Measured Pressure Distributions on an Airfoil with Oscillating Jet Flap

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

The experiments described, in conjunction with an earlier study by the author, comprise a set which enables the prediction of aerodynamic forces and moments on a two-dimensional airfoil undergoing general motions involving small displacements. The magnitude and phase angle of aerodynamic derivatives generated on a fixed airfoil by small oscillations of a jet flap at the trailing edge have been measured in incompressible flow. Results are presented for a range of frequency of oscillation and strength of the jet and Reynolds number. The apparatus and techniques used to obtain oscillatory surface pressure distributions are described. The measurements reported agree well with the majority of other experimental data. The trends are predicted by the theory of Potter, but not by the theory of Spence which should be applied only for much higher dimensionless frequencies than those used in the experiments.

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 leading edge with clockwise moment positive in Fig. 1)
$\partial\bar{C}_L/\partial\eta$, $\partial\bar{C}_M/\partial\eta$, etc.	= complex aerodynamic derivatives due to pressure (with jet thrust excluded)
$\bar{C}_{L_\eta}$	= $(\partial\bar{C}_L/\partial\eta)+C_j$ = complex lift slope (due to pressure and jet thrust)
$C_{L_{\eta o}}$	= lift slope in steady flow
ΔC_p	= $(p_{\text{upper}}-p_{\text{lower}})/q$ = differential pressure coefficient
i	= $\sqrt{-1}$
k	= $\omega c/V$ = dimensionless frequency
p	= pressure
q	= $\frac{1}{2}\rho V^2$ = freestream dynamic pressure
t	= time
$\bar{t}$	= Vt/c = dimensionless time
V	= freestream velocity
x	= distance along chord line from leading edge
z	= translation of trailing edge of airfoil (zero for these experiments)
α	= angle of pitch of airfoil relative to free stream direction. (zero for those experiments)
ρ	= density of air at ambient conditions
θ	= angle by which ΔC_p leads oscillatory rotation of the trailing edge nozzle (radians)
φ	= angle by which $\bar{C}_{L_\eta}$ leads rotation of trailing edge nozzle (radians)
η	= angle of rotation of the trailing edge nozzle (radians)
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 (radians)

Received Jan. 26, 1976; revision received May 21, 1976. 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, Dept. of Mechanical Engineering; presently adjunct professor, Dept. of Aeronautics, Naval Postgraduate School, Monterey, Calif.

I. Introduction

THERE has been a recent increase of interest in the unsteady characteristics of a jet flap airfoil, largely as a result of developments in helicoptor rotor technology and in STOL and VTOL aircraft. 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 distrubution over the airfoil. Control of lift can be achieved by changing either the strength of the jet or the angle at which it emerges.

Studies of the potential of the jet flap as a fast acting lift control device have been reviewed by Platzer[1] who draws attention to the considerable variation among the limited theoretical[2-5] and experimental[5-8] results. To help clarify this situation, this author has undertaken a series a measurements of airfoil surface pressure distributions for a number of basic motions of a jet flap airfoil. Results have already been published[9,10] from tests with a jet flap emerging at a fixed angle from an airfoil which is undergoing either oscillatory pitching about the trailing edge, or oscillatory translation normal to the freestream. Measurements of the effect of the frequency of oscillation of the jet angle on the pressure distribution over a stationary airfoil are presented here and in a report[11] which contains some finer detail. An earlier and related experiment[6] by the author was based on a jet flap emerging from a row of holes along the trailing edge. The use of a slot, in the tests reported here, has led to a more effective jet flap, and a more direct comparison with the results of other investigators.

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 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

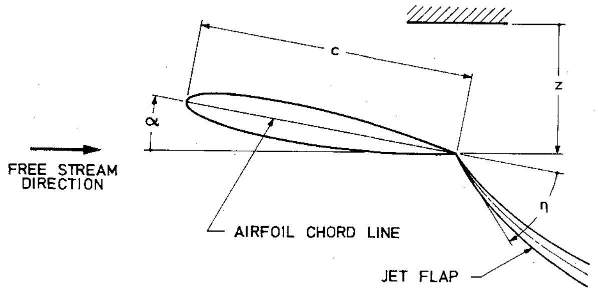

Fig. 1 Co-ordinate system for a two-dimensional jet flap airfoil.

behavior in any general motion involving small displacements. If $\alpha=\hat{\alpha}\cos k\tilde{t}$, $z=\hat{z}\cos(k\tilde{t}+\psi_1)$, $\eta=\hat{\eta}\cos(k\tilde{t}+\psi_2)$ are simultaneous inputs with the same dimensionless frequency k, but different phase angles, then, using complex variable notation, $\hat{C}_L e^{i\psi_L}$, to describe both the amplitude and phase angle of the resulting lift coefficient due to pressure and jet thrust, $C_L=\hat{C}_L\cos(k\tilde{t}+\psi_L)$, it follows that

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

Here $\partial\bar{C}_L/\partial\alpha$, $\partial\bar{C}_L/\partial(z/c)$ and $\partial\bar{C}_L/\partial\eta$ are complex aerodynamic derivatives due to pressure (with jet thrust excluded). Similarly, the moment coefficient due to pressure and jet thrust, $C_M=\hat{C}_M\cos(k\tilde{t}+\psi_M)$ can be written in complex variable notation as

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

The complex aerodynamic derivatives due to pressure, $\partial\bar{C}_L/\partial\alpha$, $\partial\bar{C}_L/\partial(z/c)$, $\partial\bar{C}_L/\partial\eta$ etc. are dependent on k, and can be evaluated by frequency response measurements in any of three tests based on a linearly independent set of inputs α, z, and η. In the tests reported here, $\partial\bar{C}_L/\partial\eta$ and $\partial\bar{C}_M/\partial\eta$ were measured in two-dimensional incompressible flow with the set of inputs, $\alpha=0$, $z=0$, $\eta=\hat{\eta}\cos k\tilde{t}$. Measurements of $\partial\bar{C}_L/\partial\alpha$, $\partial\bar{C}_M/\partial\alpha$, $\partial\bar{C}_L/\partial(z/c)$ and $\partial\bar{C}_M/\partial(z/c)$ have been made previously by the author[9] using the two sets of inputs

a) $\alpha=\hat{\alpha}\cos k\tilde{t}$, $z/c=0$, $\eta=0$ (oscillatory pitching)

b) $\alpha=0$, $z/c=(\hat{z}/c)\cos k\tilde{t}$, $\eta=0$ (oscillatory translation)

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 × 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%.

The Airfoil

The rigid two-dimensional test airfoil with a chord of 208.7 mm was larger than that used in the earlier pitching and translating tests. It spanned the full 461 mm height of the test section in the vertical plane midway between the side walls. The symmetrical airfoil was obtained from that of a NACA 0012 profile with a 228.6 mm chord by removing the aft 8.7% of the chord to accommodate the nozzle for the jet flap. The airfoil, shown in Fig. 2, was manufactured to an accuracy of better than 0.08 mm from case bronze. 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 3.12 mm diameter holes into the second plenum chamber. This chamber exhausted to the trailing edge through a nozzle which could be rotated through small angles to vary the angle of jet deflection at exit. The nozzle, shown in detail in Fig. 2, comprised a converging duct feeding into a slot with parallel sides spaced 0.38 mm apart. This slot extended along the full 457.2 mm span, except for small spacers every 50.8 mm which were incorporated to eliminate excessive elastic distortion of the slot. Care was taken in the design of the trailing edge to avoid Coanda effect in the emerging jet.

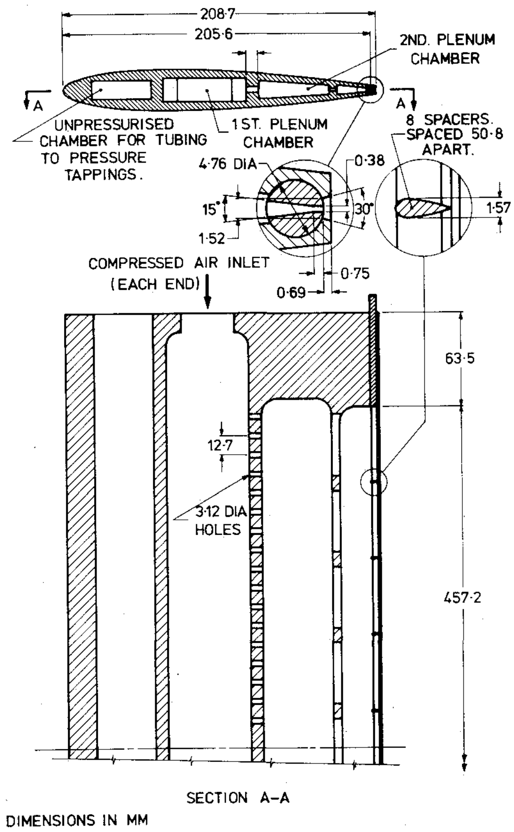

Fig. 2 Details of the test airfoil.

Surface Pressure Measurement Technique

Time-varying lift and moment on the airfoil were measured by integrating the surface pressure distribution at mid span. The pressure measurement technique of sequential connection of each pressure tapping by tubing to a scanning valve and a single Pitran presure sensitive transistor is described in detail in a previous study.[10] 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 diameter holes drilled perpendicular to the surface of the airfoil. One was located at the leading edge and another thirty-two were located in pairs, one on each side of the airfoil at the sixteen stations in Table 1. The tappings were staggered within 3 mm of the chord at mid span to facilitate their connection to

Table 1 Location of pairs of pressure tappings at mid span (expressed as per cent of 208.7 mm chord from leading edge)

0.0	8.2	27.4	76.6
1.4	10.9	32.8	82.0
2.7	16.5	43.7	90.8
5.5	21.9	54.7	94.0
			96.9

the internal tubing. Four additional pressure tappings away from the mid span were used to measure the degree of two-dimensionality of the flow.

The 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 settling chamber. Sinusoidal variations of the jet deflection angle were generated by oscillatory rotation of the trailing edge nozzle by a precision Scotch yoke mechanism acting through linkages. This introduced insignificant backlash 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. The angle of rotation η of the nozzle was measured with a differential transformer on the Scotch yoke.

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 ninety degrees. The amplitude and phase angle of the fundamental component of pressure fluctuation at each tapping were then obtained through hybrid computation. This was accomplished using a zero time-shift correlation of each of the pressure and displacement signals with each of the two orthogonal reference sinusoidal signals.[10]

III. Test Program

Tunnel Speed, Reynolds Number, and Jet Flap Strength

All tests were performed with the airfoil fixed at zero angle of attack, and surface pressure distributions with the jet flap both oscillating and stationary were measured at a wind tunnel speed of 30.5 m/sec. This corresponds to a Reynolds number based on airfoil chord of 4.06×10^5. The three values of jet momentum coefficient were 0.099, 0.195 and 0.383. Limited additional data was obtained at Reynolds numbers of 2.05×10^5, 2.90×10^5 and 4.87×10^5, with corresponding jet momentum coefficients of 0.395, 0.389, and 0.193, respectively.

Frequency and Amplitude of Oscillation

The frequency of rotational oscillation of the trailing edge nozzle was varied between 1.59 and 23.9 Hz, the equivalent range of dimensionless frequency k being 0.0684 to 1.03 at a tunnel speed of 30.5 m/sec. The amplitude $\hat{\eta}$ of sinusoidal rotational oscillation of the trailing edge nozzle was 0.0543 ± 0.0002 radians with a zero mean angle of rotation relative to the airfoil chord plane.

IV. Results

Pressure Distributions

Figures 3 and 4 are plots of the measured pressure distributions generated by an oscillating jet flap with jet momentum coefficient of 0.099. These are typical of the full set of pressure distributions.[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 rotation η of the nozzle, and $\Delta C_p \sin\theta$ normal to it. (θ is the angle by which the local differential

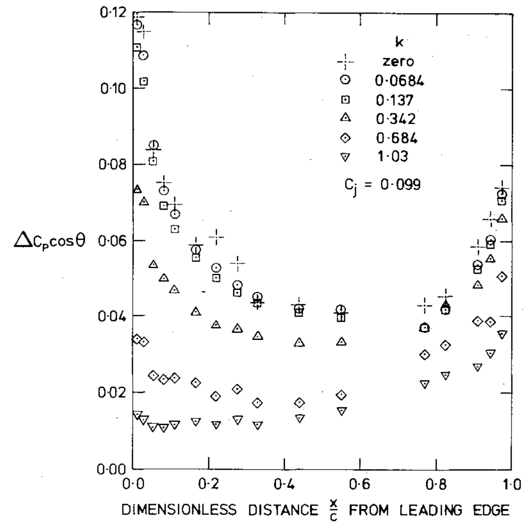

Fig. 3 Measured dependence on frequency k of component of differential pressure distribution in phase with nozzle rotation. (For $C_j = 0.099$, $V = 30.5$ m/sec., $\hat{\eta} = 0.0543$ radians).

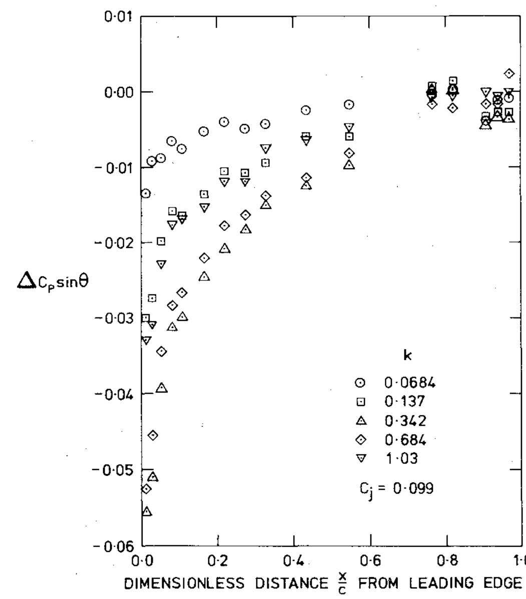

Fig. 4 Measured dependence on frequency k of component of differential pressure distribution phase = leading nozzle rotation by $\pi/2$ radians. (For $C_j = 0.099$, $V = 30.5$ m/sec., $\hat{\eta} = 0.0543$ radians).

pressure coefficient leads the angle of rotation of the nozzle). Also included in Fig. 3 is the steady pressure distribution with the nozzle fixed at an angle equal to the amplitude of nozzle rotation in the oscillatory tests.

The pressure distributions exhibit for steady flow the well known leading and trailing edge peaks, but they are very much dependent on the frequency of jet flap oscillation in unsteady flow. The component $\Delta C_p \sin\theta$ varies in a complicated manner near the trailing edge, due possibly to a small region of separated flow. However, this result may reflect errors in measurement of $\Delta C_p \sin\theta$ which is small in this region. In the absence of a jet flap some separation results from the rather blunt trailing edge, but its extent has been shown[9] to be considerably reduced if a jet flap is added.

Linearity

Pressure distributions for a stationary jet flap were integrated to give the essentially linear relationship, shown in Fig. 5, between lift coefficient due to pressure and the small angle of rotation of the nozzle. For the oscillatory tests, spec-

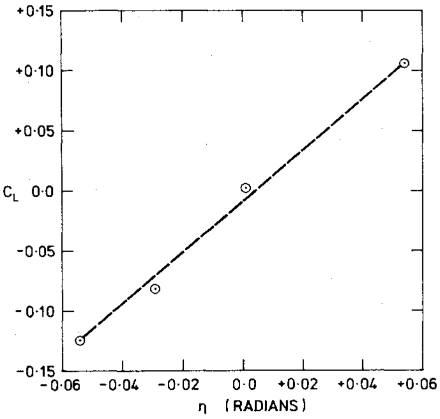

Fig. 5 Measurements to determine linearity of C_L vs η for stationary jet flap. Jet momentum coefficient, $C_j = 0.383$.

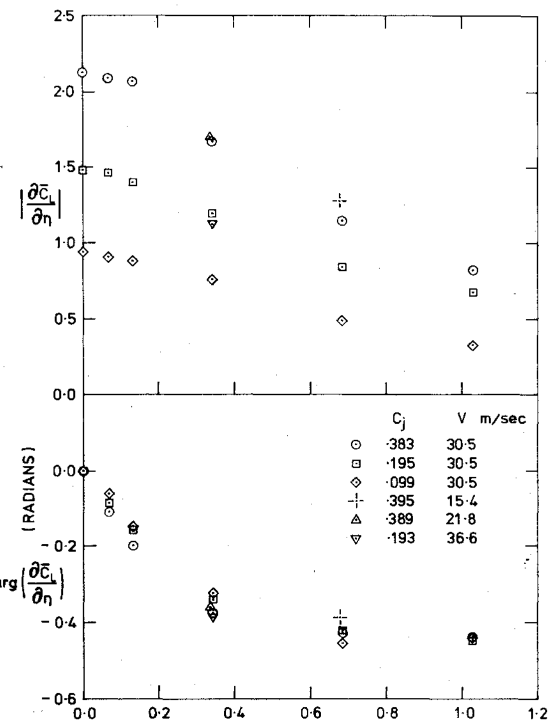

Fig. 6 Measured dependence of $(\partial \bar{C}_L/\partial \eta)$ (excluding jet thrust) on C_j and k.

tral analysis of representative pressure and displacement signals was used in the manner of the author's earlier tests[9,10] to confirm linearlity.

Aerodynamic Derivatives

The pressure distributions for the oscillatory tests were integrated to obtain the complex aerodynamic derivatives due to pressure $\partial \bar{C}_L/\partial \eta$ and $\partial \bar{C}_M/\partial \eta$, expressed in Figs. 6 and 7 in terms of their modulus (or amplitude) and argument (or phase angle) relative to the nozzle rotation η. The observation of virtual linearity of aerodynamic derivatives has been incorporated in these calculations, but the contribution from the jet flap thrust and corrections for wind tunnel wall interference have been excluded at this stage.

V. Discussion

Accuracy and Wind Tunnel Interference

From considerations of uncertainties in transducer calibration, the signal-to-noise ratios encountered, the degree

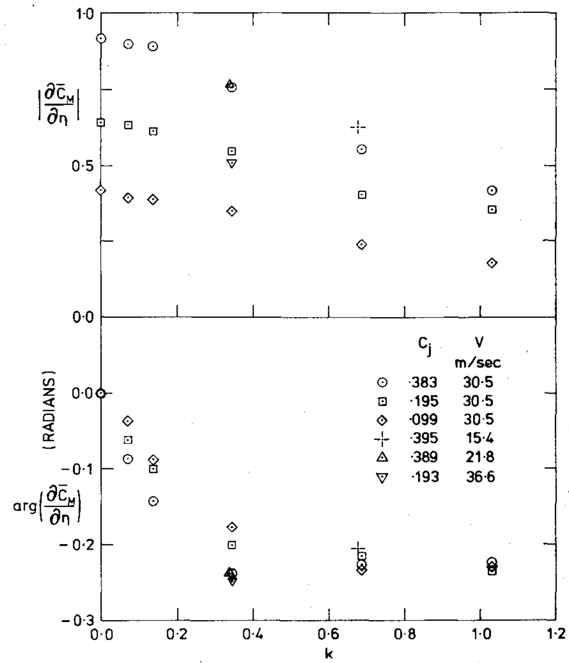

Fig. 7 Measured dependence of $(\partial \bar{C}_M/\partial \eta)$ (excluding jet thrust) on C_j and k. Moments are about leading edge of airfoil.

of two-dimensionality of the flow and the use of a finite number of pressure tappings, it is estimated that the measurements of aerodynamic derivatives are accurate in amplitude to about three per cent and in phase to about 0.03 radians. Wind tunnel wall interference on an airfoil with oscillating jet flap is not yet understood. However, the study by Lissaman[12] of ground effect on a jet flap in steady flow indicates that interference is likely to be small and, consequently, no corrections have been applied to the results reported here.

Reynolds Number

In addition to the main set of measurements at a Reynolds number of 4.06×10^5, Figs. 6 and 7 each contain three additional measurements made at Reynolds numbers of 2.05×10^5, 2.90×10^5, and 4.87×10^5. There is no discernible effect of Reynolds number over this range.

Jet Flap Angle

Aerodynamic derivatives and lift slopes have been defined here as derivatives with respect to the angle of rotation of the nozzle rather than to the 'effective' angle of the tangent to the jet flap at exit from the nozzle. The latter angle was not measured in these tests and it is conceivable that it could differ slightly from nozzle rotation. This possibility has been disregarded at this stage to enable the following comparisons with other studies.

Comparison with other Studies

Figures 8 and 9 are comparisons of the results of this study with the theoretical results of Spence[2] and Potter,[3] and the experimental results of Simmons and Platzer,[6] Kretz[7] and Takeuchi.[8] The complex lift slopes $\bar{C}_{L_\eta}$ contain contributions due to both airfoil surface pressure and jet thrust, and the measurements from various configurations of airfoil are given a common basis through normalization by the lift slope in steady flow. The measurements of Kretz, Simmons and Platzer and this study all show similar trends with small derivations which might be due to different configurations of airfoil. However, they differ markedly from the measurements of Takeuchi, even though Kretz and Takeuchi both used mechanical trailing edge flaps to vary the jet angle. (Test details have been summarized by Platzer[1]). Through their use

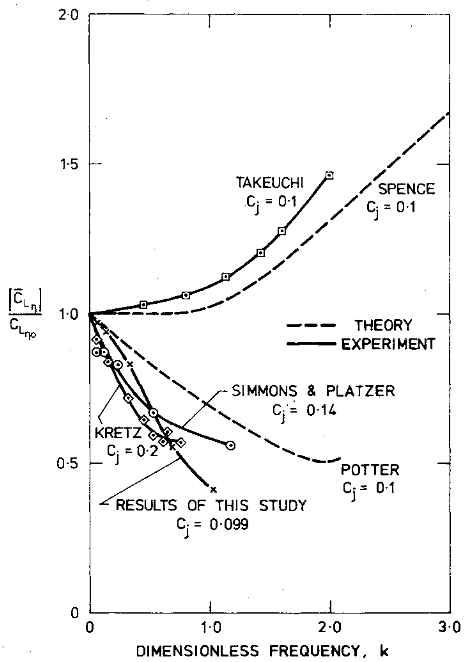

Fig. 8 Comparison of modulus of complex lift slope $\bar{C}_{L_\eta}$ with other theoretical and experimental results. (Note that jet thrust is included, and that Spence's presentation of results below $k=2\pi$ is apparently unjustified).

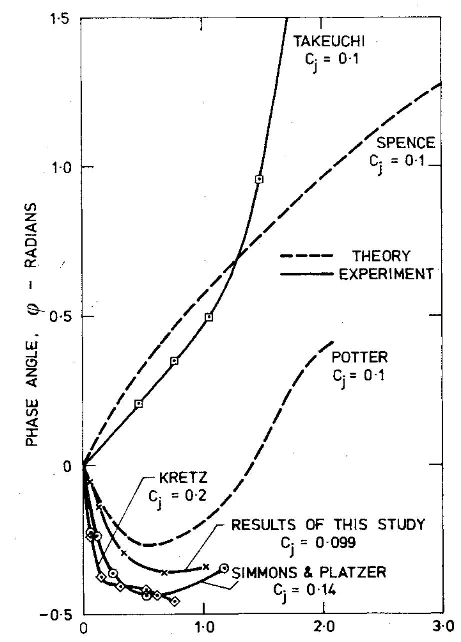

Fig. 9 Comparison of phase angle of complex lift slope $\bar{C}_{L_\eta}$ with other theoretical and experimental results. (Note that jet thrust is included, and that Spence's presentation of results below $k=2\pi$ is apparently unjustified.)

of a rotating nozzle along the trailing edge of the airfoil, Simmons and Platzer and the author in this study avoided a mechanical flap and made their designs approximate more closely the 'pure jet flap' configuration analyzed by Spence and Potter. However the nozzle used by Simmons and Platzer comprised a row of 0.74 mm diameter holes spaced 6.35 mm apart, whereas the nozzle in this study was very nearly a continuous slot. The greater effectiveness of the continuous slot is manifest in the resulting magnitudes of aerodynamic derivatives due to pressure which are typically four to five times larger than those obtained by Simmons and Platzer. However, Fig. 8 does not enable this comparison because of the normalization by the lift slope in steady flow.

Measurement of pressure distribution was the basis for all experimental results in Figs. 8 and 9 except for those of Takeuchi which were based on the use of a dynamic balance. It has been this author's experience that pressure measurements, while being quite tedious, are not prone to the difficulties of subtracting 'inertia forces' from a dynamic balance measurement, and they provide more detailed understanding of aspects such as regions of flow separation.

Although there is relatively good agreement between the potential flow theory of Spence and the measurements of Takeuchi, Potter's use of point vortex distributions and finite difference methods has predicted the trends of the majority of the experiments. Potter treated the problem as one with the jet initially specified as a straight horizontal line with zero vorticity. After the initial time the jet exit angle was oscillated continuously. No completely satisfactory solution was found because of difficulties with the stability of numerical methods. Spence assumed that the jet extends infinitely far downstream, and that the main-stream flow and the jet flow are both inviscid, incompressible and irrotational. However, assumptions were made which emphasize the influence of the jet immediately downstream of the trailing edge and restrict valid solutions to dimensionless frequencies, $k>2\pi$. As has been done in Figs. 8 and 9, Spence waived this low frequency limit in plotting his results, but the agreement with most experimental results is extremely poor.

VI. Conclusions

This paper, in conjunction with the earlier work[9] by the author, contains a complete set of measurements from which the aerodynamic forces and moments can be predicted for a two-dimensional jet flap airfoil undergoing any general motion involving small displacements. The measurements have helped clarify the contradictions among earlier theoretical and experimental results. At frequencies up to about $k=1$, there is now a significant number of studies indicating that the oscillatory lift force has a magnitude which decreases with frequency of jet flap oscillation and a phase angle which always lags the jet flap angle. It is now apparent that Spence's theory should not be used in this frequency range. However there are some indications in the trends of measured phase angles that Spence's theory may be more appropriate at mugh higher frequencies.

The work of Potter indicates that further numerical analyses should be undertaken. In this regard a better understanding of the wake is needed, and measurements of the shape and velocity profile of the oscillating jet flap should be made.

References

[1] Platzer, M.F., "The Oscillating Jet Flap," *Proceedings of Short Course on High-Lift Technology,* The University of Tennessee Space Institute, Tullahoma, Tenn., Oct. 27-31, 1975.

[2] Spence, D.A., "The Flow Past a Thin Wing with an Oscillating Jet Flap," *Philosophical Transactions of the Royal Society of London,* Ser A 257, No. 1085, June 1965, pp. 445-477.

[3] Potter, G.E., "A Numerical Solution for an Unsteady Jet-Flapped Airfoil," Thesis, Pennsylvania State University, University Park, Pa., 1972.

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

[5] Trenka, A.R. and Erickson, J.C., Jr., "The Determination of Unsteady Aerodynamics of a Two-Dimensional Jet-Flap Wing," CAL NO. AC-2260-S-1, April 1970, Cornell Aeronautical Lab. 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., "Commande Asservie des Forces Aerodynamiques Instationnaires," Rept. De 07-44E5, Giravions Dorand, Paris, France, Dec. 1973.

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

[9]Simmons, J.M., "Aerodynamic Measurements for an Oscillating Two-dimensional Jet Flap Airfoil," *AIAA Journal*, Vol. 14, June 1976, pp. 741-748.

[10]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, University of Queensland, Brisbane, Qld., Australia.

[11]Simmons, J.M., "Pressure Measurements for Two-dimensional Flow Past a Stationary Airfoil with Oscillating Jet Flap," Res. Rept. 10/75, Nov. 1975, Dept. of Mechanical Engineering, Uni. of Queensland, Brisbane, Qld., Australia.

[12]Lissaman, P.B.S., "A Linear Theory for the Jet Flap in Ground Effect," *AIAA Journal*, Vol. 6, July 1968, pp. 1356-1362.