Aerodynamic Measurements for an Oscillating Two-Dimensional Jet-Flap Airfoil

J. M. Simmons*
University of Queensland, Brisbane, Queensland, Australia

The experiments described were directed toward an understanding of the jet-flap airfoil when used as a lift control device in systems for the stabilization of undesirable aeroelastic behavior of structures. The magnitude and phase of aerodynamic derivatives for small sinusoidal motions of a modified NACA 0012 airfoil with a trailing-edge jet flap have been measured in two-dimensional incompressible flow. The motions are pitching about the trailing edge and translation normal to the freestream direction. Results are presented for a range of dimensionless frequency, jet strength, and Reynolds number. The apparatus and techniques used to obtain oscillatory surface-pressure distributions are described. Measurements with both airfoil and jet flap held stationary agree quite well with earlier experimental and theoretical results, but care must be taken to avoid misleading separation of the boundary layer near the trailing edge at low Reynolds number. It is shown that results with an oscillating jet-flap airfoil exhibit trends with frequency which are similar to those for a conventional airfoil. These trends cannot be predicted by the potential flow theory of Spence which is limited in applicability to frequencies beyond the usual range of practical interest.

Nomenclature

c	= airfoil chord
C_j	= (jet thrust per unit span)/(qc) = jet momentum coefficient
C_L	= (lift per unit span)/(qc) = lift coefficient (positive up in Fig. 1)
C_M	= (moment per unit span)/(qc^2) = moment coefficient (measured about trailing edge except in Fig. 14; clockwise moment is positive in Fig. 1)
$dC_L/d\alpha$, $dC_M/d\alpha$	= lift and moment curve slopes, respectively, for stationary airfoil and jet flap
$\partial\bar{C}_L/\partial\alpha$, $\partial\bar{C}_M/\partial\alpha$, etc.	= complex aerodynamic derivatives
ΔC_p	= $(p_{\text{upper}} - p_{\text{lower}})/q$ = differential pressure coefficient
i	= $(-1)^{1/2}$
k	= $\omega c/V$ = dimensionless frequency
p	= pressure
q	= $\frac{1}{2}\rho V^2$ = freestream dynamic pressure
t	= (real time) $\times$ (V/c)
V	= freestream velocity
x	= distance along chord line from leading edge
z	= translation of trailing edge of airfoil
α	= angle of pitch of airfoil relative to freestream direction; equivalent to angle of attack for stationary airfoil, rad
ρ	= density of air
θ	= angle by which ΔC_p leads displacement, rad
η	= angle of jet deflection measured at exit, rad
ω	= circular frequency of forced motion, rad/sec
$(\hat{\ })$	= amplitude of indicated sinusoidal quantity
$\lvert\ \rvert$	= modulus or magnitude of indicated complex quantity
arg ( )	= argument or angle of indicated complex quantity

Received July 3, 1975; revision received Sept. 2, 1975. The research reported herein was sponsored by Australian Research Grants Committee under reference no. F70/17452.

Index categories: Aircraft Aerodynamics (including Component Aerodynamics); Jets, Wakes, and Viscid-Inviscid Flow Interactions; Nonsteady Aerodynamics.

*Senior Lecturer, Department of Mechanical Engineering.

I. Introduction

ALTHOUGH recent STOL and VTOL aircraft-development projects have caused increased interest in jet-flap airfoils, there has been considerable investigation of their steady aerodynamic characteristics over the past 20 years.[1,2] The unsteady characteristics of jet-flap airfoils have received much less attention and are not understood well. Theoretical solutions have been obtained by Spence,[3] Erickson,[4] and Trenka and Erickson,[5] but even the trends do not agree consistently with the rather limited data obtained by Simmons and Platzer,[6] Trenka and Erickson,[5] Kretz,[7] and Takeuchi.[8] Consequently, there is insufficient information to assess fully the potential of the jet flap in an attractive application, viz., as a fast-acting lift control device[6] for aircraft gust-load alleviation and flutter-mode stabilization. Nevertheless, an experiment by Platzer et al.[9] has shown the feasibility of using a fluidically actuated jet flap to reduce torsional oscillation of a wing in a sinusoidal gust field. Also, the application of unsteady jet flaps to relief of rotorcraft blade stresses is being studied extensively.[10] In these applications the unsteady jet flap is likely to be faster acting and mechanically more simple and reliable than conventional control surfaces.

A jet flap is obtained if air with high momentum flux is ejected from a spanwise slot at or near the trailing edge of an airfoil. It contributes predominantly through two effects to an increased lift, viz., the component of jet thrust in the lift direction and the modification of circulation around and, hence, pressure distribution over the airfoil. Control of lift can be achieved by changing either the strength of the jet or the angle at which it emerges. In either case the aerodynamic lift and moment also are affected by motion of the airfoil caused by wing structural vibration. An understanding of this behavior is the aim of this project. If the airfoil is undergoing pitching motion, the jet flap can, theoretically, also give rise to a damping force that is associated with Coriolis acceleration of the internal jet flow. This force is, for a given jet-flap strength, characteristically proportional to the angular velocity of the airfoil and to an internal flow length, but it is shown in Sec. VII that the force is likely to be small, in practice. Much of the fine detail not presented here is available[11] from the author's Department.

Formulation of the Experiment

The starting point for studies of the unsteady characteristics is a two-dimensional jet-flap airfoil section capable of simultaneous pitching and translation oscillations with small

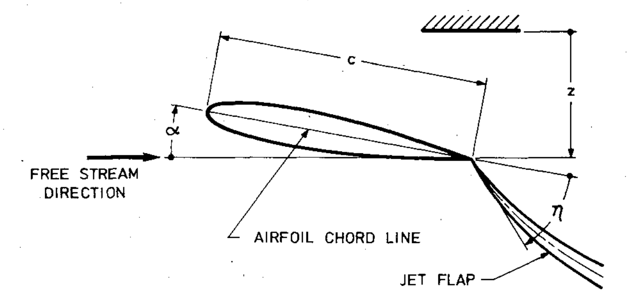

Fig. 1 Coordinate system for pitching and translation oscillations of a two-dimensional jet-flap airfoil.

amplitude. In Fig. 1 the dimensionless translation z/c of the trailing edge, the angle of pitch α of the airfoil, and the deflection angle η of the jet flap from the airfoil are small and time-varying. The assumption of linear aerodynamics enables the frequency response of the system to be used to predict behavior in any general motion involving small displacements. If

$$\alpha = \hat{\alpha}\cos kt, z = \hat{z}\cos(kt + \psi_1), \eta = \hat{\eta}\cos(kt + \psi_2)$$

are simultaneous inputs with the same dimensionless frequency k, but different phase angles, then, using complex variable notation $\bar{C}_L$ to describe both the amplitude and phase angle of the resulting lift coefficient due to pressure, $C_L = \hat{C}_L \cos(kt + \psi)$, it follows that

$$\bar{C}_L = \frac{\partial \bar{C}_L}{\partial \alpha} + \hat{\alpha}\frac{\partial \bar{C}_L}{\partial (z/c)}\frac{\hat{z}}{c}e^{i\psi_1} + \frac{\partial \bar{C}_L}{\partial \eta}\hat{\eta}e^{i\psi_2}$$

Here $\bar{C}_L$ is a complex lift coefficient with modulus or magnitude equal to $\hat{C}_L$ and argument or phase angle equal to ψ. Similarly, a complex moment coefficient due to pressure can be writen as

$$\bar{C}_L = \frac{\partial \bar{C}_M}{\partial \alpha}\hat{\alpha} + \frac{\partial \bar{C}_M}{\partial (z/c)}\frac{\hat{z}}{c}e^{i\psi_1} + \frac{\partial \bar{C}_M}{\partial \eta}\hat{\eta}e^{i\psi_2}$$

If the contribution from the jet-flap thrust has been included in the definitions of C_L and C_M, the results in this section would have been unchanged.

The complex aerodynamic derivatives $\partial\bar{C}_L/\partial\alpha$, $\partial\bar{C}_L/\partial(z/c)$, etc., are dependent on k and can be evaluated by frequency-response measurements in any three tests based on a linearly independent set of inputs α, z, and η. In the tests reported here, $\partial\bar{C}_L/\partial\alpha$, $\partial\bar{C}_M/\partial\alpha$, $\partial\bar{C}_L/\partial(z/c)$, and $\partial\bar{C}_M/\partial(z/c)$ were measured in two-dimensional incompressible flow with the following sets of inputs: 1) $\alpha = \hat{\alpha}\cos kt$, $z/c = 0$, $\eta = 0$ (oscillatory pitching); and 2) $\alpha = 0$, $z/c = (\hat{z}/c)\cos kt$, $\eta = 0$ (oscillatory translation). The pitching tests were over a wider range of frequencies than those of Trenka and Erickson,[5] and the translation tests appear to be the first reported. Measurements of $\partial\bar{C}_L/\partial\eta$ and $\partial\bar{C}_M/\partial\eta$ have been made by Simmons and Platzer,[6] Kretz,[7] and Takeuchi,[8] using the set of inputs $\alpha = 0$, $z = 0$, $\eta = \hat{\eta}\cos kt$, but the variations among them and theoretical values have yet to be resolved.

II. Apparatus and Experimental Methods

Wind Tunnel

The experiments were performed in the open-circuit wind tunnel at the School of Mechanical and Industrial Engineering, The University of New South Wales, Sydney, Australia. The tunnel has a test section 1.22 m long with basically a 461-mm-square cross section, except for corner fillets with 116-mm hypotenuses. A typical survey in the absence of a model showed that local mean axial velocities in the test section differed by a maximum of 0.4% from an average test section velocity of 30.5 m/sec, and that rms turbulence levels were less than 0.1%.

Table 1 Comparison of profiles of test airfoil at midspan and NACA 0012 airfoil[a]

Distance from leading edge as a percent of chord	NACA 0012 thickness as percent of chord	Test airfoil thickness as percent of chord
1.25	3.788	3.60
2.5	5.230	5.15
5.0	7.110	7.10
7.5	8.400	8.30
10	9.366	9.21
15	10.690	10.42
20	11.474	11.32
25	11.882	11.70
30	12.004	11.82
40	11.606	11.42
50	10.588	10.37
60	9.126	9.08
70	7.328	7.24
80	5.246	5.07
90	2.896	2.72
95	1.614	1.45
98	...	0.741
100	0.252	0.500

[a] For both cases leading edge radius is 1.58% of chord.

Airfoil

The rigid two-dimensional test airfoil had a chord of 150.9 mm and spanned the full 461-mm height of the test section in the vertical plane, midway between the sidewalls. The symmetrical airfoil, with 11.8% maximum thickness, had very nearly the NACA 0012 profile, except that it was slightly thickened at the trailing edge to accommodate the nozzle for the jet flap. Measured dimensions of the profile of the test airfoil at its midspan and a comparison with the NACA 0012 profile[12] are given in Table 1.

The airfoil shown in Fig. 2 was manufactured to an accuracy of better than 0.1 mm from stress-relieved aluminum alloy bar. It was machined in two halves about the plane of symmetry $A-A$ by milling along the span and then by hand-finishing to a polished surface. Air to form the jet flap entered the first plenum chamber from both ends of the span and then passed through a row of 3.0-mm-diam holes into the converging second plenum chamber. This chamber exhausted to the trailing edge through a slit with parallel sides spaced 0.396 mm apart and extending along the full 461-mm span.

The design of the airfoil was a compromise among some conflicting requirements, viz., 1) the need to achieve sufficiently high Reynolds number, dimensionless frequency, and jet momentum coefficient; 2) the need to minimize wind-tunnel wall interference effects; and 3) the need to reduce oscillating mass and the force requirement of the mechanical oscillator, while maintaining sufficient strength and rigidity for the airfoil to withstand internal pneumatic pressure and to be free of troublesome mechanical resonances.

Surface Pressure Measurement Technique

Time-varying lift and moment on the airfoil were measured by integrating the surface pressure distribution at midspan. The pressure measurement technique, based on sequential connection of each pressure tapping by vinyl tubing to a scanning valve and a single transducer, was used in a previous jet-flap study,[6] and its application to this series of tests is described in detail by Simmons.[11] Experimentally determined transfer functions of the tube-scanning valve system are required to enable conversion of transducer outputs to pressures at the surface of the airfoil. The pressure tappings were 0.508-mm-diam holes drilled perpendicular to the sur-

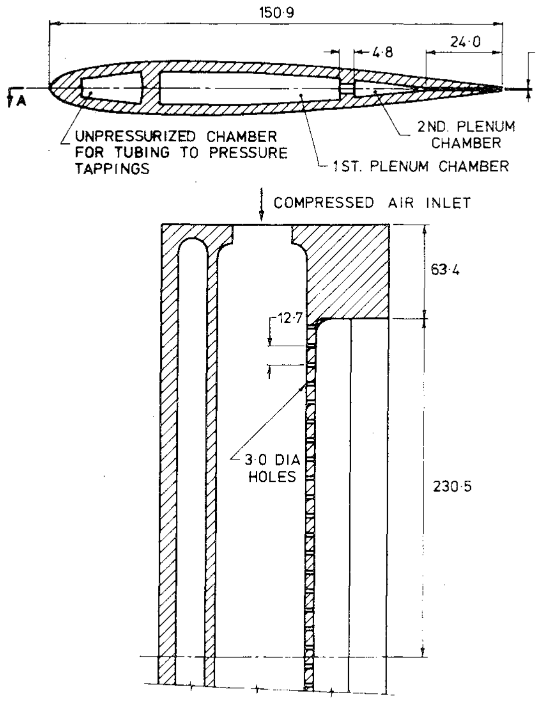

Fig. 2 Details of the test airfoil (dimensions in millimeters).

face of the airfoil. One was located at the leading edge and 22 others were located in pairs, one on each side of the airfoil, at the 11 stations in Table 2. The tappings were staggered within 6 mm of the chord at midspan to facilitate their connection to the internal tubing. Two additional tappings at 19.7% of the chord from the leading edge, and at distances of 40 and 100 mm from the midspan, allowed measurement of the degree of two-dimensionality of the flow in the vicinity of midspan.

Jet Flap

The jet-flap thrust was measured outside the wind tunnel with a pendulum-type balance over a range of pressures in the first plenum chamber. The degree of uniformity of the jet flap was obtained from a spanwise traverse with a small pitot-static tube. Away from the extreme ends of the slit, local deviations from spanwise uniformity of jet momentum coefficient were of the order of 6% and their spatial distribution was correlated strongly with that of the row of holes between the plenum chambers.

Airfoil Oscillator

Sinusoidal displacements of the airfoil in either the pitching or the translating mode were measured with a differential transformer and were generated by a precision Scotch-yoke mechanism, acting through linkages which introduced insignificant blacklash and other distortion. Variation of the frequency of oscillation was achieved by the use of a variable-speed gear box between the Scotch yoke and the electric motor driving it. There were sliding seals between the airfoil and the walls of the wind tunnel.

Data Reduction

Differential transformers on the Scotch-yoke mechanism provided two sinusoidal reference signals, each with the frequency of the airfoil motion, but differing in phase by 90°. Even before some subsequent filtering, the distortion and noise content of these reference signals was found to be more than 40 dB in power below the fundamental. The amplitude and phase angle of the fundamental component of pressure fluctuation at each tapping then were obtained through the analog and digital computation, using a zero time-shift correlation[11] of each of the pressure and displacement signals with each of the two orthogonal reference sinusoidal signals.

Table 2 Location of pairs of pressure tappings at midspan (expressed as percent of chord from leading edge)

0	19.7	70.6
2.78	30.1	80.6
5.00	42.2	90.8
10.1	59.2	95.7

III. Test Program

Tunnel Speed, Reynolds Number, and Jet-Flap Strength

Pressure distributions, with the airfoil both oscillating and stationary, were measured at wind-tunnel speeds of 12.3 and 24.6 m/sec, corresponding to Reynolds numbers based on airfoil chord of 1.29×10^5 and 2.58×10^5, respectively. The six values of jet momentum coefficient were 0, 0.215, 0.407, 0.438, 0.862, and 1.76. Some additional data for a stationary airfoil were obtained at 35.9 m/sec, corresponding to a Reynolds number of 3.81×10^5.

Frequency and Amplitude of Oscillation

The frequency of mechanical oscillation was varied between 0.796 and 15.9 Hz, the equivalent range of dimensionless frequency k being 0.031 to 1.24. The amplitude $\hat{\alpha}$ of pitching oscillation about the trailing edge was 0.0213 ± 0.0002 rad, with a zero mean angle of pitch. The amplitude $\hat{z}$ of translational oscillation normal to the freestream was 2.19 ± 0.02 mm, with the airfoil chordline always parallel to the freestream. Hence the dimensionless ratio $\hat{z}/c$ was 0.0145. In all tests the jet-flap deflection angle η was zero.

IV. Results with Stationary Airfoil

Initial tests, with both the airfoil and the jet flap held stationary, were directed toward a study of the effect of Reynolds number. It has been pointed out by Pope and Harper[13] that tests of a NACA 0015 airfoil at low Reynolds number (e.g., 150,000) will yield possibly misleading lift and drag results. For such relatively thick airfoils at low Reynolds number and zero angle of attack, there is trailing-edge separation on both upper and lower surfaces. The separation point moves, with small angle of attack, more rapidly on one side than the other, giving rise to lift-curve slopes $dC_L/d\alpha$ which are higher than both the maximum of 2π predicted for a thin wing by potential flow theory and experimental results obtained at higher angle of attack and higher Reynolds number. There is the additional complication with the test airfoil in the thickening of the trailing edge and the presence of a jet flap.

In the absence of a jet flap, pressure distributions indicated trailing-edge separation which varied in extent with Reynolds number. Lift curve slopes $dC_L/d\alpha$ were obtained from these pressure distributions at three angles of attack, viz., -0.0236, 0, and $+0.0190$ rad. The dependence of C_L on α was essentially linear. Results are plotted in Fig. 3, where small corrections for wind-tunnel wall interference (viz., solid and wake blockage, and lift effect) have been applied in the manner presented by Pankhurst and Holder.[14] Not unexpectedly, the dependence of $dC_L/d\alpha$ on Reynolds number decreases with increasing Reynolds number. At 3.81×10^5 dependence is small and the corresponding value of 5.92 for $dC_L/d\alpha$ agrees well with the value of 6.02 reported by Jacobs and Sherman[15] for a NACA 0012 airfoil at the same angle of attack and Reynolds number.

Effect of Jet Flap

Figure 4 contains differential pressure distributions representative of those obtained with both airfoil and jet flap stationary. The influence of the jet flap on pressures near the trailing edge is clear. The region of positive differential pressure coefficient attributable to the trailing-edge

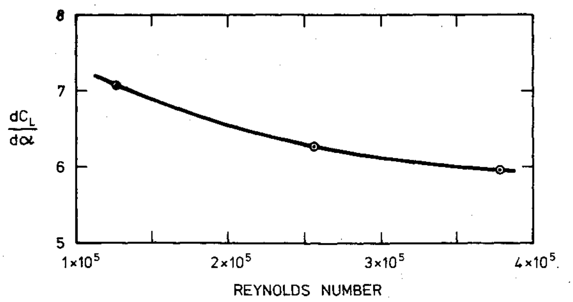

Fig. 3 Measured dependence of $dC_L/d\alpha$ on Reynolds number for stationary airfoil without jet flap.

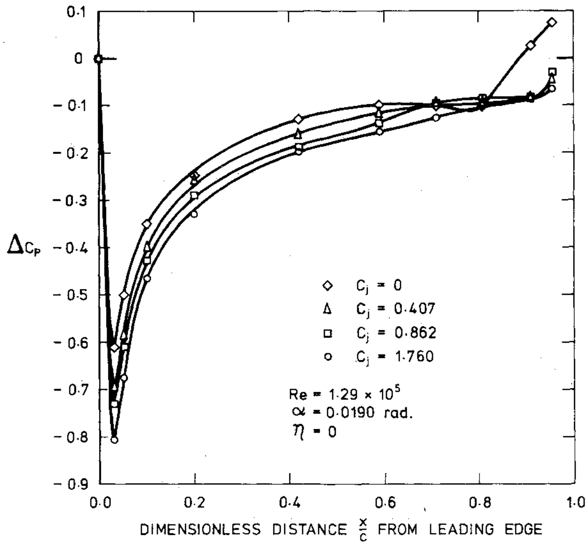

Fig. 4 Measured dependence on C_j of distribution of differential pressure coefficient between upper and lower surface of stationary airfoil.

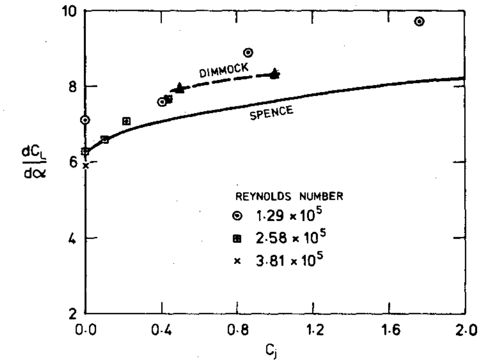

Fig. 5 Measured dependence of $dC_L/d\alpha$ (excluding jet thrust) on C_j for stationary airfoil; and a comparison with other experimental (Dimmock [18]) and theoretical (Spence [18]) results.

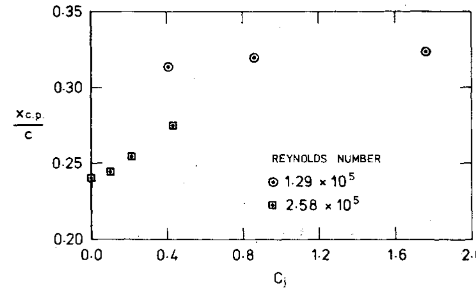

Fig. 6 Measured dependence on C_j of location x_{cp} of center of pressure as fraction of chord from leading edge.

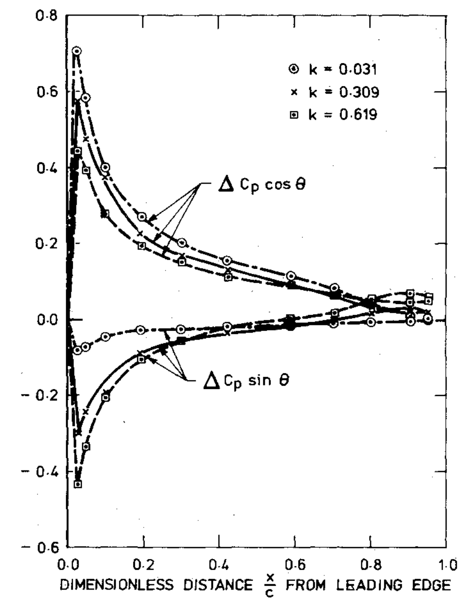

Fig. 7 Typical measured dependence on k of in-phase ($\Delta C_p\cos\theta$) and quadrature ($\Delta C_p\sin\theta$) components of differential pressure distribution for oscillatory pitching with $C_j = 0.438$ and Reynolds number of 2.58×10^5.

separation disappears when the jet flap is present. Figures 5 and 6 show the dependence of the lift curve slope and the location of the center of pressure on Reynolds number and jet momentum coefficient, again with linearity being indicated over the range of angle of attack. As jet momentum coefficient C_j is increased from zero, the values of lift curve slope for Reynolds numbers of 1.29×10^5 and 2.58×10^5 approach each other and merge for C_j greater than about 0.4. An extrapolation of the results in Fig. 6 indicates that the location of the center of pressure is similarly insensitive to Reynolds number only if C_j exceeds about 0.7.

Although there is a need for tests at other Reynolds numbers, it is reasonable to draw the following conclusion. Aerodynamic derivatives, measured in these tests at a Reynolds number of 2.58×10^5, are within about 5% of those which would be measured at higher Reynolds numbers, irrespective of the value of C_j. The same can be said of measurements at a Reynolds number of 1.29×10^5 only if C_j is greater than about 0.7.

V. Results with Oscillatory Pitching

Linearity

The linearity of this group of tests was studied through the use of a real-time spectrum analyzer to obtain power spectral densities of some representative excitation and response signals. At the highest test frequency, the amplitudes of the second and third harmonics in the output of the airfoil-displacement transducer were less than 1/20 and 1/40, respectively, of the fundamental, and at lower frequencies they were considerably less. In power spectra of pressure fluctuations at 42.2% of the chord, the second and third harmonics were comparable, their amplitudes varying with test conditions from about 1/20 of the fundamental, at the lowest frequency, to about 1/10 at the highest frequency. The harmonic content in the pressure signals largely was due to that present in the displacement, and the assumption of a linear excitation-response relationship is justified at this small pitching amplitude of 0.0213 rad.

Oscillatory Pressure Distributions

Figure 7 contains representative pressure distributions extracted from the full set of test results.[11] The differential pressure coefficient ΔC_p between the upper and lower surfaces of the airfoil has been resolved into two components: $\Delta C_p\cos\theta$, in phase with the angle of pitch, and $\Delta C_p\sin\theta$, normal

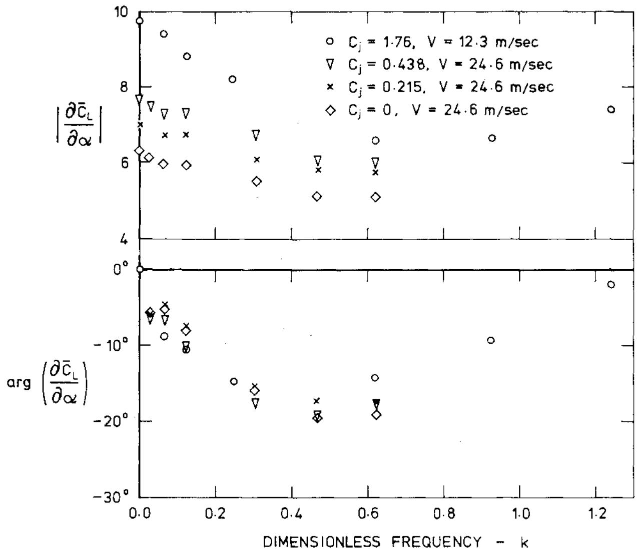

Fig. 8 Measured dependence on C_j and k of $\partial \bar{C}_L/\partial\alpha$ (excluding jet thrust) for oscillatory pitching of airfoil about trailing edge.

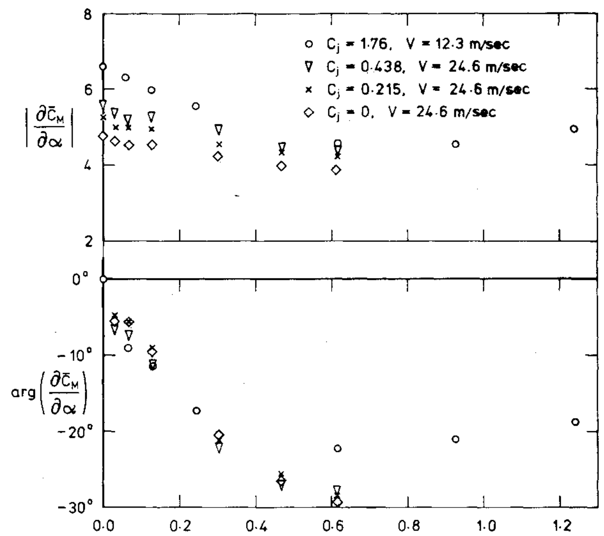

Fig. 9 Measured dependence on C_j and k of $\partial \bar{C}_M/\partial\alpha$ (excluding jet thrust) for oscillatory pitching of airfoil about trailing edge.

to it. (θ is the angle by which the local differential pressure coefficient leads the angle of pitch)

Aerodynamic Derivatives

The pressure distributions were integrated to obtain complex lift and moment coefficients expressed in terms of their amplitude and phase angle relative to the angle of pitch. The observation of virtual linearity has been incorporated in the calculation of the complex aerodynamic derivatives $\partial \bar{C}_L/\partial\alpha$ and $\partial \bar{C}_M/\partial\alpha$, but the contribution from jet-flap thrust has been excluded at this stage. For test conditions in which trailing-edge separation effects are minor, the dependence of the complex aerodynamic derivatives on dimensionless frequency and jet-momentum coefficient is shown in Figs. 8 and 9, where corrections have been made for three forms of wind-tunnel wall interference, viz., solid and wake blockage and lift effect. These corrections, as presented by Pankhurst and Holder[14] for a stationary airfoil without a jet flap, were applied by treating the jet-flap airfoil as an equivalent airfoil generating the same lift and moment, and by assuming quasistatic aerodynamic behavior. Thus, at each frequency, the amplitude of angle of pitch and the amplitude of moment coefficient have been corrected, but the amplitudes of lift coefficient and phase angles have not.

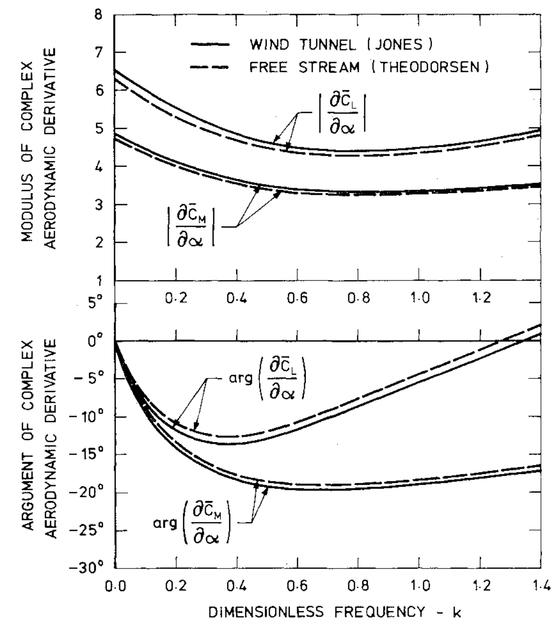

Fig. 10 A comparison of theoretical complex aerodynamic derivatives for an airfoil, without jet flap, undergoing oscillatory pitching about the trailing edge both in the wind tunnel and a freestream.

This use of quasistatic corrections for lift effect is justified in view of the results obtained by Jones[16] for wind-tunnel wall interference effects on measurement of aerodynamic derivatives for oscillating airfoils. For the model without jet flap and the wind-tunnel dimensions used in these tests, Jones' theory gives the results in Fig. 10, where a comparison is made with the results of Theodorsen's[17] analysis in perfectly freestream conditions. Clearly, the lift and moment corrections are small; in fact the magnitude corrections differ insignificantly from those for a stationary airfoil. Phase corrections are always 1° or less and are comparable with experimental error.

VI. Results with Oscillatory Translation

Signal-to-Noise Ratio

In these tests at constant amplitude of translation, the amplitude of pressure fluctuations increased with frequency of oscillation. In the presence of wind-tunnel turbulence there is obviously a lower limit to frequency of oscillation below which the pressure signal-to-noise ratio becomes too small for measurements of acceptable accuracy. For translation tests, it was in general, not possible to test at frequencies as low as those used in the pitching tests.

Aerodynamic Derivatives

Oscillatory pressure distributions were integrated and again the observation of virtual linearity, based on the previously described study of power spectra of the signals, has been incorporated in the calculation of the complex aerodynamic derivatives $\partial \bar{C}_L/\partial(z/c)$ and $\partial \bar{C}_M/\partial(z/c)$. The results, in Figs. 11 and 12 with jet-flap thrust excluded, are for tests in which trailing-edge separation is negligible and are corrected for wind-tunnel wall interference in the manner described for the pitching tests. Again, this use of quasistatic corrections is justified by a comparison[11] of the predictions of Theodorsen and Jones for a translating airfoil in a freestream and the wind tunnel, respectively.

VII. Discussion

Accuracy

The accuracy of the results was determined mainly by the following factors:

1) Some nonuniformity of the jet flap along the slit caused an uncertainty of about 6% in the local C_j. However, on the

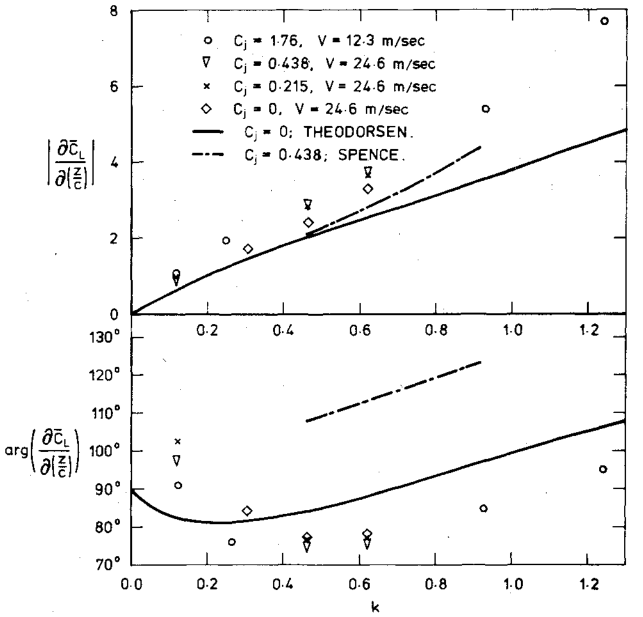

Fig. 11 Measured dependence on C_j and k of $\partial\bar{C}_L/\partial(z/c)$ (excluding jet thrust) for oscillatory translation of airfoil.

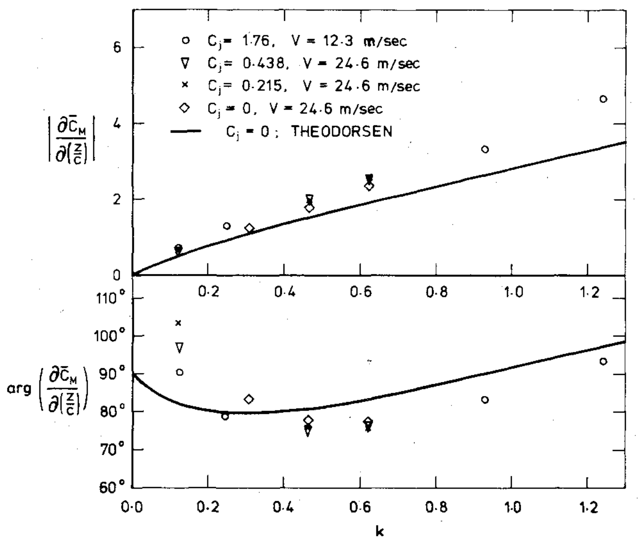

Fig. 12 Measured dependence on C_j and k of $\partial\bar{C}_M/\partial(z/c)$ (excluding jet thrust) for oscillatory translation of airfoil.

airfoil surface this nonuniformity was less pronounced and deviations of about 3% from a two-dimensional pressure distribution were observed over the middle 200 mm of the span.

2) From spectral measurements of the signal-to-noise ratios encountered, it is estimated that pressure coefficients are generally accurate in amplitude to about 3% and in phase to about 2°. At the lowest frequencies the phase accuracy was poorer and is best estimated from the scatter of points on the various graphs.

3) The limited number of pressure tappings, particularly in the vicinity of the leading and trailing edges, introduced inaccuracy in the lift and moment coefficients of about 2% in amplitude.

4) Wind-tunnel wall interference effects on the unsteady aerodynamics of a jet-flap airfoil are not well understood but, in view of the small lift coefficients generated in these tests, the small corrections used are expected to give freestream results with insignificant error.

Stationary Tests

In Fig. 5 there is good agreement, particularly at small C_j, between the stationary test results and some high-lift experiments of Dimmock (taken from Spence[18]). The latter results were obtained with a 12.5% thick elliptic cylinder of 203-mm chord, with a jet flap close to the trailing edge and deflected through an angle $\eta = 31.4°$. The potential flow theory of Spence[18] for thin jet-flap airfoils underestimates the experimental lift coefficients due to pressure, particularly at high C_j, but this is a significantly better agreement than that with the much lower experimental lift coefficients of Trenka and Erickson.[5] Although their measurements were at Reynolds numbers similar to those used by this author, Trenka and Erickson tested a somewhat different configuration, viz., a jet exhausting over the upper surface of a 20% flap from a spanwise slot located at 80% of the chord from the leading edge.

Oscillatory Tests

Spence[3] extended his theoretical work with stationary jet-flap airfoils to three oscillatory situations: 1) a fixed airfoil with oscillating jet deflection angle, 2) oscillatory translation (or plunging) of an airfoil with zero jet deflection angle, and 3) oscillatory pitching of an airfoil about its trailing edge, with zero jet deflection angle. The following assumptions were made, thereby restricting valid solutions to an unrealistically high range of frequencies but to a realistically low range of jet strengths: $k \geq 2\pi$, $C_j/4 \ll 1$, and $C_j k < 8$. Complex lift coefficients were found by Spence for the first two oscillatory situations but not for the third, because of albegraic complications. This missing solution for airfoil pitching was found later, together with the moment coefficient, by Trenka and Erickson,[5] who used Spence's equations and assumptions.

Figures 13 and 14 are comparisons of the lift and moment coefficients found theoretically and experimentally by Trenka and Erickson with interpolations between this author's experimental results. The latter have been transformed by the appropriate linear combination of the pitching and translation results in Secs. V and VI to the situation of airfoil pitching about an axis at 38.15% of the chord from the leading edge. Jet thrust has been included, but the damping force associated with Coriolis acceleration of the internal jet flow has been assumed negligible from an analysis of the following simple model. The internal jet flow, as a first approximation, can be treated as incompressible and inviscid with constant cross-sectional area and with the contraction confined to the vicinity of the trailing edge. It is then easy to show, for oscillatory pitching of the airfoil through small angles, that the ratio of the magnitude of the Coriolis force to the component of jet thrust in the lift direction is $2\ell\omega/V_j$, where V_j is the mean velocity of jet at exit, and ℓ is internal flow length in chordwise direction. For the high subsonic values of V_j used in these tests, this force ratio is about 0.05 at $\omega = 100$ rad/sec. In full-scale configurations the value of ℓ will be greater, but ω will be considerably less so that the force ratio is likely to be small.

The small value of 0.34 for C_j in Fig. 13 and 14 meets the requirements of the theory and implies an upper limit to k of 23.5 The low-frequency limit to the theory, $k = 2\pi$, has been waived in these comparisons so that the very poor agreement with this author's results is not surprising. Even the trends of lift-coefficient amplitude with frequency are opposite, a finding similar to that by Simmons and Platzer[6] for the situation of a fixed airfoil with oscillating jet deflection angle. The experimental results of Trenka and Erickson, with the somewhat different configuration, are far too limited to allow particularly meaningful comparisons. The predictions of Theodorsens' theory, with $C_j = 0$, shown by Halfman[19] to be quite good in practice, are included in Figs. 13 and 14. They exhibit the same trends with frequency as this author's results, as would be expected if C_j is sufficiently low. On the other hand, the theoretical results of Trenka and Erickson do not reduce to those of Theodorsen and Halfman as C_j approaches zero.

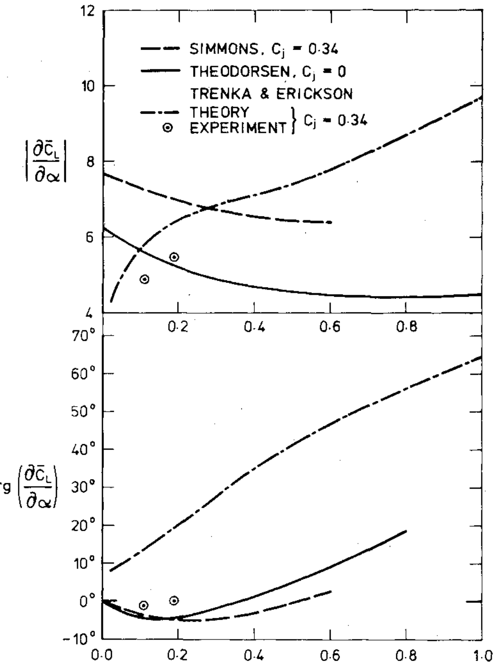

Fig. 13 Comparison of measured $\partial \bar{C}_L/\partial\alpha$ with other theoretical and experimental results for oscillatory pitching about axis at $x/c = 0.3815$; jet thrust is included. (Note that the low-frequency limit, $k = 2\pi$, to the theory of Trenka and Erickson has been waived here, and that their experimental configuration differs from that of Simmons.)

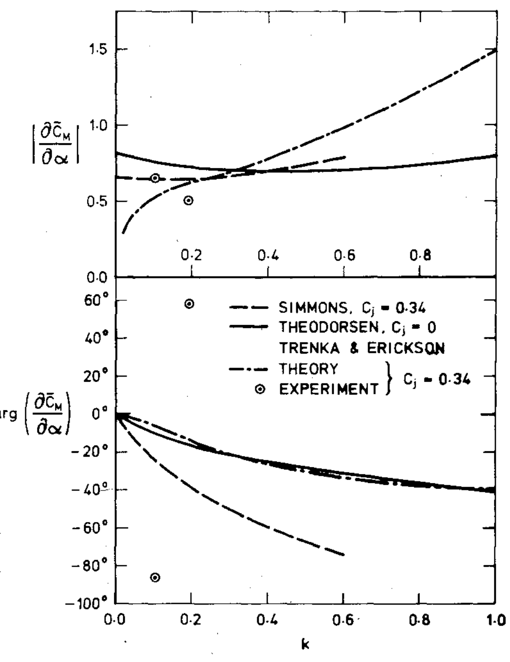

Fig. 14 Comparison of measured $\partial \bar{C}_M/\partial\alpha$ with other theoretical and experimental results for oscillatory pitching about axis at $x/c = 0.315$; $\bar{C}_M$ is measured about $x/c = 0.3815$, and jet thrust is included.

It is noticeable that the magnitudes of measured aerodynamic derivatives are considerably more dependent on C_j than are the phase angles, especially for frequencies k less than 0.6. This suggests that, at these frequencies, curvature of the jet is small in that region of the jet flap which affects the airfoil significantly. The main influence of the jet flap at zero deflection angle is its increase of the "effective" chord. Obviously, at sufficiently high frequencies, jet curvature will become large, but then the acceleration of the airfoil and aerodynamic forces due to noncirculatory flow will dominate the effects of the jet flap. This behavior is indicated in Figs. 8 and 9 by the tendency of the magnitudes of measured aerodynamic derivatives to merge with increase of frequency.

For translational oscillation of the airfoil with jet flap at frequencies high enough to allow reasonable pressure measurement accuracy, the experimental trends are again the same as those from Theodorsen's theory with $C_j = 0$ (Figs. 11 and 12). Spence's theory also predicts these trends in magnitude of lift coefficient, but it gives phase angles which differ markedly from the other results.

VIII. Conclusions

The experimental results reported here provide information, previously unavailable, for an assessment of the feasibility of the jet flap as a lift control device in aircraft gust-load alleviation and flutter-mode stabilization systems. Although relatively low Reynolds numbers and small displacements have been used, it has been shown that the presence of a jet flap can reduce the significance of the boundary layer on the airfoil. This should be verified by tests at higher Reynolds numbers and with larger displacements, but experimental difficulties will be increased greatly if the range of dimensionless frequency is to be maintained.

Because of the assumptions in the theory, the results of Spence, and Trenka and Erickson are applicable only to frequencies much higher than those used in these tests. The theory is incapable of predicting even experimental trends when used at the lower frequencies which are of practical interest. Typically, for a full-scale airfoil with a chord of 2 m, a vibration frequency of 50 rad/sec corresponds to a dimensionless frequency, $k = 1$, at the relatively low freestream velocity of 100 m/sec. This value of k is within the range of these tests and decreases with increase in freestream velocity. There is a need for a fresh look at the theory of the unsteady jet flap, and pressure distributions obtained by this author are fundamental data for evaluation of future developments. Mathematical modeling of the jet wake appears to be inadequate, and measurements of the shape and velocity profile of the oscillating jet flap now are needed.

References

[1] Korbacher, G. K. and Sridhar, K., "A Review of the Jet Flap," UTIA Review, 1960, University of Toronto.

[2] Korbacher, G. K., "Aerodynamics of Powered High-Lift Systems," *Annual Review of Fluid Mechanics*, Vol. 6, 1974, pp. 319-358.

[3] Spence, D. A., "The Flow Past a Thin Wing with an Oscillating Jet Flap," *Philosophical Transactions of the Royal Society of London*, Ser. A, Vol. 257, June 1965, pp. 445-477.

[4] Erickson, J. C., Jr., "A Theory of Unsteady Motions of Jet-Flapped Thin Airfoils," Ph.D. Thesis, 1962, Cornell University.

[5] Trenka, A. R. and Erickson, J. C., Jr., "The Determination of Unsteady Aerodynamics of a Two-Dimensional Jet-Flap Wing," CAL AC-2260-S-1, April 1970, Cornell Aeronautical Laboratory, Inc., Buffalo, N.Y.

[6] Simmons, J. M. and Platzer, M. F., "Experimental Investigation of Incompressible Flow Past Airfoils with Oscillating Jet Flaps," *Journal of Aircraft*, Vol. 8, Aug. 1971, pp. 587-592.

[7] Kretz, M., "Comme Asservie des Forces Aerodynamiques Instationnaires," Rept. DE 07-44E5, Dec. 1973, Girvaions Dorand., Suresnes, France.

[8] Takeuchi, K., "Two and Three-Dimensional Unsteady Lift Measurement of Jet-Flapped Wings," M. S. Thesis, June 1970, Pennsylvania State University.

[9] Platzer, M. F., Deal, L. J., and Johnson, W. S., "Experimental Investigations of Oscillatory Jet Flow Effects," *Proceedings of Symposium on Unsteady Aerodynamics*, March 1975, U.S. Air Force Office of Scientific Research, University of Arizona, Tuscon, Ariz.

[10] McLeod, J. J., III and Kretz, M., "Multicyclic Jet-Flap Control for Alleviation of Helicopter Blade Stresses and Fuselage Vibration," *Specialists' Meeting on Rotorcraft Dynamics*, Paper 23, Feb. 1974, NASA Ames Research Center.

[11] Simmons, J. M., "Experimental Aerodynamic Derivatives of a Sinusoidally Oscillating Aerofoil with Jet Flap in Two-Dimensional Incompressible Flow," Res. Rept. 11/74, Dec. 1974, Dept. Mechanical Engineering, Univ. of Queensland, Brisbane, Queensland, Australia.

[12]Abbott, I.H., and Von Doenhoff, A.E., *Theory of Wing Sections, Including a Summary of Aerofoil Data*, McGraw-Hill, New York, 1949.

[13]Pope, A and Harper, J. J., *Low-Speed Wing Tunnel Testing*, Wiley, New York, 1966, p. 403.

[14]Pankhurst, R. C. and Holder, D. W., *Wind Tunnel Techniques*, Pitman, London, 1952, Chap. 8.

[15]Jacobs, E. N. and Sherman, A., "Airfoil Section Characteristics as Affected by Variations of the Reynolds Number," Rept. 586, June 1936, NACA.

[16]Jones, W. P., "Wind-Tunnel Interference Effects on Measurements of Aerodynamic Coefficients for Oscillating Aerofoils," R&M 2786, Sept. 1950, National Physical Laboratory.

[17]Theodorsen, T., "General Theory of Aerodynamic Instability and the Mechanism of Flutter," Rept. 496, 1935, NACA.

[18]Spence, D. A., "The Lift Coefficient of a Thin, Jet-Flapped Wing," *Proceedings of the Royal Society of (London)*, Vol. A238, Dec. 1956, pp. 46-68.

[19]Halfman, R. L., "Experimental Aerodynamic Derivatives of a Sinusoidally Oscillating Airfoil in Two-Dimensional Flow," Rept. 1108, 1952, NACA.