Wind-Tunnel Measurement of Dynamic Cross-Coupling Derivatives

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An oscillatory apparatus and the associated data-reduction procedure for routine measurement of the 12 static and dynamic moment derivatives due to pitching and yawing have been developed. The list of derivatives includes some dynamic cross-coupling derivatives, which have never been systematically measured before. It was therefore considered desirable to develop an independent calibration system to verify the basic principles of the method and to confirm the validity of the data-reduction procedure used. A three-degrees-of-freedom dynamic calibrator was constructed, with which the aerodynamic moments in pitch, yaw, and roll could be simultaneously simulated. The moments were induced electromagnetically, at the same frequency as that of the primary motion, but with an arbitrary amplitude and arbitrary phase relative to the primary motion. The calibrator was used, with most satisfactory results, to verify the experimental method and the associated data analysis.

Introduction

A NOVEL experimental technique to determine cross and cross-coupling moment derivatives has been developed at the National Aeronautical Establishment in the last few years.[1,2] This technique emerged as a result of the increasing recognition that coupling terms between the longitudinal and lateral degrees of freedom of an aircraft may be significant under some flight conditions where asymmetric flow exists, as in the case of flight at high angles of attack and nonzero sideslip angle.

The apparatus and instrumentation described in Ref. 1 have been substantially modified to improve the mechanical characteristics of the balance-support system, as well as to automate the data processing and to adapt the experimental procedure to continuous wind-tunnel applications.

This paper describes the new apparatus, the associated instrumentation system, and the modified data-reduction procedure. For the sake of completeness it was found desirable to include some of the material from Ref. 1. The paper also contains a description of a special calibrating system that was developed to verify both the validity of the experimental method and the various aspects of the data-reduction procedure. Typical results from the calibration tests and from a series of wind-tunnel experiments conducted at NASA Ames Research Center are also presented. For a more complete discussion of the theoretical basis of the technique and of the experimental results the reader is referred to Ref. 3.

Description of Derivative Apparatus

The apparatus consists of a dynamic balance mounted on a sting and supporting the model, as shown in Fig. 1. The balance has two basic parts: 1) an elastic model suspension unit capable of providing deflections in the three angular degrees-of-freedom, viz., in pitch, yaw, and roll, and 2) a model-driving mechanism. Elastic constraint in yaw and roll is provided by two cruciform flexures, whereas that in pitch is obtained with a cross-flexure pivot and two cantilever beams.

The apparatus provides a primary oscillatory motion in pitch with resulting secondary oscillatory motions in yaw and roll. Alternatively, with the balance rotated 90 deg in roll with respect to both the model and support, a primary oscillatory motion is achieved in yaw with resulting secondary oscillatory motions in pitch and roll.‡ In each case, the torque, the amplitude, and the frequency of the primary motion, as well as the in-phase and quadrature components of the two secondary motions with respect to the primary motion, are measured.

A set of two experiments is required to obtain, from the in-phase and quadrature components of the two secondary motions, a complete set of four static cross and cross-coupling derivatives ($C_{m\beta}$, $C_{n\alpha}$, $C_{l\alpha}$, and $C_{l\beta}$) and four dynamic cross and cross-coupling derivatives ($C_{mr} - C_{m\dot\beta}\cos\alpha_0$, $C_{nq} + C_{n\dot\alpha}$, $C_{lq} + C_{l\dot\alpha}$ and $C_{lr} - C_{l\dot\beta}\cos\alpha_0$). The same two experiments also provide a complete set of direct, one-degree-of-freedom derivatives, i.e. the two static derivatives $C_{m\alpha}$ and $C_{n\beta}$, and the two damping derivatives $C_{mq} + C_{m\dot\alpha}$ and $C_{nr} - C_{n\dot\beta}\cos\alpha_0$.§ This latter information is obtained from the torque, amplitude, and frequency characteristics of the primary motion, using standard methods of data reduction. All derivatives are defined in the body system of axes and represent the aerodynamic moments due to small deflections and small rates of change of the deflections from a nominal angle of attack α_0 and a nominal angle of sideslip β_0.

The oscillatory motion is provided by an electromagnetic drive mechanism that consists of two semicircular permanent magnets anchored to the supporting sting and a rigid, high-current (up to 50 A), single-turn coil attached to the balance and free to move within the air gaps between the magnets. The coil is driven by an amplitude-stabilizing feedback system.

The resonant frequencies in the three degrees-of-freedom are determined by the inertia characteristics of the model and the stiffness of the corresponding elastic members. For a given model, a set of cantilever springs has to be selected in such a way that the primary resonant frequency is as far away from the two secondary resonant frequencies as possible. Failure to observe that requirement may result in excessive amplitudes of the secondary motions and a reduced accuracy of the experiments. If this condition is observed, the actual relation between the two secondary frequencies is relatively

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‡"Primary" and "secondary" are used here instead of "forcing" and "forced" employed in Refs. 1 and 2.

§The aerodynamic symbols are the same as those used in Ref. 3.

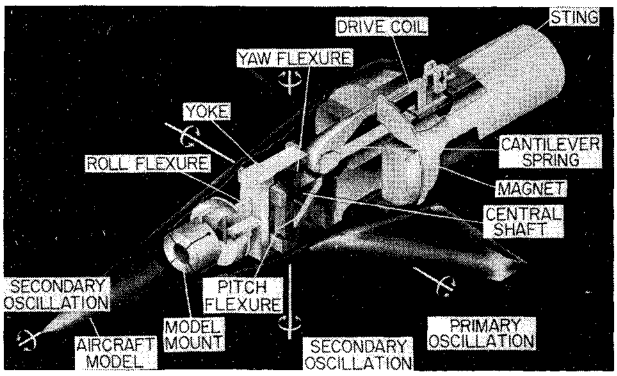

Fig. 1 Cut-away view of balance and drive mechanism (model mounted for oscillation in pitch).

unimportant. If necessary, all three frequencies can be adjusted by modifying the inertia characteristics of the model.

Instrumentation

The signals corresponding to the angular deflections in the secondary degrees of freedom are obtained from strain-gage bridges mounted on cruciform flexures. However, the gages in the plane of the primary motion are mounted on the two cantilever springs that provide part of the stiffness in that degree-of-freedom. Semi-conductor gages are employed for the sensing of the two secondary motions to improve the signal-to-noise ratio of the pertinent output signals, which usually represent amplitudes of the order of a tenth of a degree only. Furthermore, the vertical and lateral accelerations ($\ddot{z}$ and $\ddot{y}$) are sensed by means of accelerometers mounted on the sting at a station inside the model.

A special effort was made, with considerable success, to minimize the induced and common-mode noise by using balanced lines in conjunction with suitable shielding and grounding techniques. These precautions are particularly important in view of the large current at the critical frequency flowing through the driving coil, which is unavoidably located near the sensing elements. The signals are nonetheless contaminated by noise of aerodynamic origin to such an extent that conventional filters are ineffective for the extraction of the necessary information.

However, the small amplitude of the mechanical oscillation of the model warrants the assumption that, for a given model attitude, the system is linear around its equilibrium position, in which case the pertinent components of the secondary motions are sinusoidal and of the same frequency as that of the primary motion. The a priori knowledge of the nature of these motions allows the use of more sophisticated signal extraction methods to obtain the information necessary for the eventual determination of aerodynamic derivatives. Figure 2 shows a block diagram of the system used to acquire the pertinent data. The system is based on four pairs of lock-in amplifiers capable of extracting signals, coherent with a reference one, that are deeply buried in noise. The signal corresponding to the primary displacement can be used as the reference by virtue of its high signal-to-noise ratio. Thus the in-phase and quadrature components of the secondary motions and accelerations with respect to the primary motion can be determined.

The instrumentation associated with the determination of direct derivatives consists of a driving-current monitor, frequency counter, RMS/DC converter, analog divider, and phasemeter, all of which are used as in the well-known single-degree-of-freedom experiments.

All the signals of interest are digitized and then processed on an off-line basis using a programmable-calculator-based data acquisition system.[4] The data processing is completely automatic, including tabulating and plotting of the final results immediately after each series of runs.

Data Analysis

The method chosen to obtain cross and cross-coupling derivatives involves oscillatory experiments in which a primary oscillation is imparted to the system at the natural frequency in that degree-of-freedom and any resulting in-phase and quadrature components of the deflections of the secondary motions are measured. The deflections are converted into moments (in the case of angular deflections considered here), and the cross and cross-coupling derivatives are determined from the relation between secondary moments, primary deflections or angular velocities, and the appropriate phase angles. This is a direct method in the sense that there exists a physical quantity associated with every aerodynamic reaction to be measured; the method also has the

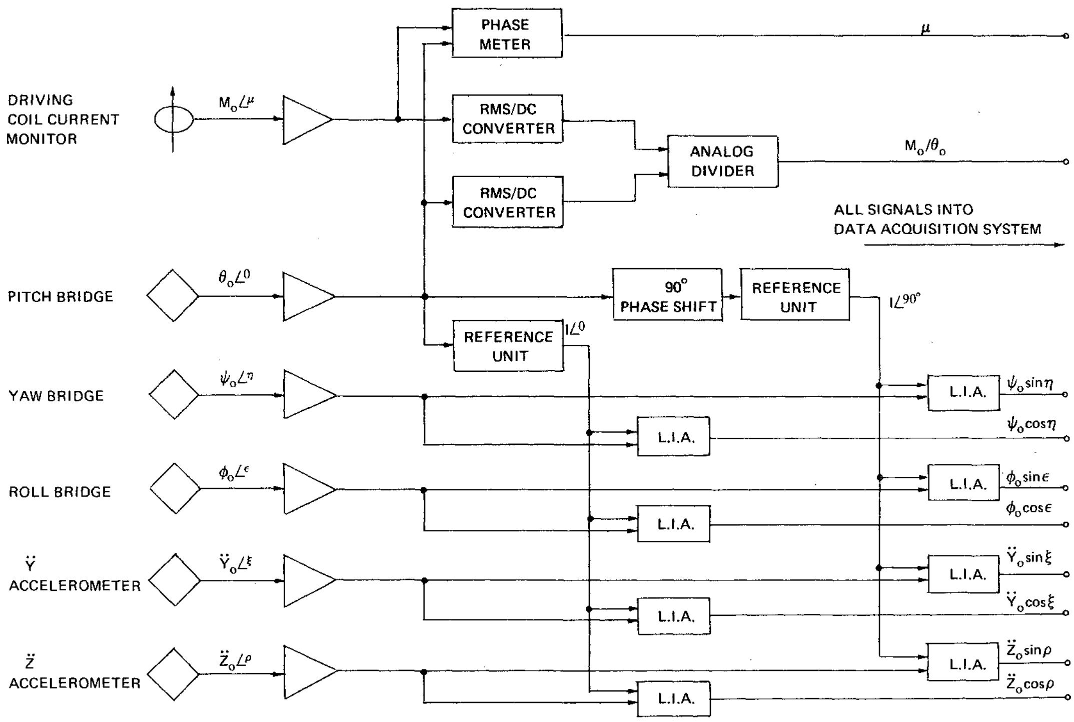

Fig. 2 Instrumentation system.

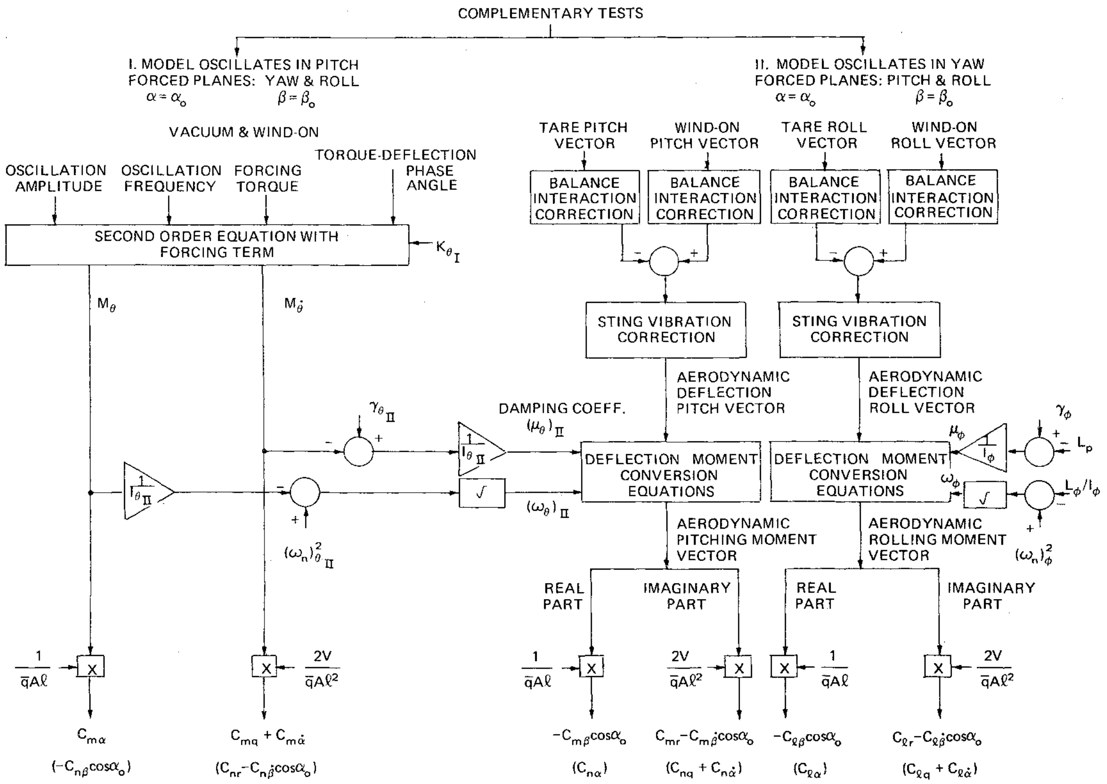

Fig. 3 Wind-tunnel data-reduction flowchart (all vectors referred to primary deflection).

advantage of not requiring any information on the products of inertia of the system.

The flow diagram describing the data reduction is given in Fig. 3, which shows a pair of so-called "complementary tests" required for obtaining the direct derivatives due to pitching and cross and cross-coupling derivatives due to yawing. Another pair of such complementary tests would result from applying procedure I to oscillation in yaw and procedure II to oscillation in pitch, leading to the determination of the direct derivatives due to yawing and cross-coupling derivatives due to pitching (shown in brackets). Thus, for each model attitude a complete set of moment derivatives due to yawing and pitching can be obtained from two experiments: one involving oscillation in pitch and the other oscillation in yaw. Each experiment provides sufficient data to determine the direct derivatives in the plane of the primary motion and part of the information necessary for the determination of the pertinent cross and cross-coupling derivatives.

Procedure I employs standard methods of single-degree-of-freedom constant-amplitude oscillation to yield the direct aerodynamic derivatives, such as M_θ and $M_{\dot\theta}$. These derivatives are calculated from the following equations:

$$M_\theta = M_\alpha = -I_\theta(\omega^2 - \omega_a{}^2) - \left[\left|\frac{M_T}{\theta}\right|\cos\lambda - \left|\frac{M_T}{\theta}\right|_a \cos\lambda_a\right]$$

$$M_{\dot\theta} = M_q + M_{\dot\alpha} = -\left[\left|\frac{M_T}{\theta}\right|\frac{\sin\lambda}{\omega} - \left|\frac{M_T}{\theta}\right|_a \frac{\sin\lambda_a}{\omega_a}\right]$$

where subscript a refers to tare conditions and λ is the phase angle between the driving torque M_T and the displacement θ. I_θ is the moment of inertia around the pitch axis and ω is the (circular) frequency. Derivatives M_θ and $M_{\dot\theta}$ are also required for the determination of the corresponding cross and cross-coupling derivatives, as discussed below.

In procedure II, the sinusoidal time variations (coherent with the primary oscillation) of the secondary angular deflections are represented by tare and wind-on vectors. All phases are referred to the primary deflection. The subtraction of the tare vectors from the wind-on vectors gives the "aerodynamic deflection vectors," representing the angular deflections caused solely by aerodynamic moments due to the primary motion.

These aerodynamic deflection vectors are assumed to represent the response of a second-order system to an excitation by sinusoidal aerodynamic moments synchronous with the primary motion. To compute the cross and cross-coupling derivatives involved, the aerodynamic deflection vectors must first be converted into these aerodynamic moments and then resolved into in-phase and quadrature components relative to the primary motion. Considering, for example, the secondary oscillation in pitch caused by a primary oscillation in yaw, $\psi = |\psi|\cos\omega t$, the equation of motion can be written as

$$\ddot\theta + \mu_\theta\dot\theta + \omega_\theta{}^2\theta = |(\bar M/I_\theta)|\cos(\omega t + \eta_\theta)$$

where the damping coefficient μ_θ and the wind-on natural frequency in pitch ω_θ are, respectively,

$$\mu_\theta = \frac{\gamma_\theta - M_{\dot\theta}}{I_\theta} \qquad \omega_\theta = \left[(\omega_n)_\theta^2 - \frac{M_\theta}{I_\theta}\right]^{1/2}$$

and where $\bar M$ is the aerodynamic moment in pitch – the magnitude and phase of which are to be determined – and t is time.

The direct aerodynamic derivatives M_θ and $M_{\dot\theta}$ are obtained from the complementary test with the model oscillating in pitch, and the mechanical characteristics of the system – such as the moment of inertia I_θ, the damping constant γ_θ, and the tare natural frequency $(\omega_n)_\theta$ – are determined by separate calibration tests, *with the model mounted for the oscillation-in-yaw experiment* (as denoted by subscript II in Fig. 3).

The conversion of the aerodynamic pitch deflection vector θ into the aerodynamic moment in pitch $\bar M$ is accomplished by considering the equations for amplification and phase shift in a second-order forced-oscillation system (see, e.g., Ref. 5), leading to the following expressions:

$$|\bar{M}| = |\theta| \cdot I_\theta \left[(\omega_\theta^2 - \omega^2)^2 + \mu_\theta^2 \omega^2 \right]^{1/2}$$

$$\angle (\bar{M} - \theta) = \epsilon_\theta = \arctan \frac{\mu_\theta \omega}{\omega_\theta{}^2 - \omega^2}$$

In turn, the phase angle between $\bar{M}$ and ψ is determined from

$$\angle (\bar{M} - \psi) = \eta_\theta = \angle (\theta - \psi) + \epsilon_\theta$$

where $\angle (\theta - \psi)$ is the measured phase angle between θ and ψ.

The static and dynamic cross-coupling derivatives of the pitching moment due to yawing are finally obtained as

$$C_{m\psi} = -C_{m\beta}\cos\alpha_0 = \frac{1}{\bar{q}S\bar{c}} \frac{\partial \bar{M}}{\partial \psi} = \frac{1}{\bar{q}S\bar{c}} \frac{|M|\cos\eta_\theta}{|\psi|}$$

$$C_{mr} - C_{m\dot{\beta}}\cos\alpha_0 = \frac{1}{\bar{q}S\bar{c}} \cdot \frac{2V}{b} \frac{\partial M}{\partial \dot{\psi}} = \frac{2V}{\bar{q}S\bar{c}b} \frac{|\bar{M}|\sin\eta_\theta}{\omega|\psi|}$$

The above expressions are identical to those in Ref. 1, except for the additional factor of $\cos\alpha_0$, by which $C_{m\dot{\beta}}$ is now multiplied and which was inadvertently omitted in Ref. 1.

Similar expressions and procedures are used for the reduction of data to obtain the two cross-coupling derivatives of the yawing moment due to pitching, and to obtain all four cross and cross-coupling derivatives of the rolling moment due to both yawing and pitching; the derivatives involved are indicated in Fig. 3, where the cross-coupling derivatives due to pitching are shown in brackets and must be obtained by applying procedure II to *primary oscillation in pitch*.

The above data-reduction procedure is based on the assumption that the aerodynamic interactions between the two secondary motions are negligible and that the primary motion is not affected by the two secondary motions. This assumption is considered realistic by virtue of the very high stiffness in the planes of the two secondary motions which results in secondary amplitudes that are small both in an absolute sense and relative to the primary amplitude. This is particularly true with regard to the component of the secondary motion that is coherent with the primary one. Mechanical and electrical interactions, obtained from the static balance calibration, are taken into account by means of a first-order correction. Furthermore, since vertical and lateral accelerations ($\ddot{z}$ and $\ddot{y}$) may induce moments in the secondary degrees-of-freedom due to the presence of pertinent products of inertia of the moving system, a correction for this effect was incorporated in the data-reduction procedure. The corresponding acceleration effect in the primary degree-of-freedom appeared to be very small for the present experimental setup and was therefore neglected.

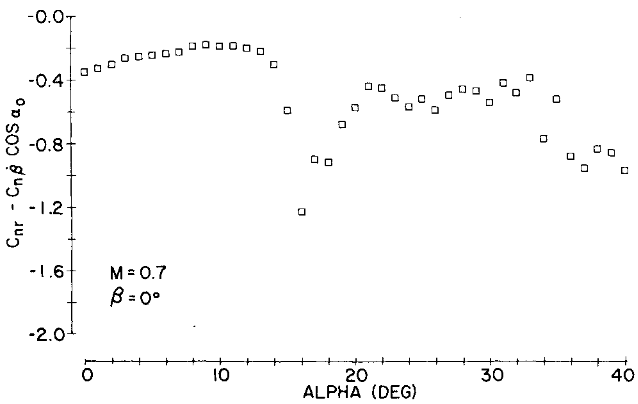

Fig. 4 Damping-in-yaw derivative.

It can be seen in Fig. 3 that procedure II requires the input of the direct aerodynamic derivatives due to rolling, namely L_p and L_ϕ. Only approximate values of these derivatives are needed since L_ϕ enters as a relatively small correction of the mechanical stiffness in roll, $(\omega_n)_\phi^2 I_\phi$, and the combined effect of L_p and the mechanical damping in roll γ_ϕ on the conversion from deflection to moment is small.

Figures 4 and 5 show examples of dynamic direct and cross-coupling derivatives, respectively, obtained with this apparatus in the NASA Ames 6×6-ft wind tunnel at a Mach number of 0.7. Similar information on the other derivatives may be found in Refs. 2 and 3. As already pointed out in these references, some of the preliminary results in Ref. 1 have been found erroneous and should be disregarded.

Verification of Experimental Method

The method described in the previous section is new and based on certain assumptions that need to be confirmed. In view of the absence of data on some of these never-before-measured derivatives, it has been deemed necessary to develop a calibrating technique that can corroborate the validity of the approach in an independent fashion.

The following assumptions used in the cross and cross-coupling derivative determination need to be verified:

1) Mechanical and electrical interactions of the primary motion on the secondary outputs are proportional to the primary oscillation amplitude only and can therefore be eliminated by means of tare measurements.

2) Aerodynamic interactions among the secondary degrees-of-freedom are negligible by virtue of the small amplitude (<0.1 deg) of the secondary motions. This is particularly applicable to the coherent component of the secondary motions with respect to the primary one. Effects of these on the primary output are neglected for the same reason.

3) On the basis of assumptions 1 and 2, it is assumed that the mechanical system behaves independently in each of the three degrees-of-freedom, the response in each one of them

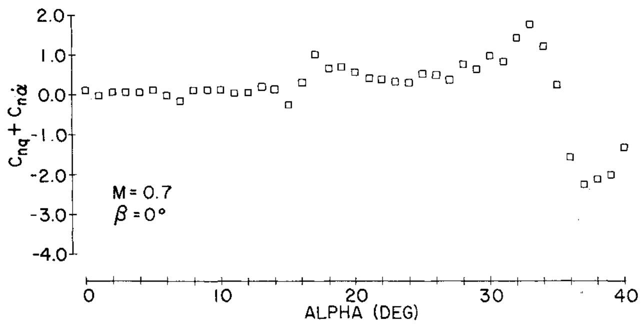

Fig. 5 Dynamic derivative of the yawing moment due to pitching.

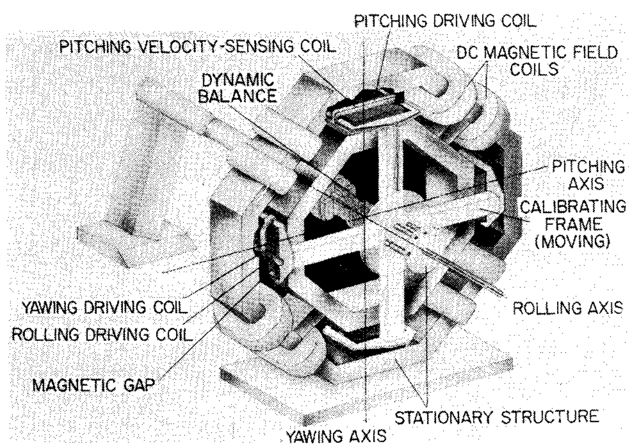

Fig. 6 Pictorial view of calibrator.

being describable by a linear one-degree-of-freedom second-order equation of motion. However, since the primary deflection is small, it is assumed that the aerodynamically induced moments in the three degrees-of-freedom are of the same frequency as that of the primary motion, in which case the responses of interest must also be coherent with that motion.

The above assumptions are the basis for the deflection-to-moment conversions that lead to the determination of the derivatives. A verification system based on an electromagnetic calibrator has therefore been developed. This system provides suitable, *accurately known moments* in the three degrees-of-freedom, such that a comparison between these moments and those resulting from the application of a slightly modified version of the aerodynamic data-reduction procedure to the induced deflections can provide a measure of the validity of the complete experimental technique and its analytical basis.

Description and Operation of Calibrator

The operation of the three-degrees-of-freedom calibrator is based on the application of electromagnetically generated moments to a calibration frame mounted on the dynamic balance and subjected to an oscillatory motion in the primary plane. The applied moments are coherent with the primary motion and their amplitude and phase can be adjusted to represent a wide range of aerodynamic parameters.

Figure 6 shows a simplified pictorial drawing of the calibrator. It consists of two concentric, octagonally shaped, stationary structures that form a magnetic circuit necessary to establish a dc magnetic field across four air gaps located on the horizontal and vertical axes of symmetry of the octagons.

In addition to the stationary structure, there is a floating cruciform-shaped calibration frame that is mounted on the dynamic balance which, to assure mechanical reproducibility, is mounted on the same sting-support system as normally used in wind-tunnel testing. The outer ends of the four arms of the calibration frame support single-turn driving coils located within the four air gaps. The necessary moments are obtained by passing suitable alternating currents through the driving coils, which thus interact with the surrounding magnetic field. Since the calibration frame must be able to move in three rotational degrees-of-freedom (θ, ψ, and ϕ), the calibrator must have spherical symmetry about the point in the balance where the three axes intersect. This requires the magnetic fields across the gap to be radially oriented. The orientation is achieved by spherically shaping the pole pieces. Likewise, the driving coils are curved to preserve the necessary angular relationship between the currents and magnetic field.

Since the applied moments must have arbitrary phase relationships with respect to the primary motion, the driving currents are synthesized from the deflection and angular velocity (90 deg apart for a sinusoidal motion) in the primary plane. The velocity is sensed directly by means of conductors moving within the magnetic field so as to induce electromotive forces proportional to their velocity.

Since the effectiveness of the calibrator depends on the accuracy of the applied moments, it is necessary to determine them in terms of the easily measurable driving currents. Such a determination could possibly be performed analytically; however, the difficulty of accurately including the effect of fringing outside the air gaps renders this approach unacceptable. In its stead, the driving-current-to-moment transfer functions were experimentally determined by applying accurately known dc currents to the driving coils and measuring the induced moments by means of the static calibration of the balance. It is important to note that this approach does not contradict the principle on which this apparatus rests – namely that of using the outputs of the system (which originate from the balance) as the basis for the analytical determination of the applied moments. The fact that during calibration the moments are known because of the outputs of the balance is acceptable solely because of the static nature of this calibration. Therefore, this fact does not conflict with the dynamic principle of operation of the apparatus.

Although no theoretical reason appeared to justify the presence of interactions between applied moments, e.g., yawing or rolling moments when only an applied moment in pitch is imposed, the absence of such interactions was deemed to be essential for the proper operation of the system. An experimental determination of these quantities proved that this requirement was satisfied.

Furthermore, it was found that the alignment between the stationary and moving parts of the calibrator was not very critical – a situation to be expected in view of the geometry involved and nature of the magnetic field in the air gaps. It is possible, therefore, to use the calibrator without prior complex alignment procedures. The positioning of the calibrating frame on the balance, however, is more critical since it directly affects the generation of applied pitching-yawing moment interactions.

Verification Procedure and Data Reduction

The verification procedure is quite analogous to an actual wind-tunnel test and is, therefore, handled in a similar fashion as that employed in aerodynamic experiments. In the verification tests the model is substituted by the calibrating frame and the aerodynamic moments are simulated by electromagnetically induced ones. Both "tare" and "wind-on" measurements are taken, i.e., in the absence and presence of applied moments, respectively.

Since it is not viable to use a calibrating frame that exactly reproduces the inertial characteristics of a given model, the verification procedure is generally performed in the presence of different resonant frequencies than those associated with the model. This procedure does not lead to a direct calibration in the sense of obtaining input-output transfer functions. Rather, a verification of the approach employed, under the specific set of conditions present during the "calibration" test, is obtained. Since the ratios between the various resonant frequencies are usually closer to unity in the "calibration" experiment than in the wind-tunnel experiment, the verification obtained must be considered conservative, i.e., an even better agreement between the input and measured moments can be expected for the conditions of the wind-tunnel experiment.

Once the "philosophy" of the method has been verified, the calibrator is still needed to ensure that all interaction corrections have been accounted for and that the data evaluation program contains no errors. In general, the calibrator provides an overall evaluation of the system performance.

The symmetry of the calibrating frame obviates the need for separate pitching and yawing oscillations. Likewise, under calibration conditions the damping and stiffness in the secondary degrees-of-freedom are of mechanical origin only and thus eliminate the need for aerodynamic terms in the deflection-to-moment conversions.

To avoid the uncertainties associated with large amplification factors and their high vectorial rates of change with respect to frequency, it is desirable to select resonant frequency ratios between the primary and secondary degrees-of-freedom as remote from unity as possible. The nature of the calibrating frame used limited the fulfillment of this requirement to ratios of 0.67 and 0.83 for pitch/yaw and pitch/roll, respectively. These values are indeed not ideal, but did nonetheless permit the obtaining of good results. It is important to note that the corresponding values for the wind-tunnel tests reported in Ref. 2 were 0.67 and 0.45, respectively, thereby rendering the test conditions more favorable for accurate deflection-to-moment conversions.

Calibration Results

Initially, only moments in one degree-of-freedom were applied, resulting in the polar plots shown in Figs. 7-9. As

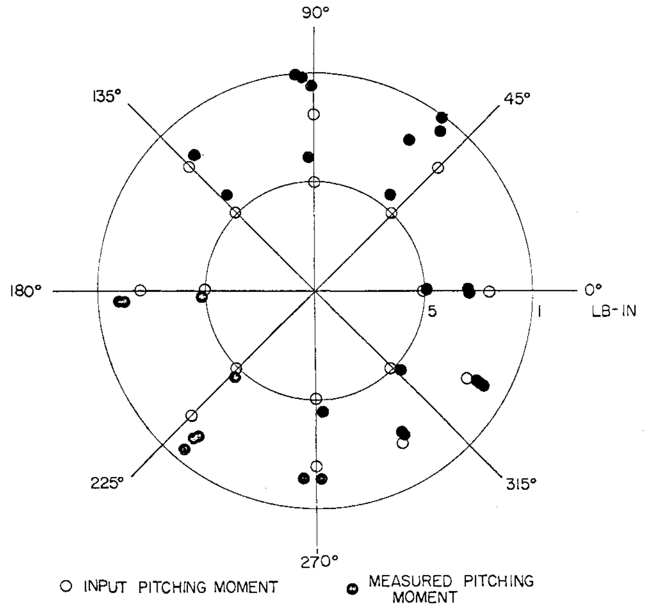

Fig. 7 Comparison between applied and measured pitching moments.

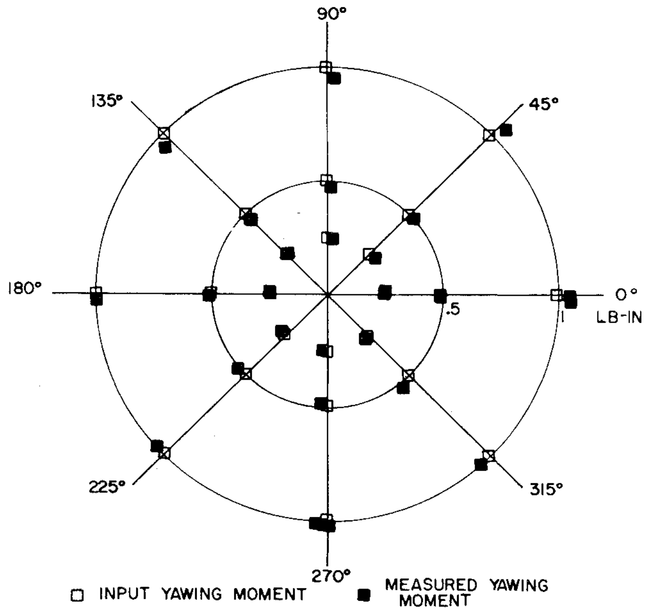

Fig. 8 Comparison between applied and measured yawing moments.

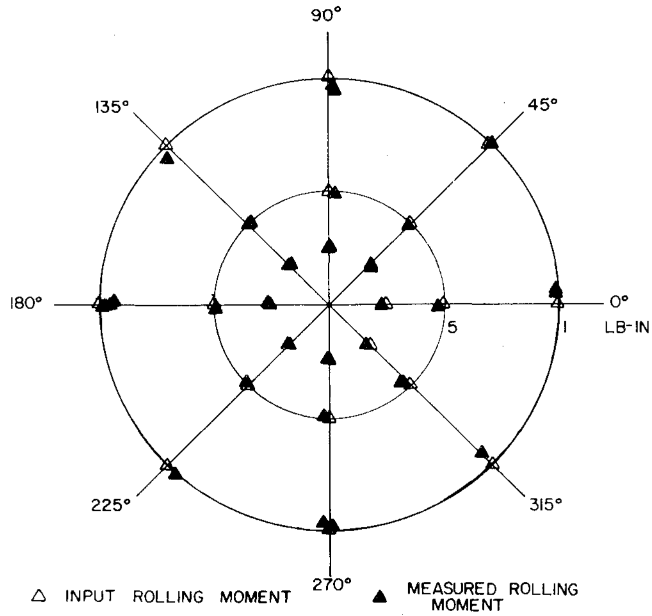

Fig. 9 Comparison between applied and measured rolling moments.

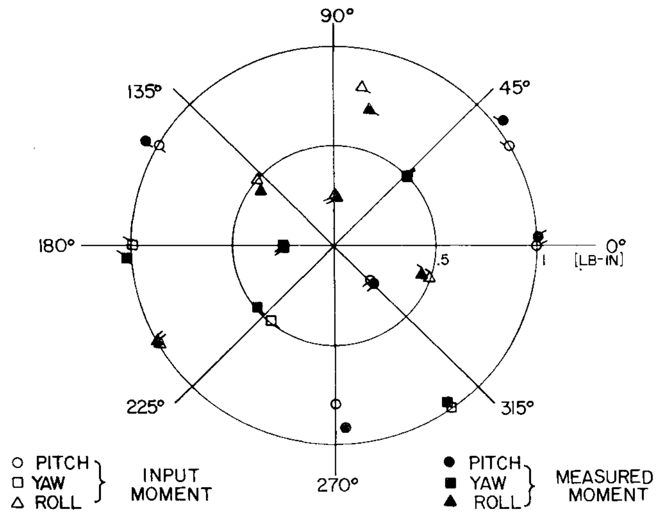

Fig. 10 Comparison between applied and measured *L, M, N* moment combinations (individual runs denoted by flags).

mentioned before, the oscillation was always in pitch and, therefore, all phases are referred to the deflection in that degree-of-freedom.

Figure 7 shows the results obtained when only a pitching moment was applied, its real and imaginary parts being associated with aerodynamic stiffness and damping, respectively. These results were obtained by means of a procedure analogous to that shown on the left side of Fig. 3. This procedure is quite different from that used to determine the "cross" moments. No interactions were detected on the secondary degrees-of-freedom outputs, a confirmation that the use of a tare measurement successfully eliminates such effects.

Figures 8 and 9 depict the results obtained when only yawing or rolling moments were applied. The differences between applied and measured moments in these cases are considerably smaller than in the pitching one. The net interactions (not shown) are, however, more important. These interactions are a maximum of 3% of yaw into roll and 10% of roll into yaw. Average interactions were 1 and 4%, respectively. No interactions were detected on pitch.¶

Figure 10 shows the results obtained when all three moments were simultaneously applied. The various runs shown correspond to different combinations of these moments.

The results obtained with the calibrator are generally very satisfactory. For detailed discussion of the results and various sources of errors the reader is referred to Ref. 6. The maximum errors found in the present calibration results for the *cross-coupling* effects were of the order of 15%. On the average, however, the errors are substantially smaller than this maximum value. The somewhat larger maximum discrepancy between the applied and measured *direct* moments is attributable to the nonsinusoidal model-drive current waveform whose rms value is used as an indication of the driving torque, a quantity required for the computation of the direct moments. Means to reduce this discrepancy are currently being implemented.

¶Interaction percentages are defined as the apparent moment that produces the interaction signal in terms of the actual moment applied in the interacting degree-of-freedom.

Keeping in mind that errors of the order of 10% in dynamic stability parameters, and especially in the dynamic cross-coupling derivatives, can easily be tolerated, the above experimental accuracies must be considered fully satisfactory.

Summary and Conclusions

An oscillatory apparatus for the determination of the 12 static and dynamic moment derivatives due to pitching and yawing oscillation is now available for routine-type dynamic experiments in both intermittent and continuous-flow wind tunnels. The only significant limitation is that the apparatus can only be used for models that are relatively small and that have a conically shaped longitudinal cavity. Work is now in progress on a more advanced version of the apparatus that would not have this limitation. The associated instrumentation system permits nearly automatic data processing, including tabulating and plotting of the final results immediately after each series of runs.

An electromagnetic three-degrees-of-freedom calibrator for the above apparatus has been developed. This calibrator verified the experimental method used and the associated data acquisition procedure. The use of this calibrator is not limited to systems where the forcing oscillation is in pitch or yaw, but can also be extended to systems with primary oscillation in roll. With suitable modifications, it can also be applied to translational oscillations.[7]

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