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Transonic Unsteady Airloads on an Energy Efficient Transport Wing with Oscillating Control Surfaces

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An aspect-ratio 10.8 supercritical wing with oscillating control surfaces is described. The wing is instrumented with 252 static orifices and 164 in situ dynamic pressure transducers for studying the effects of control surface deflection on steady and unsteady pressures at transonic speeds. Selected results from initial wind-tunnel tests conducted in the Langley transonic dynamics tunnel are discussed. Unsteady pressure results are presented for two trailing-edge control surfaces oscillating separately at the design Mach number of 0.78. Some experimental results are compared with analytical results obtained by using linear lifting-surface theory.

Nomenclature

b	= wing root semichord, 0.400 m
c	= wing local chord, m
C_L	= wing lift coefficient
f	= frequency of oscillating control surface, Hz
k	= reduced frequency ratio, $(b\omega)/V$
M	= freestream Mach number
R	= Reynolds number based on wing average chord of 0.425 m
V	= freestream velocity, m/s
t/c	= local thickness-to-chord ratio
x/c	= fraction of chord
α	= wing angle of attack, positive leading edge up, deg
δ	= control surface deflection angle, positive trailing edge down, deg
ΔC_p	= unsteady lifting pressure coefficient
η	= fraction of semispan
ω	= circular frequency of oscillating control surface, rad/s

Introduction

CURRENTLY there is considerable interest in applying active control techniques to new and derivative airplane designs. This is particularly true for configurations, such as an energy efficient transport, that operate at transonic speeds. Although considerable effort is being placed on developing methods for predicting unsteady transonic aerodynamics, and significant progress has been made^{1,2} no theoretical method has been developed to the point that it can be used to predict unsteady transonic loads reliably. Therefore, a research program employing a large three-dimensional wing model was initiated at the NASA Langley Research Center to investigate the effects of oscillating control surfaces on transonic unsteady aerodynamics. The primary objective of this research program is to generate a comprehensive data base of measured unsteady pressures. This data base will be used in the design of active control systems for proposed energy efficient transport configurations and in validating transonic unsteady aerodynamic theories currently being formulated.

The supercritical wing configuration is equipped with 10 oscillating control surfaces. The wing is instrumented extensively to measure both steady and unsteady pressures.

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Initial wind-tunnel tests have been conducted in the Langley transonic dynamics tunnel at Mach numbers up to 0.82. Model parameters investigated include wing angle of attack, control surface static deflection angles, and control surface oscillating deflections and frequencies.

The purpose of this paper is to present selected results from these initial tests in which two trailing-edge control surfaces were oscillated to generate unsteady aerodynamic pressures. All of the steady and unsteady measured data has been compiled in tabular form and published in NASA TM-81888.³ Although the focus is on measured unsteady data, analytical results obtained using subsonic lifting-surface theory⁴ are compared with measured results.

Wind Tunnel Model

General

The model consisted of a half-body fuselage similar to that of a "wide-body" transport and a stiff semispan wing having a planform representative of current energy efficient transport designs. The model was mounted on the tunnel sidewall on a turntable mechanism which allowed the angle of attack to be varied (see Fig. 1).

Geometry

A sketch of the wing is presented in Fig. 2. The wing has a leading-edge sweepback angle of 28.8 deg, an aspect-ratio of 10.76, and a semispan of 2.286 m. The side of the half-body fuselage was located at a wing station 0.219 m.

The wing is equipped with 10 oscillating control surfaces. Outlined in Fig. 2 are five leading-edge control surfaces hinged about the 15% chord and five trailing-edge control surfaces hinged about the 80% chord. For these initial wind-tunnel tests only two trailing-edge control surfaces, shown in Fig. 2 by the cross-hatched areas, were oscillated to generate unsteady airloads. These two control surfaces are designated hereafter as the inboard control surface and the outboard control surface.

The wing contour was formed from three different supercritical airfoils. These three airfoils were located at wing stations 0.219, 0.876, and 2.286 m and had thickness-to-chord ratios of 0.16, 0.14, and 0.12, respectively. The three supercritical airfoil shapes are shown in Fig. 3. Straight line interpolation along constant percent chords was used between adjacent airfoil sections. The section twist angles at each station, referenced to a horizontal reference plane, are also shown in Fig. 3.

Construction

The wing was constructed from aluminum alloy and consisted of upper and lower sections. Each section was stiffened in bending by a boron filament insert bonded to the

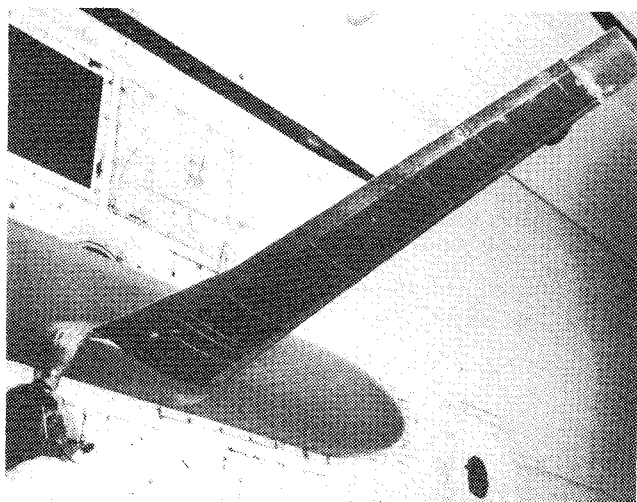


Fig. 1 Photograph of complete model mounted in wind tunnel.

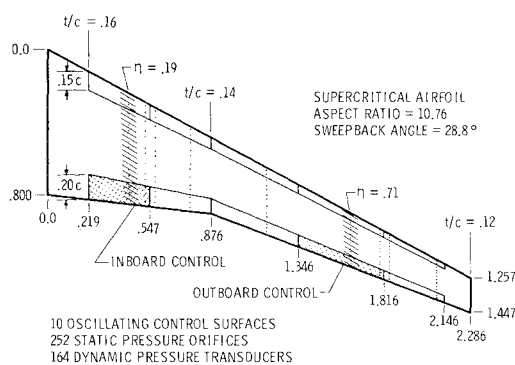


Fig. 2 Sketch of wing planform (all linear dimensions are in meters).

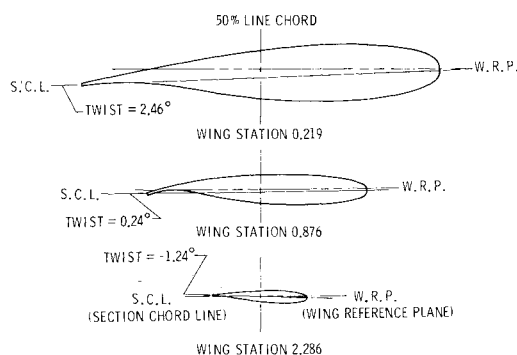


Fig. 3 Pictorial view of supercritical airfoil shape at three wing stations.

internal cutout area shown in Fig. 4. The sections were permanently bonded together to form a box cross section. This type of construction produced a stiff, lightweight wing structure whose fundamental frequency (23 Hz) was well above the maximum control surface excitation frequency used during the tests (15 Hz). These requirements for a stiff, high-frequency wing structure were dictated by the need to minimize the dynamic and static deformations of the model due to aerodynamic loads.

Lightweight control surfaces were constructed using stiff Kevlar-balsawood sandwich material thereby minimizing the control surface inertia loads and deformations. A typical control surface is shown in Fig. 5. Miniature hydraulic actuators⁵ of the rotating vane type were used both to position the control surfaces statically and to oscillate them at amplitudes of ± 6 deg over a frequency range from 5 to 15 Hz. A typical actuator is shown in Fig. 5.

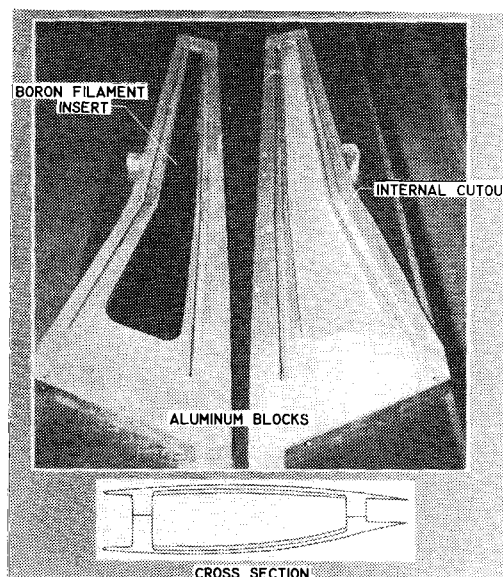


Fig. 4 Illustration of wing box construction.

OSCILLATING CONTROL SYSTEM COMPONENTS

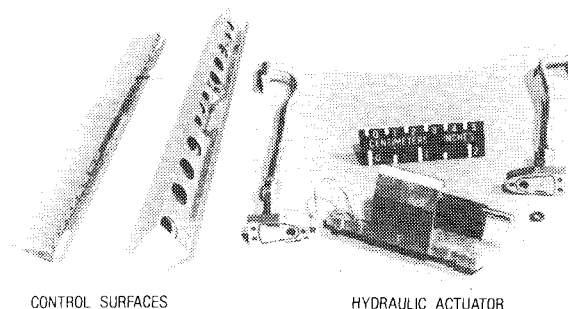


Fig. 5 Photograph of typical control surface and hydraulic actuator.

Instrumentation

The model was instrumented with 252 static pressure orifices and 164 in situ dynamic pressure transducers. Small precision potentiometers were used to measure directly the control surface angular displacement. The model root angle of attack was measured by a digital encoder that was mechanically linked to the turntable in the wind-tunnel wall. The wing was mounted to a five-component balance which measured the wing static forces and moments. Six accelerometers were installed in the model to detect wing vibrations.

Wind Tunnel

The Langley transonic dynamics tunnel is a closed-circuit continuous-flow tunnel which has a 4.88-m^2 test section with slots in all four walls. Mach number and dynamic pressure can be varied simultaneously, or independently, with either air or freon as a test medium. Freon was used for all tests of this investigation.

Data Acquisition and Analysis

General

Acquisition of data from the large number of varied sensors located on this model and analysis of these data in a "near real-time" manner required the use of a computer. The transonic dynamics tunnel facility has a computer uniquely designed and programmed for this purpose.⁶ The following paragraphs describe the data acquisition and analysis procedures used during the tests.

Unsteady Pressures Data

Pressure time-history signals from the transducers were digitized and recorded on magnetic tapes for 75-100 cycles of control surface oscillation. During playback of the digital tapes, the Fourier components of the data were determined at the frequency of oscillation of the control surface. Values of pressure coefficient magnitude and phase angle relative to the oscillating control surface position were calculated for each transducer.

Steady Pressure Data

Static pressures were measured using six 48-port scanning valves that were stepped simultaneously from port to port. For each measurement, the pressure was allowed to settle for 0.3 s and then was averaged for approximately 1 s to acquire a mean value of pressure coefficient for each orifice.

Force-Balance Data

The lift, drag, and moments were measured using a five-component balance that was mounted between the wing and the side-wall turntable. The data were averaged for approximately 3 s to acquire a mean value for each load.

Hinge Moment Data

A technique for measuring static control surface moments was developed using a high quality differential pressure gage installed between the two hydraulic supply lines to the actuator. The mean value of the differential pressure gage output is related directly to the control surface hinge moment. The control surface was oscillated at a low frequency of 0.5 Hz and amplitude of ± 1 deg to eliminate the influence of high friction loads in the internal seal of the actuator. The gage signals were averaged for 20 s to acquire a mean value for the hinge moment.

Results and Discussion

General

Data from the initial tests included both steady and unsteady pressure measurements, static force-balance measurements, and control surface static hinge-moment measurements. Although steady pressures and force-balance results are not presented herein, the steady pressure distributions, the drag rise characteristics, and the force and moment coefficients did exhibit characteristics expected of supercritical wing aerodynamics. The following discussions focus on the unsteady pressure results for the design condition: $M = 0.78$, and $\alpha = 2.05$ deg. The Reynolds number was 2.2×10^6 based on the average wing chord. Comparisons between measured and calculated results are presented for chordwise distributions of unsteady lifting pressures, spanwise distributions of incremental loads, and static hinge moments.

Measured Unsteady Results

Inboard Control Surface Deflection Results

Chordwise distributions of lifting pressures due to oscillations of the inboard control surface at 10 Hz are shown in Fig. 6 for span stations $\eta = 0.19$ and $\eta = 0.71$. Results are given for oscillatory deflection angles $\delta = \pm 2$, ± 4 , and ± 6 deg. First, observe the results for $\eta = 0.19$ which is near the midspan of the inboard control surface. The lifting pressure magnitude increases rapidly from a small value at the leading-edge $x/c = 0$ to a peak near the 80% chord (control surface hinge axis) and then decreases very rapidly to a small value near the trailing-edge $x/c = 1.0$. The corresponding phase angle results show a large phase lag near the leading edge that decreases to zero near the 65% chord and shows a phase lead over the rear portion of the chord. The magnitude of ΔC_p increases with control surface deflection amplitude in an approximate linear manner over the entire chord. That is, the magnitude of ΔC_p for $\delta = \pm 6$ deg is about three times the value for $\delta = \pm 2$ deg. The phase angle results are essentially independent of the amplitude of control surface deflection.

Second, observe the results for $\eta = 0.71$ which is near the midspan of the outboard control surface. Although the oscillating control surface is well removed from the pressure measurement station, its effect on the unsteady pressures is significant. The magnitude rises sharply to a peak near the 25% chord, drops abruptly to near zero at the 40% chord and remains near zero to the trailing edge. Except for the wide excursions in phase angle near the 40% chord, the phase angle trends for the outboard station are similar to those at the inboard station in that a large phase lag exists at the leading edge and decreases toward zero going rearward along the chord.

Inboard Control Surface Frequency Results

The chordwise distributions of lifting pressures for three frequencies of the inboard control surface oscillating at amplitude of ± 6 deg are presented in Fig. 7 for $\eta = 0.19$ and $\eta = 0.71$. Results are shown for frequencies of 5, 10, and 15 Hz which correspond to reduced frequency values k of about 0.1, 0.2, and 0.3. For $\eta = 0.19$, control surface frequency has a much greater effect on phase angles than on magnitudes of unsteady pressures. The largest effects occur at the leading edge where the 5 Hz data show a phase lag of about 40 deg and the 15 Hz data show a phase lag of about 120 deg. For $\eta = 0.71$, the results indicate the effects of frequency to be much more pronounced in the phase angle data than in the magnitude data. These results show again the significant influence the inboard oscillating control surface has on unsteady lifting pressures far outboard on the wing.

Outboard Control Surface Deflection and Frequency Results

Unsteady lifting pressure distribution results for the oscillating outboard control surface are presented in Figs. 8 and 9. The deflection and frequency effects show general

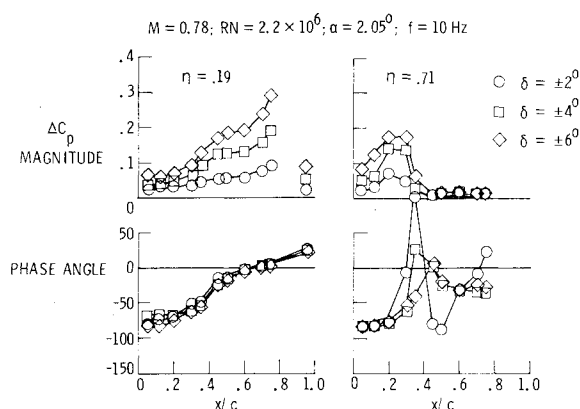


Fig. 6 Inboard control surface oscillating deflection results.

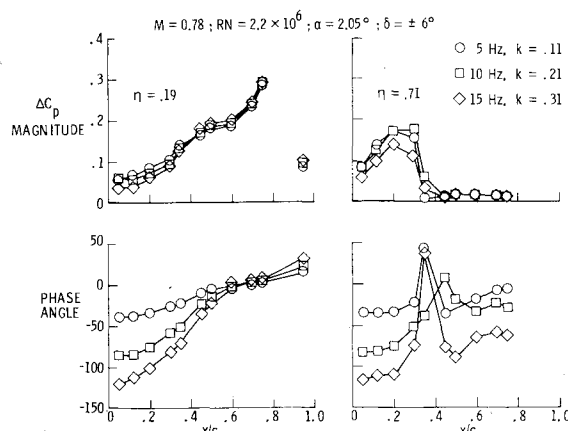


Fig. 7 Inboard control surface oscillating frequency results.

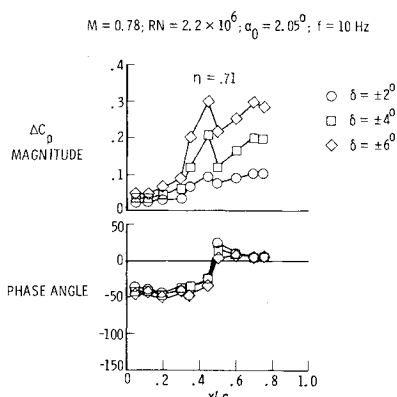


Fig. 8 Outboard control surface oscillating deflection results.

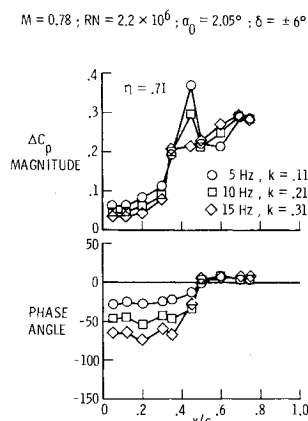


Fig. 9 Outboard control surface oscillating frequency results.

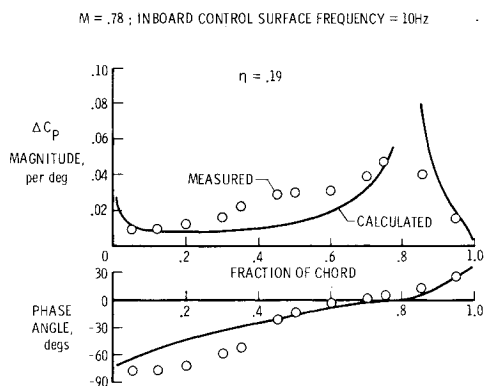


Fig. 10 Comparison of measured and calculated chordwise unsteady lifting pressure distributions.

trends similar to those discussed for the oscillating inboard control surface. A significant difference, however, is the sharp hump in the lifting pressure magnitude data near the 50% chord. Although data for $\eta = 0.19$ are not presented in the figures, neither the magnitude nor phase angle data at this station was affected by the oscillating outboard control surface.

Comparison of Measured and Calculated Results

General

The calculated results presented herein were obtained from an analysis based on linear theory for the acceleration potential on zero thickness lifting surfaces.⁴ This subsonic kernel-function method accounts for edge and hinge line singularities of the control surface. Effects of airfoil thickness are partially accounted for by modifying the local streamwise velocity.

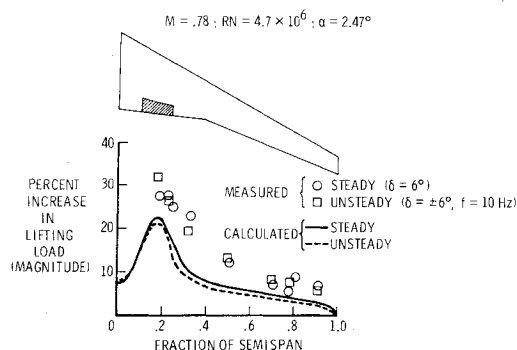


Fig. 11 Comparison of measured and calculated spanwise incremental lifting loads generated by a deflected control surface.

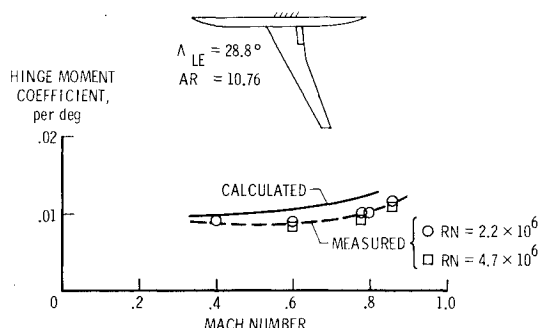


Fig. 12 Comparison of measured and calculated static hinge moments.

Chordwise Lifting Pressure

A comparison between measured and calculated chordwise distribution of lifting pressures at $\eta = 0.19$ generated by oscillating the inboard control surface is presented in Fig. 10. These results are for $M = 0.78$ and control surface frequency of 10 Hz. The variation of lifting pressure magnitude per degree and of phase angle, referenced to the control surface position, is plotted as a function of fraction of chord. Measured and calculated magnitude results show reasonable agreement up to the 20% chord. From 20 to 70% chord, the calculations underestimate the measured data which are characterized by a broad hump that peaks near the 50% chord. Calculations overestimate measured data behind the hinge axis at 80% chord. The calculated results show a smaller phase lag than the measured data ahead of the 40% chord. Aft of the 40% chord, the calculated and measured results are in good agreement.

Spanwise Incremental Loads

An additional comparison between calculated and measured results is presented in Fig. 11 as spanwise incremental loads generated by a deflected inboard control surface. Figure 11 shows both steady and unsteady results as percent increase in lifting load (magnitude), above that of the basic wing load with no deflected control surface, plotted as a function of fraction of semispan. Measured steady data for the control deflected statically $+6^\circ$ are represented by circle symbols. The measured unsteady data for the control surface oscillating $\pm 6^\circ$ at 10 Hz are represented by square symbols. Corresponding calculated steady results are shown as the solid line, and unsteady results are shown as the dashed line. Comparisons of the steady and unsteady magnitude results, measured and calculated, show no significant differences. The magnitude of wing incremental loading, therefore, must be primarily a function of the control surface deflection angle and does not depend on whether the control surface is deflected statically or dynamically at this frequency. Phase effects are not included in the unsteady magnitude results. Comparison between measured and calculated

magnitudes, however, indicates a significant difference for both the steady and unsteady cases. Across the entire span, the calculated incremental loads are lower than the measured loads.

The poor agreement between measured and calculated results is probably due to the fact that the present analysis does not account for transonic, nonlinear, or viscous effects.

Static Hinge Moment

Measured hinge moments for the inboard trailing-edge control surface at Reynolds numbers of 2.2×10^6 and 4.7×10^6 are presented in Fig. 12. The results are shown in terms of hinge-moment coefficient per degree as a function of Mach number. Also shown in Fig. 12 is a comparison between the measured and calculated static hinge moment results. These results show reasonably good agreement over the Mach number range from 0.4 to 0.8.

Concluding Remarks

An experimental investigation has been conducted on an aspect ratio 10.8 supercritical wing model with oscillating control surfaces. Selected measured unsteady results from the initial wind-tunnel tests have been presented and discussed. Briefly, the measured results show that unsteady lifting pressures generated by oscillating control surfaces are substantial. In particular, the inboard oscillating control surface was shown to have a significant influence on the unsteady

lifting pressures far outboard on the wing. Also, measured data were compared with calculated results obtained using a subsonic lifting surface theory. Results indicate a need for better prediction methods in the transonic speed range.

In summary, the purpose of this model research program is to produce a comprehensive data base of measured transonic unsteady pressure for use in designing active control systems and for use in validating transonic unsteady aerodynamic theories currently being formulated.

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Turbulent flows involving injection and mixing occur in many engineering situations and in a variety of natural phenomena. Liquid or gaseous fuel injection in jet and rocket engines is of concern to the aerospace engineer; the mechanical engineer must estimate the mixing zone produced by the injection of condenser cooling water into a waterway; the chemical engineer is interested in process mixers and reactors; the civil engineer is involved with the dispersion of pollutants in the atmosphere; and oceanographers and meteorologists are concerned with mixing of fluid masses on a large scale. These are but a few examples of specific physical cases that are encompassed within the scope of this book. The volume is organized to provide a detailed coverage of both the available experimental data and the theoretical prediction methods in current use. The case of a single jet in a coaxial stream is used as a baseline case, and the effects of axial pressure gradient, self-propulsion, swirl, two-phase mixtures, three-dimensional geometry, transverse injection, buoyancy forces, and viscous-inviscid interaction are discussed as variations on the baseline case.

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