from Abbott and Doenhoff[6] (solid airfoil). The provoked bubble increases the lift with about 10% and tends to bring the lift curve near that of potential flow. At incidences higher than 13 deg, when the flow separates, the very simple flow model does not work well. In Figs. 4a and 4b, the displacement and momentum thickness on the upper surface of the airfoil, at 13-deg incidence, are presented. On the entire permeable region, the displacement and momentum thickness are thinner for the permeable airfoil. Only at the end of this region, is there an increase which is the result of the pressure hollow. The V_n in the permeable region, is shown in Fig. 4c. A great suction can be observed at the end of the permeable region (negative normal velocity) which can be helpful for the behavior of the boundary layer. The diminution of the positive pressure gradient after the l.e. peak, determines a delay in transition on the upper surface of the airfoil.

These theoretical results, obtained using a simple flow model, are encouraging. They must be verified by a more complex flow model for detached regions and especially by comparison with experiments.

References

[1]Savu, G., and Trifu, O., "Porous Airfoils in Transonic Flow," *AIAA Journal*, Vol. 22, No. 7, 1984, pp. 989–991.

[2]Musat, V. M., "A Simple Integral Method of Potential Flow Analysis Around Airfoils" (in Romanian), *Studii si Cercetari de Mecanica Aplicata*, Vol. 51, No. 1, 1992, pp. 49–59.

[3]Rosenhead, L., "Laminary Boundary Layers," Clarendon Press, Oxford, England, UK, 1963, pp. 303–308.

[4]Sasman, P. K., and Cresci, R. J., "Compressible Turbulent Boundary Layer with Pressure Gradient and Heat Transfer," *AIAA Journal*, Vol. 4, No. 1, 1966, pp. 19–25.

[5]Musat, V. M., "A Direct Viscous-Inviscid Interaction Method for the Flow Calculation Around Airfoils," *Revue Roumaine des Sciences Techniques, Serie de Mecanique Applique*, Vol. 37, No. 3, 1992, pp. 17–29.

[6]Abbott, I. H., and Von Doenhoff, A. E. N., "Theory of Wing Sections," Dover, New York, 1958, pp. 462–463.

Dynamic Stability Derivatives Evaluation in a Low-Speed Wind Tunnel

G. Guglieri*
National Research Council, Torino, Italy
and
F. B. Quagliotti†
Turin Polytechnic Institute, Torino, Italy

Introduction

THE origin of the program developed at TPI/TU is that, with the improvement in fighter aircraft maneuverability, the analysis of flight at high angles of attack and in poststall conditions has become more relevant. As a consequence, the dynamic derivatives evaluation becomes even more important for the recent aircraft configurations. In particular, the measurement of dynamic stability derivatives has been refined in order to investigate the nonlinearities of the aerodynamic coefficient trends as a function of motion variables.

One of the most widely used methods to obtain dynamic stability parameters is the direct forced oscillation technique, where the model oscillates at constant amplitude and frequency in a single degree of freedom (DOF). Therefore, any aerodynamic reaction is supposed to be coherent with the primary motion. Hence, a direct causal relationship between the aerodynamic reactions and the primary motion itself is established, when small angular displacements are considered. This condition permits a rather simple determination of the derivatives, as discussed in Ref. 1.

In this note, a set of experimental results—obtained with the new TPI/TU rig—is presented. These data reproduce, with small discrepancies, the measurements on similar calibration models, performed by NRC/IAR, DLR, and FFA.

Experimental Facilities

The TPI/TU D3M low-speed wind tunnel is a closed-circuit tunnel with a contraction ratio of 5.44. The test section is circular with a 3-m diameter. The maximum speed is 98 m/s and the turbulence level is 0.3% at 50 m/s.

The propelling system is driven by a 1.1-MW dc motor and it consists of two fans with four blades that are mechanically linked to the motor by a gear box.

The model tested was the standard dynamics model (SDM). This is a calibration model introduced by NRC/IAR in 1978, specifically for dynamic tests. The weight of the model (machined in aluminum alloy) without the internal balance is 8 kg. The wing surface is trapezoidal with a 40-deg sweep angle and the main geometrical dimensions are length 0.943 m, wing span 0.609 m, wing surface 0.117 m^2, and mean aerodynamic chord 0.220 m. The center of gravity (c.g.) of the oscillating system (i.e., balance reference center) is at 35% of the mean aerodynamic chord.

A specific servomechanical unit (see Fig. 1) was designed in order to perform static tests on the model and to generate the harmonic motion of the SDM in the three separate rotational DOF. The final design of the unit was the result of previous experience and development.[2,3]

A vertical strut supports the model that is connected to a strain gauge balance by an internal leverage that links the

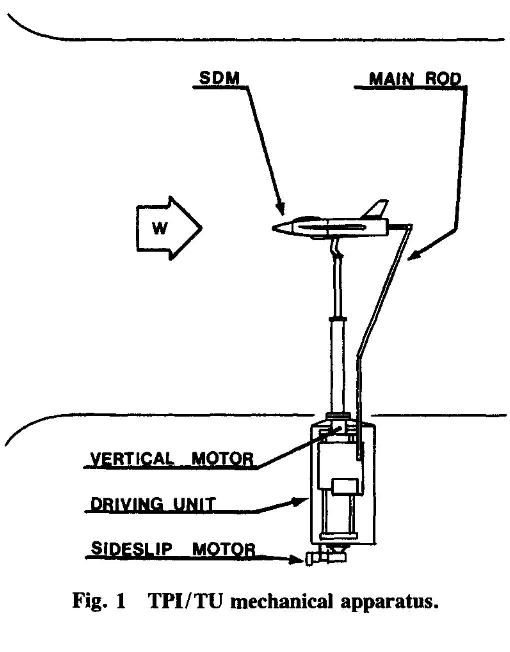

Fig. 1 TPI/TU mechanical apparatus.

Presented as Paper 91-3245 at the AIAA 9th Applied Aerodynamics Conference, Baltimore, MD, Sept. 23–26, 1991; received Feb. 19, 1992; revision received June 15, 1992; accepted for publication June 15, 1992.

*Scientist Researcher, Centro Studi Dinamica Fluidi. Member AIAA.

†Associate Professor, Aerospace Engineering Department. Member AIAA.

rear of the SDM with an oscillating vertical rod. The leverage configuration can be easily changed according to the different primary oscillations (pitch, roll). When yaw oscillations are performed, a different strut is used and the model is suspended in a 90-deg rotated position.

The harmonic motion of the model is excited by a driving unit, powered by a dc motor that is placed under the floor of the test section. It is linked to the main rod that supports the SDM, by a gear box which is connected to an adjustable flywheel. Setting the flywheel radius, it is possible to modify the oscillation amplitude of the model (± 3 deg), while the oscillation frequency (maximum 5 Hz) is set by the rotation speed of the motor.

Two step motors are used to change the angle of attack and the angle of sideslip: 1) the former, translating vertically the dynamic motion unit, acts on the rod and changes the main leverage position that determines the angle of attack (α ranges from -7 to $+60$ deg); and 2) the latter rotates the vertical strut, modifying the angle of sideslip (β ranges from -15 to $+15$ deg).

An electronic control unit (ECU) is interfaced to the mechanical apparatus and is linked to the control PC by a special digital device. Synchronization with the data acquisition computer is possible (handshake or triggering). The distortions of the primary motion, induced by the different geometrical configurations of the support and of the leverages, are corrected by the software routines acting on the control loop.

The five-component internal force transducer connects the model to the mechanical support and permits the measurement of the dynamic loads.

For static tests, the conditioned signals are multiplexed and measured by a high-precision integrating voltmeter, interfaced with the computer by a programmable software language simulation card.

In dynamic conditions, a multisample unit and a high-speed analog to digital converter are adopted. The software elaboration is based on the Fourier analysis of the signals, identifying the in-phase and the out-of-phase vectorial components of the driving torque acting on the oscillating model. The sampling rate can be synchronized with the internal clock of the data acquisition PC or with an external trigger signal.

Experimental Program

The results presented here (related essentially to damping derivatives evaluation) are part of an experimental program for the measurement of direct, cross, and cross-coupling derivatives on different model configurations. The SDM was tested at Mach numbers ranging from 0.1 to 0.2, corresponding, respectively, to Reynolds numbers (referred to the mean aerodynamic chord) of 0.45×10^6 and 0.89×10^6 at angles of attack up to 60 deg. The measurement of the damping derivatives was carried out using the pitch/yaw-roll apparatus discussed above.[4]

The TPI/TU mechanical apparatus, based on a vertical suspension, is different from other rigs[5] based on rear sting supporting systems. The vertical strut, generally adopted for wind-tunnel experiments on transport aircraft models, prevents the model plunging, as the support deflections are limited during the tests.

The pressure distribution on the lower side of the SDM fuselage has been measured in static conditions, even at high angles of attack. These measurements confirm that the aerodynamic interference of the model suspension is small.

The experimental results of the TPI tests are generally in good agreement with those obtained in other laboratories[6–10] (IAR—formerly NAE, FFA, DLR—formerly DFVLR), taking into account the different suspension systems, test conditions, and model sizes. The aerodynamic coefficients are related to the body axes reference system.

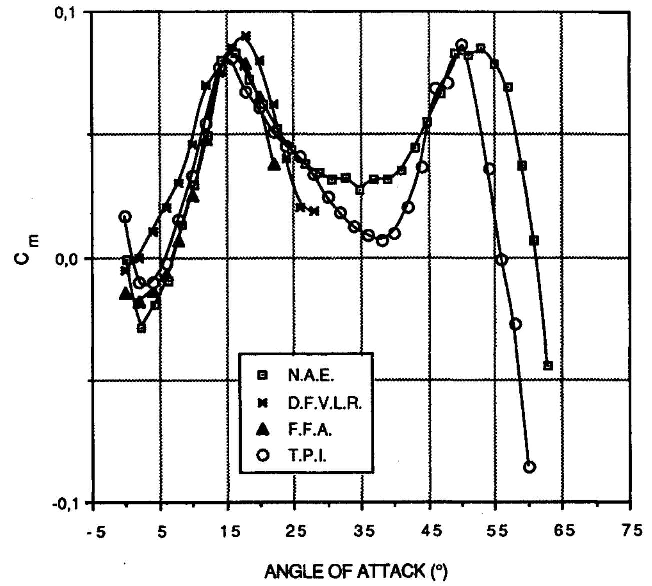

Fig. 2 Pitching moment coefficient.

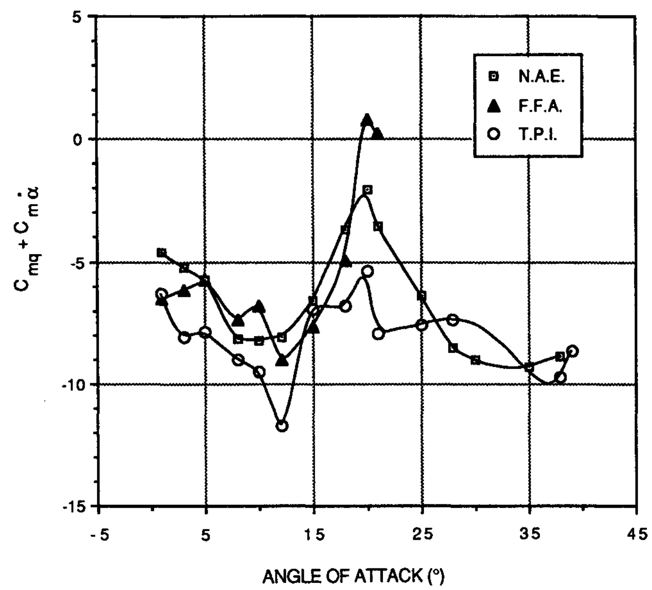

Fig. 3 Pitch damping derivative.

The trend of the static coefficient C_m measured at TPI and in the other laboratories, is presented in Fig. 2. The results related to DLR are time-averaged from dynamic tests. The values are in good accordance, even at high angles of attack (the comparison is possible up to $\alpha = 60$ deg only with NAE results). The shape of C_m curve shows a linear behavior of this coefficient up to the wing stall.

A stabilizing effect due to downwash induced by the wings on the horizontal tail was also found for $\alpha > 15$ deg.

The damping derivatives, in pitch and in roll, respectively, are presented in Figs. 3 and 4 as a function of the angle of attack. These data are related to the small amplitude oscillation tests with comparable angular displacements.

The damping derivative $C_{mq} + C_{m\dot{\alpha}}$ peaks at $\alpha = 12$ deg. It then reaches a minimum at $\alpha = 20$ deg, and after this drop, slowly rises again with some oscillation in its trend. The experimental data deviation is moderate ($\delta_{\%} = 5.5\%$).

The derivative $C_{lp} + C_{l\dot{\beta}} \sin \alpha$ remains fairly constant in the range tested, and the correlation of the different results and the data deviation ($\delta_{\%} = 3.8\%$) are satisfactory.

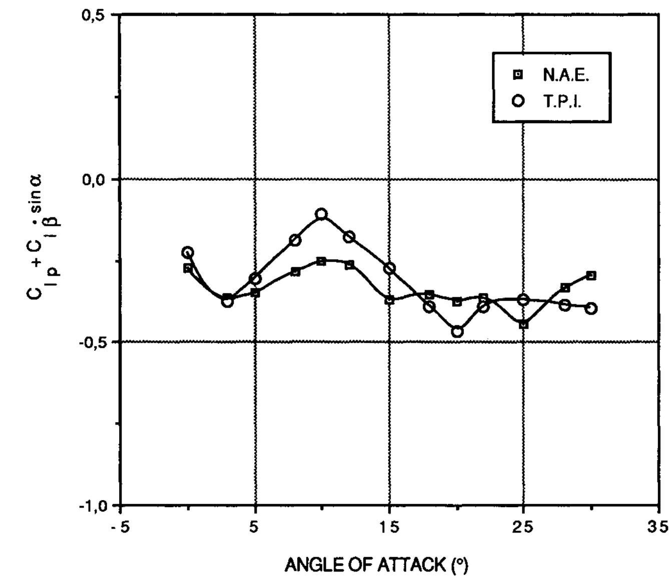

Fig. 4 Roll damping derivative.

Concluding Remarks

The results obtained with the calibration tests of the pitch/yaw and roll mechanism (related to the SDM) were in good accordance with the data published by NAE (IAR), DFVLR (DLR), and FFA, taking into account the different characteristics of the wind tunnels and of the model suspensions.

As a consequence, the research program has been extended to different model configurations, developed with the aim of investigating their aerodynamic behavior in a wide maneuvering field.

Acknowledgment

The authors would like to acknowledge the technical staff of SACIMEX (Torino-Italy) for their contribution in the design and manufacturing of the apparatus.

References

[1]Hanff, E. S., "Direct Forced Oscillation Techniques for the Determination of Stability Derivatives in Wind Tunnel," AGARD-LS-114, March 1981.

[2]Cavallari, A. Guglieri, G., and Quagliotti, F., "Development of a Measurement Technique for Damping Derivatives in Pitch," 17th ICAS Congress, Stockholm, Sweden, Sept. 1990.

[3]Cavallari, A., Guglieri, G., and Quagliotti, F., "Development of Experimental Methods for Dynamic Derivatives Measurement in Wind Tunnels," International Aerospace Congress, Melbourne, Australia, May 1991.

[4]Guglieri G., and Quagliotti, F., "Determination of Dynamic Stability Parameters in a Low Speed Wind Tunnel," AIAA 9th Applied Aerodynamics Conf., Baltimore, MD, Sept. 1991.

[5]Orlik-Rueckemann, K., "Review of Techniques for Determination of Dynamic Stability Parameters in Wind Tunnels," AGARD-LS-114, March 1981.

[6]Huang, X. Z., and Beyers, M. E., "Subsonic Aerodynamic Coefficients of the SDM at Angles of Attack up to 90°," LTR-UA-93, Ottawa, Canada, Jan. 1990.

[7]Beyers, M. E., and Moulton, B. E., "Stability Derivatives Due to Oscillation in Roll for the SDM at Mach 0.6," LTR-UA-64, Ottawa, Canada, Jan. 1983.

[8]Beyers, M. E., Kapoor, K. B., Moulton, B. E., "Pitch and Yaw Oscillation Experiments on the SDM at Mach 0.6," LTR-UA-76, Ottawa, Canada, June 1984.

[9]Torngren, L., "Dynamic Pitch and Yaw Derivatives of the SDM," FFA TN 1985-05, Bromma, Sweden, Oct. 1985.

[10]Schmidt, E., "SDM Experiments with the DFVLR/AVA Transonic Derivative Balance," AGARD-CP-386, May 1985.

Shape Sensitivities and Approximations of Modal Response of Laminated Skew Plates

Sarvesh Singhvi* and Rakesh K. Kapania†
Virginia Polytechnic Institute and State University, Blacksburg, Virginia 24061

Introduction

THE derivatives of the natural frequencies and mode shapes of a generally laminated tapered skew plate with respect to various shape parameters are obtained. The frequencies and mode shapes of the composite cantilevered plate are initially determined as a function of a particular design variable using the Rayleigh-Ritz method. The derivatives of the eigenvalues and eigenvectors with respect to the shape variables are computed analytically and the results are compared with those obtained using the finite-difference method in order to confirm their accuracy. The four independent shape parameters considered are 1) the plate surface area, 2) the aspect ratio, 3) the taper ratio, and 4) the sweep angle. The eigenvalues and eigenvectors are then approximated over the range of the variable using linear, exponential, and pseudoexponential approximation schemes, and compared with the values obtained from reanalysis. Numerical results are obtained for both symmetrically and unsymmetrically laminated plates.

Mathematical Formulation

Recently, a number of studies have been conducted on the sensitivity of various static and dynamic aeroelastic responses (e.g., flutter, divergence, etc.) to four wing shape variables such as surface area, taper ratio, aspect ratio and sweep angle (e.g., Kapania et al.[1,2]). All these studies required the derivatives of the stiffness and mass matrices with respect to the four shape design variables mentioned previously. These derivatives were obtained using a finite-difference approach. Such an approach, though very easy to implement, suffers from one major drawback: the results may be extremely sensitive to the step size. A larger step size leads to significant truncation errors and a too-small step size may lead to round-off errors. To avoid these problems, it is desired that the derivatives be obtained analytically as far as possible.

In addition to the sensitivity of the stiffness and mass matrices, the sensitivity of the modal response (free vibrations and mode shapes) is also of interest. Sheena and Karpel[3] performed the static aeroelastic analysis of wings using free vibration modes. Recently, Karpel[4] also obtained the sensitivity derivatives of flutter characteristics and stability margins for aeroservoelastic design of wings by representing the wing in terms of its modal coordinates. The sensitivity analysis of aeroelastic responses therefore needs the sensitivity of the modal response. Accurate and efficient determination of this sensitivity information for the case of a generally laminated wing is the key objective of this research.

It is highly desirable in optimization to be able to calculate the effect of design variable changes without having to perform a full analysis for each design iteration. This need has

Received Oct. 16, 1991; presented as Paper 92-2391 at the AIAA/ASME/ASCE/AHS/ASC 33rd Structures, Structural Dynamics, and Materials Conference, Dallas, TX, April 13–15, 1992; revision received July 31, 1992; accepted for publication Aug. 4, 1992.

*Graduate Research Assistant, Department of Aerospace and Ocean Engineering. Student Member AIAA.

†Associate Professor, Department of Aerospace and Ocean Engineering. Associate Fellow AIAA.