zeta_a = 0.029 \sqrt{\sigma} .$$

For an aircraft of the Hunter type the period of the dutch roll oscillation is of the order of

$$T_\psi = \frac{1500}{V_i} \text{ sec}$$

and the period of the high frequency pitching oscillation of the order of

$$T_\theta = \frac{750}{V_i} \text{ sec.}$$

If the above vane is used to record these aircraft modes it will work at a relative frequency of

$$\frac{\omega}{\omega_n} = \frac{15.6}{1500} \approx \frac{1}{100}$$

for the lateral case, and at

$$\frac{\omega}{\omega_n} = \frac{15.6}{750} \approx \frac{1}{50}$$

for the pitching case. Obviously for this application the windvane defined above measures without any noticeable dynamic error.

However if the same vane is used to measure gusts on an aircraft flying at a given speed the maximum frequencies that can be measured are limited if the maximum permissible error is specified. Ignoring position errors, the limiting relative frequencies can be obtained from Fig. 9 and then,

$$\text{maximum frequency, } f_{max} = \left(\frac{\omega}{\omega_n}\right)_\Delta \frac{V_i}{15.6} \,[\sec^{-1}] .$$

For a vane with negligible damping $(\zeta_a+\zeta_i) = 0$, at two aircraft speeds V_i = 310 ft/sec and 620 ft/sec, these maximum frequencies are, for given error limits,

Maximum error	$\left(\frac{\omega}{\omega_n}\right)_\Delta$	V_i = 310 ft/sec maximum frequency c.p.s.	V_i = 620 ft/sec maximum frequency c.p.s.
5%	0.225	4.45	8.90
10%	0.3	6.0	12.0
20%	0.41	8.2	16.4

In particular at low speeds the dynamic response of the vane can therefore significantly limit the range of data it will reliably record.

Another application where the performance of this vane may be expected to be unsatisfactory is the measurement of the stability modes of a small scale free flight model. Assuming that the aircraft mentioned previously is scaled down by a factor of 20, the frequencies of the corresponding modes of motion of the model will be increased by the same factor at a given speed. The vane will then be working within the range of relative frequency $\frac{1}{2.5} < \frac{\omega}{\omega_n} < \frac{1}{5}$. Fig. 9 shows that the component of the flight incidence resulting from the translatory motion of the model will be measured with an error of between 20% and 4%, if one assumes negligible vane damping.

It is interesting to note that a windvane used exclusively for the recording of gusts (when phase is not important) could be made satisfactory by providing mechanical damping to approximately 0.7 of critical.

However at the same time the pitching response of the aircraft (see Fig. 6) would be grossly misread by this vane at relative frequencies significantly greater than $\frac{\omega}{\omega_n} = 0$.

For incidence measurements on small scale models for the same reason internal damping would be most detrimental to the faithful recording of the stability modes.

6 DISCUSSION

It has been shown that there are many potential sources contributing to the overall static "position error" of an incidence vane installed on an aircraft and that care has to be taken to reduce these to an acceptable magnitude. The best method to account for these effects is a flight calibration, which is strongly advised if vanes are to be used for accurate measurements.

Friction within the vane assembly is another potential source of inaccuracy which will mainly affect the recording of dynamic phenomena.

The dynamic response characteristics of incidence vanes are affected by aerodynamic damping (as generated by the vane itself) and by mechanical damping, which will normally be generated by friction and in certain cases may be deliberately introduced into the vane by a viscous damper.

Vanes have been shown to respond in a distinctly different manner to the two kinematic components into which the quantity normally summarised as incidence (or sideslip) can be separated. One is generated by rotary aircraft motion, i.e. by pitching or yawing, the other by translatory motion (i.e. plunging or heaving) of the aircraft.

In general dynamic effects will diminish when the natural frequency of the vane, ω_n, is increased in relation to the frequencies of the flight phenomena to be recorded. This fundamental consideration suggests that one should choose vanes with small dimensions and inertias. When vanes are used on relatively small aircraft such as small scale free flight models it may become necessary to consider the frequency response of the vane more seriously. This is of course also true even for measurements on larger aircraft if there is significant friction in the vane.

When considering the use of incidence vanes for the measurement of gusts it is interesting to observe that for this purpose the addition of internal viscous damping may be advantageous. In fact in common with general instrument practice, approximately 0.7 of critical damping would appear to give the most truthful recording of amplitudes for gust frequencies up to the natural frequency of the vane. At the same time for frequencies near ω_n the corresponding pitching response of the aircraft (see Fig. 8) will be largely ignored by such a vane.

This example of a possible unorthodox application of the results of the present study shows that vane design, assembly and operation must be carefully tailored to the particular purpose of the investigation.

7 CONCLUSIONS

The conventional incidence vane has been shown to respond differently to the various aircraft modes and to gusts. Whereas for the measurement of aircraft stability a vane without damping is more suitable, for the measurement of gusts, a vane with a high degree of internal damping may have advantages. However, care has to be taken to minimise, and calibrate incidence vanes for, the various contributions to the position error, and also to reduce friction before the potential accuracy of this type of instrument is realised.

LIST OF SYMBOLS

$a_1 = \frac{\partial C_L}{\partial \alpha}$	lift slope of vane block
$d = \frac{\partial M}{\partial \dot{\delta}}$	damping of vane
$i_o = \sqrt{\frac{I}{W} g}$	inertia radius of vane assembly
I	inertia of vane assembly
$k = \frac{\partial M}{\partial \delta}$	restoring moment of vane
ℓ	distance of centre of pressure of vane from pivot
M	moment about vane pivot
S	area of vane blade
V	airspeed
V_i	indicated airspeed
W	weight of vane assembly
α	incidence
β	angle of sideslip
δ	deflection of vane
γ	aircraft angle of climb
χ	aircraft flight path azimuth angle
ζ	damping ratio
ω rad/sec	frequency
ω_n rad/sec	natural frequency of vane
θ	aircraft attitude
ψ	aircraft yaw

LIST OF REFERENCES

No.	Author	Title, etc.
1	Friedman, G.J.	Frequency response analysis of the vane type angle of attack transducer. Aero/Space Engineering. 18(3) March. 1959, 69-75.
2	Dee, F. Mabey, G.	Wind tunnel calibration of incidence vanes for use on the Fairey E.R.103. A.R.C. 23,611. September, 1961.

WT.2078.C.P.652.K3 - Printed in England

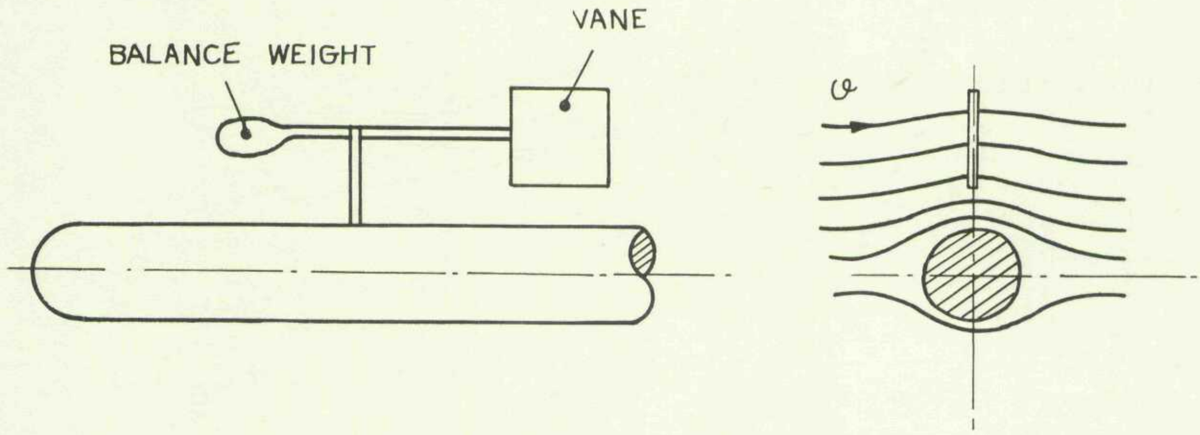


FIG. 1. VANE FOR MEASURING INCIDENCE IN THE POTENTIAL FLOW FIELD OF THE VANE SUPPORT

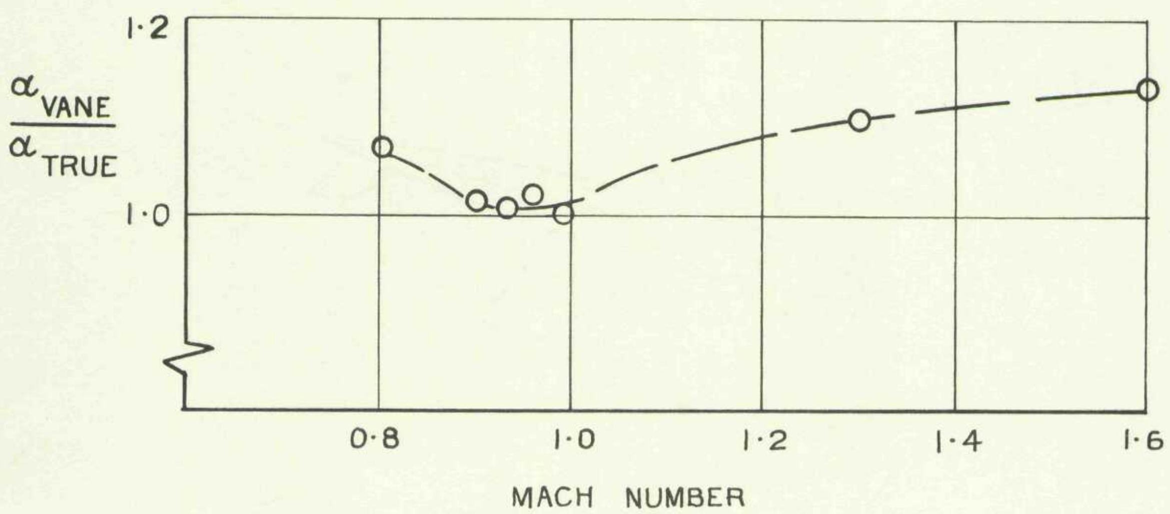
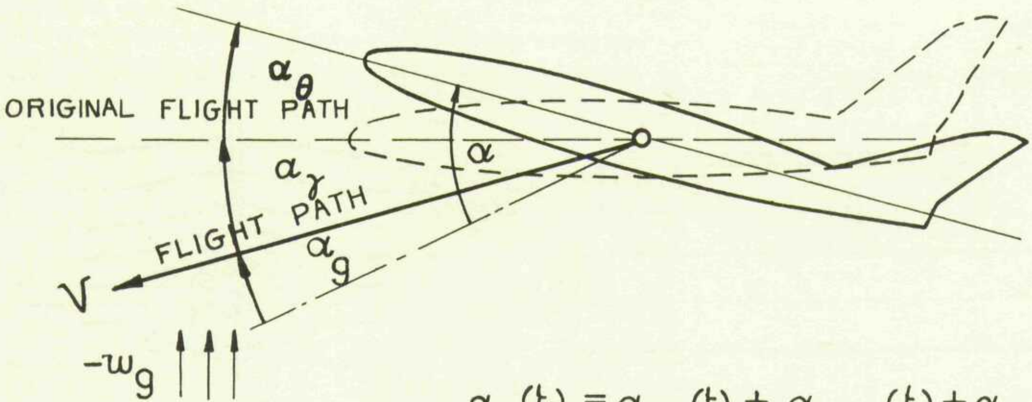


FIG. 2. FROM REF. 2. CALIBRATION OF THE SENSITIVITY OF A CRUCIFORM ASSEMBLY OF INCIDENCE VANES IN A SUPERSONIC WIND TUNNEL



$$\alpha\ (t) = \alpha_\theta\ (t) + \alpha_\gamma\ (t) + \alpha_g\ (t)$$

FIG. 3. THE THREE COMPONENTS OF INCIDENCE GENERATED ON AN AIRCRAFT IN FREE FLIGHT (ONLY POSITIVE ANGLES ARE SHOWN)

$$\beta\ (t) = \beta_\psi\ (t) + \beta_\gamma\ (t) \mp \beta_g\ (t)$$

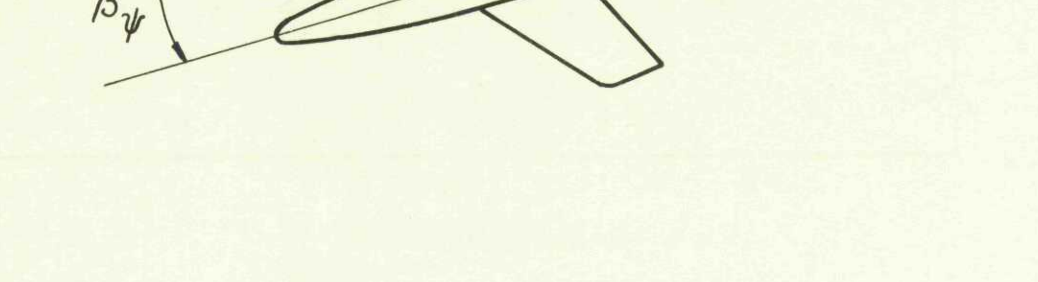


FIG. 4. THE THREE COMPONENTS OF SIDESLIP GENERATED ON AN AIRCRAFT IN FREE FLIGHT (ONLY POSITIVE ANGLES ARE SHOWN)

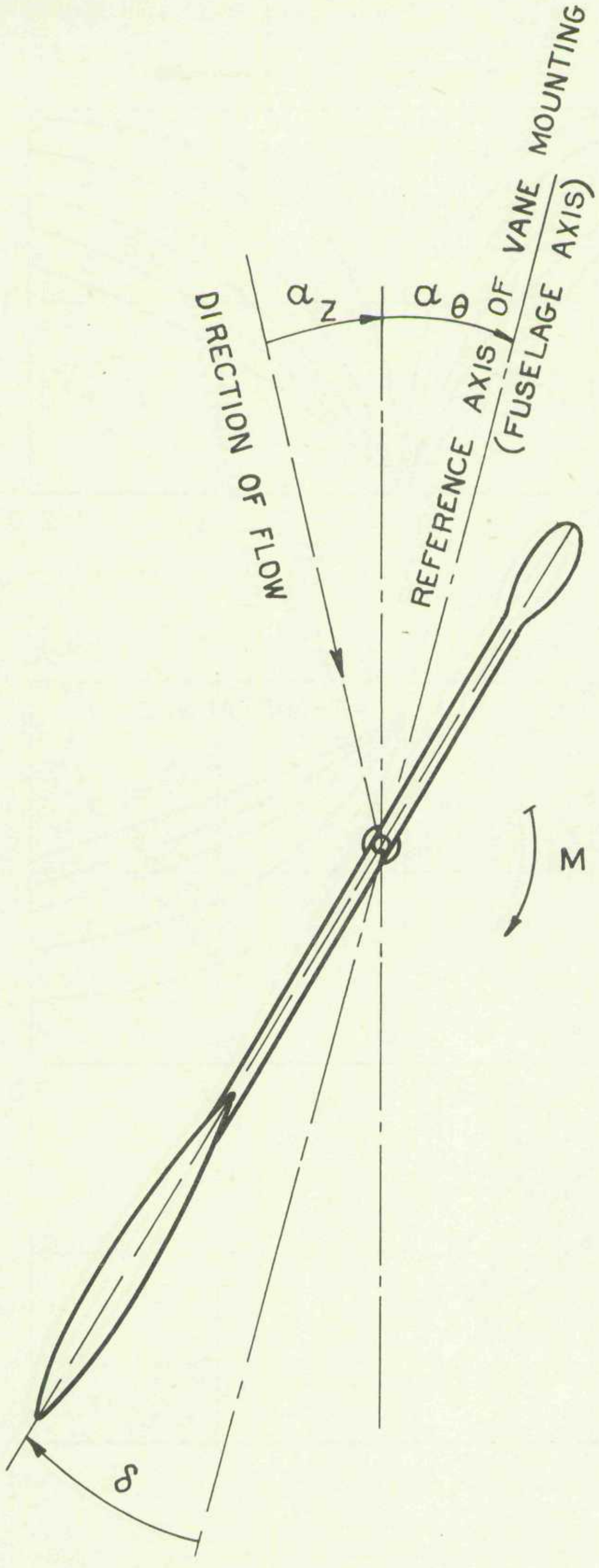


FIG. 5. DEFINITIONS OF ANGLES RELEVANT TO THE RESPONSE OF A WIND VANE TO INCIDENCE OR SIDESLIP

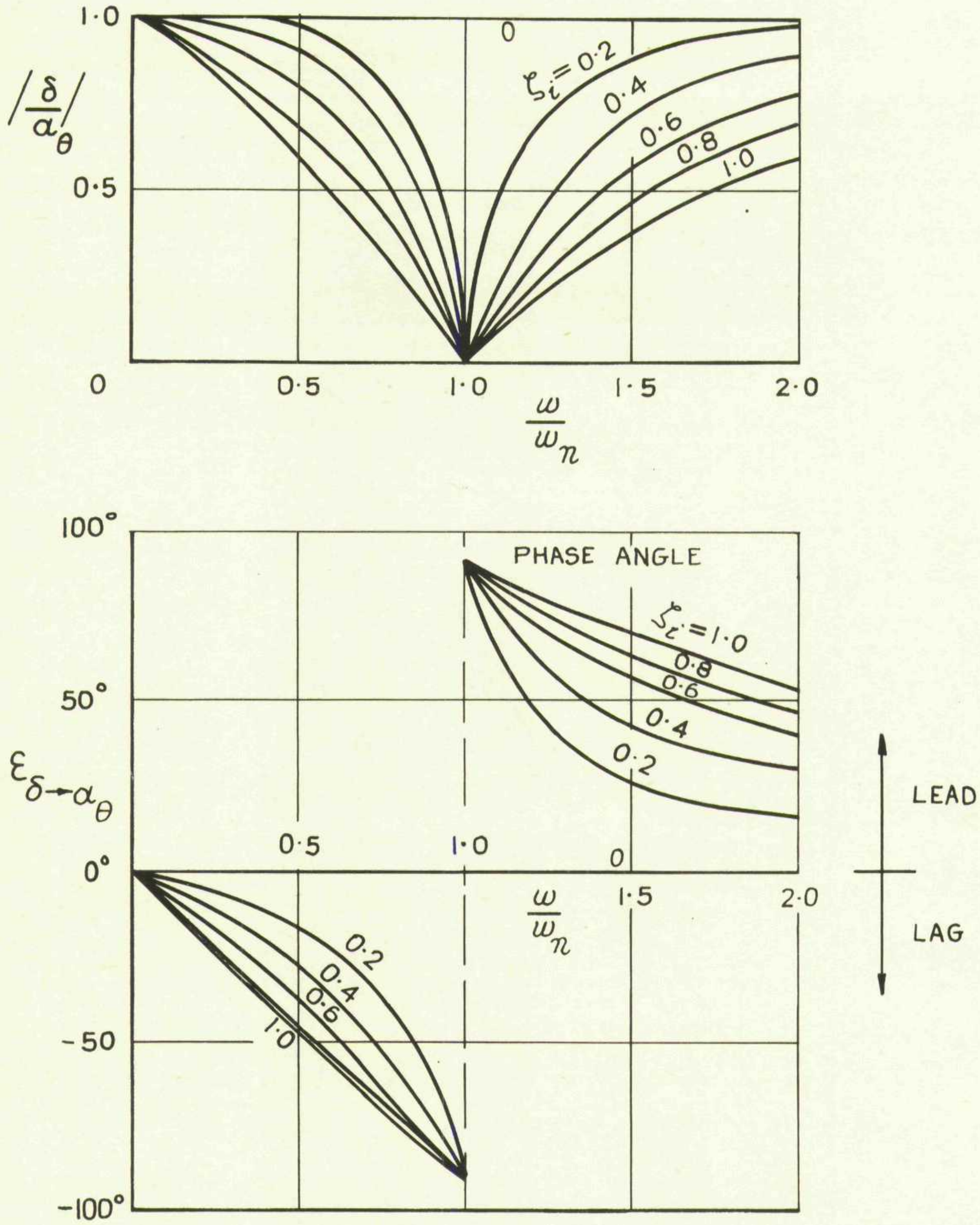


FIG 6. FREQUENCY RESPONSE OF WINDVANE WITH INTERNAL DAMPING (ζ_i) ONLY TO INCIDENCE GENERATED BY ROTARY AIRCRAFT MOTION (α_θ) OR (β_ψ)

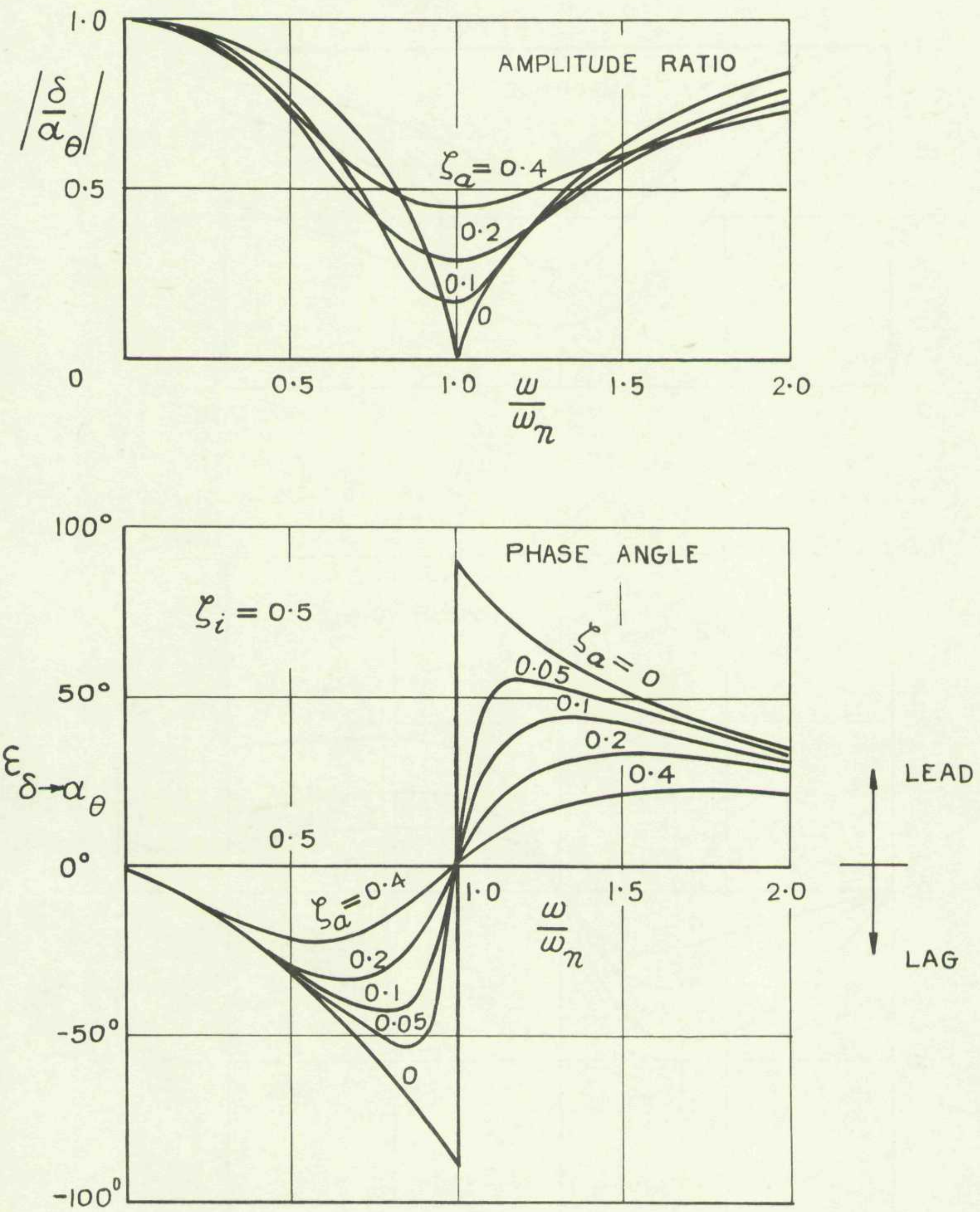


FIG. 7. FREQUENCY RESPONSE OF WINDVANE WITH CONSTANT INTERNAL DAMPING ($\zeta_i = 0.5$) AND VARIABLE AERODYNAMIC DAMPING TO INCIDENCE PRODUCED BY ROTARY AIRCRAFT MOTION

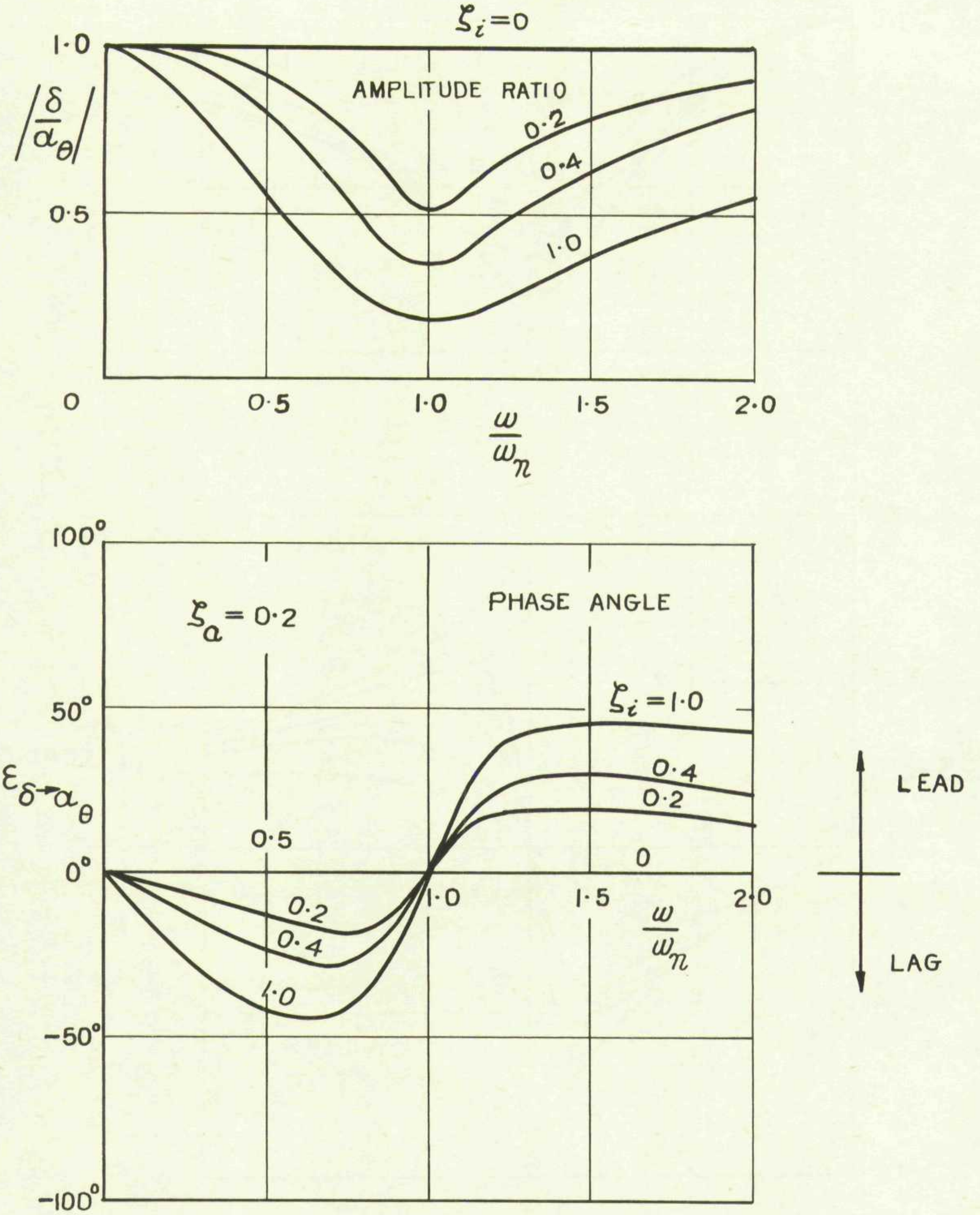


FIG. 8. FREQUENCY RESPONSE OF WINDVANE WITH CONSTANT AERODYNAMIC DAMPING ($\zeta_a = 0 \cdot 2$) AND VARIABLE INTERNAL DAMPING TO INCIDENCE PRODUCED BY ROTARY AIRCRAFT MOTION

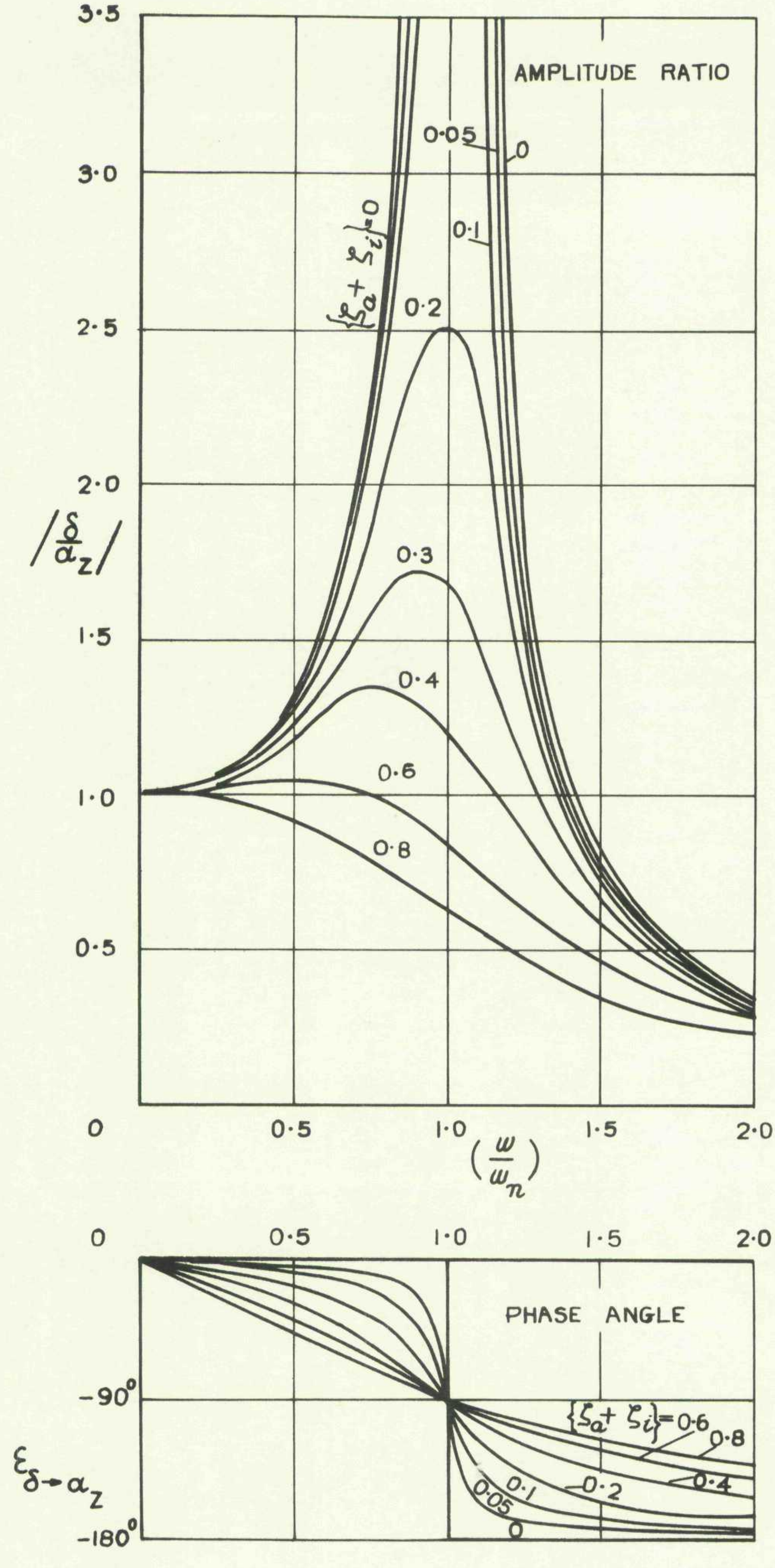


FIG. 9. FREQUENCY RESPONSE OF WINDVANE WITH AERODYNAMIC AND INTERNAL DAMPING, TO INCIDENCE PRODUCED BY AIRCRAFT PLUNGING MOTION α_Z OR BY GUSTS

A.R.C. C.P. No.652

629.13.052.42:
533.6.013.423:
533.6.013.6

THE STATIC AND DYNAMIC RESPONSE PROPERTIES OF INCIDENCE VANES WITH AERODYNAMIC AND INTERNAL VISCOUS DAMPING. Pinsker, W.J.G. Aug. 1962.

The various contributions to the static position error of practical incidence vanes are briefly reviewed. The dynamic response of a windvane is shown to depend critically on the aerodynamic damping and viscous friction acting on the vane. It is also shown that the vane responds differently to incidences generated by gusts, aircraft plunging and by aircraft rotary motion. Frequency response formulae and graphs are given to illustrate some typical cases.

A.R.C. C.P. No.652

629.13.052.42:
533.6.013.423:
533.6.013.6

THE STATIC AND DYNAMIC RESPONSE PROPERTIES OF INCIDENCE VANES WITH AERODYNAMIC AND INTERNAL VISCOUS DAMPING. Pinsker, W.J.G. Aug. 1962.

The various contributions to the static position error of practical incidence vanes are briefly reviewed. The dynamic response of a windvane is shown to depend critically on the aerodynamic damping and viscous friction acting on the vane. It is also shown that the vane responds differently to incidences generated by gusts, aircraft plunging and by aircraft rotary motion. Frequency response formulae and graphs are given to illustrate some typical cases.

A.R.C. C.P. No.652

629.13.052.42:
533.6.013.423:
533.6.013.6

THE STATIC AND DYNAMIC RESPONSE PROPERTIES OF INCIDENCE VANES WITH AERODYNAMIC AND INTERNAL VISCOUS DAMPING. Pinsker, W.J.G. Aug. 1962.

The various contributions to the static position error of practical incidence vanes are briefly reviewed. The dynamic response of a windvane is shown to depend critically on the aerodynamic damping and viscous friction acting on the vane. It is also shown that the vane responds differently to incidences generated by gusts, aircraft plunging and by aircraft rotary motion. Frequency response formulae and graphs are given to illustrate some typical cases.

A.R.C. C.P. No.652

629.13.052.42:
533.6.013.423:
533.6.013.6

THE STATIC AND DYNAMIC RESPONSE PROPERTIES OF INCIDENCE VANES WITH AERODYNAMIC AND INTERNAL VISCOUS DAMPING. Pinsker, W.J.G. Aug. 1962.

The various contributions to the static position error of practical incidence vanes are briefly reviewed. The dynamic response of a windvane is shown to depend critically on the aerodynamic damping and viscous friction acting on the vane. It is also shown that the vane responds differently to incidences generated by gusts, aircraft plunging and by aircraft rotary motion. Frequency response formulae and graphs are given to illustrate some typical cases.

C.P. No. 652

Published by
HER MAJESTY'S STATIONERY OFFICE

To be purchased from
York House, Kingsway, London w.c.2
423 Oxford Street, London w.1
13A Castle Street, Edinburgh 2
109 St. Mary Street, Cardiff
39 King Street, Manchester 2
50 Fairfax Street, Bristol 1
35 Smallbrook, Ringway, Birmingham 5
80 Chichester Street, Belfast 1
or through any bookseller

Printed in England

S.O. CODE No. 23-9013-52

C.P. No. 652