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Experimental Investigation of Incompressible Flow Past Airfoils with Oscillating Jet Flaps

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Controlled jet flaps have been studied for use as rapid lift and moment generators in aircraft gust load alleviation and mode stabilization systems. Wind-tunnel tests of a two-dimensional NACA 0012 airfoil, with a jet flap at the trailing edge, demonstrate useful lift augmentation up to a reduced frequency k of about 0.5 in incompressible flow. The jet flap, with momentum coefficients of 0.58 and 0.14, was oscillated mechanically and fluidically. Oscillatory pressures were measured up to $k = 2.5$ at forty chordwise locations, using one transducer, pressure tubes and a scanning valve. Graphs show pressure distributions, lift amplitude and phase as functions of frequency. Lift decreases with increasing frequency; e.g., at $k = 0.5$ lift is about 70% of the steady value and lags the jet deflection by about 20°. Practical implementation and advantages of controlled jet flaps are discussed. Results of tests of a jet flap airstream oscillator are presented.

Nomenclature

c = airfoil chord
S = airfoil reference area
η = angle of jet deflection from airfoil chordline
α = angle of attack of airfoil
V = freestream velocity
q = freestream dynamic pressure
ω = circular frequency of jet flap oscillation
k = $\omega c/V$ = reduced frequency
T = jet thrust
C_j = T/qS = jet momentum coefficient
C_{Lj} = jet induced pressure lift coefficient
ϕ = phase difference between lift and jet deflection

I. Introduction

BECAUSE of the demand for increasing size and structural efficiency, modern airplanes are becoming structurally more flexible and hence more sensitive to flight operations in rough air. The excitation of the structural modes by gusts and by pilot commands results in degraded ride and handling qualities and in inadequate fatigue life. On the other hand, the higher cost of these aircraft puts a premium on extending their useful life. For this reason, systems for control of structural dynamic response have received considerable attention and study during the past several years.[1–3] Using advanced control techniques, state-of-the-art high response actuators and conventional control surfaces, such as ailerons, spoilers and elevators, flight tests were recently completed on a B-52 test airplane. These tests proved the feasibility of active load alleviation and mode stabilization systems (LAMS).

However, technical feasibility is not the only criterion for the application of gust response control. The high cost of present systems makes it mandatory to search for other systems which combine operational efficiency with a high degree of mechanical simplicity and reliability. For control force generation, mostly conventional aerodynamic controls have been employed. The effectiveness of leading edge control surfaces has recently been studied[4] in an investigation of the control of a binary bending-torsion mode. However, control surface inertia, actuator frequency response requiremens, and aerodynamic performance degradation due to spoiler actuation, are serious obstacles in the way of further development of gust response control systems.

The lack of information about the unsteady aerodynamic characteristics of the various possible aerodynamic control surfaces makes a comparative evaluation very difficult. This is quite apparent when the jet flap is included in the list of contenders. The jet flap has been recognized for some time as the most efficient way of generating high lift. Spence[5] mentions that its use as a fast-acting lift control device for gust alleviation purposes seems to have been first suggested by W. R. Sears. However, there is scant test information to allow an assessment of the control effectiveness of the jet flap. This is all the more surprising in view of the availability of the powerful and extremely simple fluidic techniques which lend themselves to jet flap control. Therefore it was decided to study a representative airfoil-oscillatory jet flap combination in two-dimensional incompressible flow. These tests are described in the following sections and the findings are used

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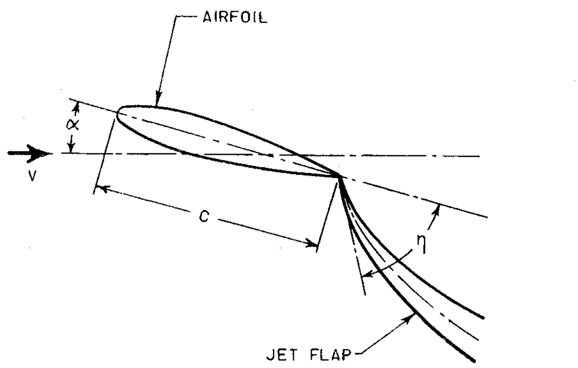

Fig. 1 Two-dimensional airfoil with a pure jet flap at the trailing edge.

in discussions of the applicability of controlled jet flap systems for gust alleviation, flutter test excitation and tunnel airstream oscillation.

II. Discussion of Jet Flap Principle

A jet flap is obtained if air with high momentum is ejected from a narrow spanwise slot at the trailing edge of an airfoil. A detailed discussion of the jet flap principle is contained in Ref. 6, together with a review of pertinent work in this field up to 1960.

Consider the jet flapped airfoil shown in Fig. 1. Blowing at the trailing edge modifies the circulation around the airfoil. This circulation may be greater than the maximum obtainable by boundary-layer control. Theoretically, arbitrarily high "supercirculation" can be achieved with sufficiently high blowing rates, although, in practice, leading-edge separation sets an upper limit. Two effects contribute to an increased lift on the airfoil. Firstly, the component of the jet momentum in the lift direction produces the so-called "reaction lift." In addition, the supercirculation reduces the static pressure on the upper airfoil surface and increases it on the lower airfoil surface, thus producing "jet induced pressure lift." The total lift is the resultant of all pressure forces on the airfoil in the lift direction, i.e., basic lift plus jet induced pressure lift, plus the reaction lift.

A measure of the jet effectiveness is given by the ratio of jet induced pressure lift plus reaction lift to reaction lift. This is the "lift gain factor." The jet momentum coefficient C_j is used as a measure of blowing rate and indicates the ratio of available jet momentum flux to freestream dynamic pressure. It is noteworthy that good jet flap effectiveness has been measured far into the critical transonic Mach number range (Ref. 6, p. 131). Hydrofoils with oscillating jet flaps have been tested by Kaplan and Lehman[7] for use in submarine control. Representative airfoil tests are those by Yuan et al.[8] with pulsating jet flaps and those by Dimmock[9] and Jousserandot[10] with steady jet flaps. Incompressible flow past airfoils with jet flaps has been studied theoretically by Stratford[11] and Jacobs[12] for steady jet flaps, and by Spence[5] for both the steady and the oscillatory case.

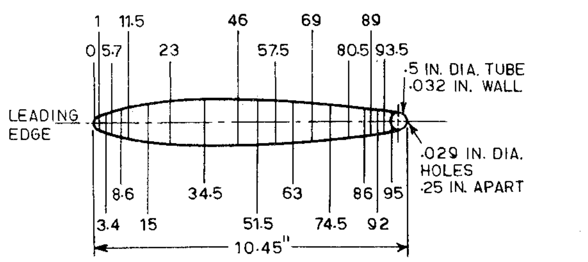

Fig. 2 Cross section of modified NACA 0012 airfoil showing location of pressure tappings as percentage of chord.

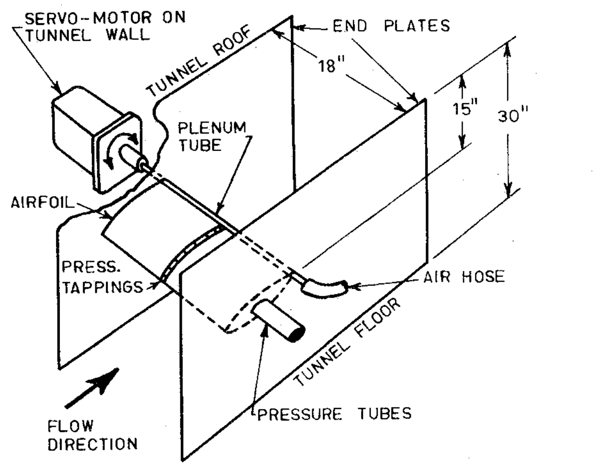

Fig. 3 Jet flap model installation in wind tunnel.

III. Apparatus and Experimental Methods

Wind Tunnel

The tests were performed in the Research Low Speed Wind Tunnel of the Lockheed-Georgia Aerospace Sciences Laboratory. This is a single-return tunnel with a test section 30 in. high, 43 in. wide and 58 in. long.

Model

The rigid two-dimensional airfoil, before addition of the jet flap, had a NACA 0012 profile, a 12-in. chord and an 18-in. span. The aft 15% of the chord was removed and replaced across the full span by a circular steel tube with 0.5-in. o.d. and 0.436-in. i.d. as shown in Fig. 2. There was no gap between the tube and the airfoil. The tube was free to rotate in bearings at each end and it served as a plenum for the jet flap which was formed by a row of 0.029-in. diam holes spaced 0.25 in. apart along the trailing edge of the tube across the full span. Air was supplied by an air hose connected to one end of the plenum tube. Figure 3 is a diagram of the test apparatus. The airfoil was clamped between rectangular end plates extending from the roof to the floor of the tunnel. The end plates also extended 0.6 chord lengths upstream and 2.6 chord lengths downstream of the airfoil.

Twenty-one pressure tappings were located on both the upper and lower surface along the chord at midspan, at the stations shown in Fig. 2. Two additional tappings at 57.4% chord were located on the upper surface one inch either side of midspan to provide measures of the two-dimensionality of the test.

Excitation

For the first series of tests the plenum tube was extended through a bearing in one of the end plates and coupled to the shaft of an electrohydraulic servo-motor fastened to the rear wall of the tunnel (Fig. 3). The jet deflection angle could then be varied, at frequencies up to 30 cps, by rotational oscillation of the plenum tube. A potentiometer, connected to the motor shaft, provided a measure of the plenum tube position and was used both for the experiment instrumentation and for feedback stabilization of the servo-motor.

In the second series of tests the mechanical oscillation of the jet flap was replaced by a fluidic actuation system (Fig. 4). Two 0.25-in. diam control tubes were fastened across the full span of the trailing edge, above and below the existing plenum tube. The plenum tube was set so that the jet flap was in the airfoil chord plane from which it could be deflected upwards or downwards by jets issuing from the control tubes. These control jets, formed by 0.029-in. diam holes in the control tubes, were spaced opposite the main jets and were directed normal to the chordline of the airfoil. By a combination of control jet momentum and jet attachment to the control

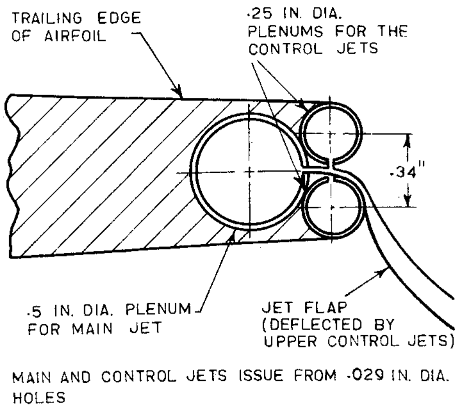

Fig. 4 Fluidically controlled jet flap.

tubes (Fig. 4), the main jet flap could be oscillated through angles up to 80° either side of the chordline in still air. Air was supplied alternately to the upper and lower control tubes by a variable speed rotary valve located outside the tunnel.

Pressure Measurement Technique

The oscillatory pressure measurement technique was based on that developed by Bergh[13] at the National Aerospace Laboratory NLR, Amsterdam. Using 6-ft lengths of vinyl tubing with 0.053-in. i.d., the pressure tappings on the model surface were connected to a scanning valve with a single transducer located outside the tunnel. A highly sensitive (16 v/psi) but relatively delicate pressure sensitive Pitran transistor could be used for the transducer because it was not subjected to the unsteady acceleration and thermal environment inside the tunnel. This technique therefore avoids the expense and calibration of a large number of transducers but requires the use of the frequency dependent transfer function of the tube-scanning valve system shown in Fig. 5 to reduce transducer outputs to actual pressures at the surface of the model.

Data Reduction

The servo-motor, which oscillated the jet flap, was driven by the sinusoidal reference signal from a frequency response analyzer. Pressures and the plenum tube rotational position were correlated with each of the analyzer internal quadrature reference signals. In this way only the fundamental amplitude and phase were measured relative to the rotational position of the plenum tube. During tests with fluidic actuation of the jet flap only the amplitude of the oscillatory pressures was measured. The fundamental frequency component was extracted with a tuned 1.5-Hz bandwidth filter.

IV. Test Program

All tests were performed with the model at zero angle of attack and with the jet flap oscillating about the airfoil chord line. The tunnel speeds were 103 and 51.1 fps, corresponding to Reynolds numbers, based on airfoil chord, of 5.61×10^5 and 2.79×10^5, and to dynamic pressures of 11.4 and 2.78 lb/ft^2, respectively. Frequencies of 1, 2.2, 4.7, 10, and 22 cps were used. Thus, the reduced frequency was varied from 0.053 at 103 fps to 2.36 at 51.1 fps. The jet flap plenum tube was mechanically oscillated with 13.2° amplitude, except during some additional measurements to study the effect of other amplitudes. When fluidic actuation was used the amplitude of jet flap oscillations was a function of frequency and tunnel speed and was not measured. For this series of tests the amplitude of pressure fluctuations in the control tubes was held constant.

The jet thrust was always 2.0 lb. This was measured statically with a strain gauge balance and held constant by

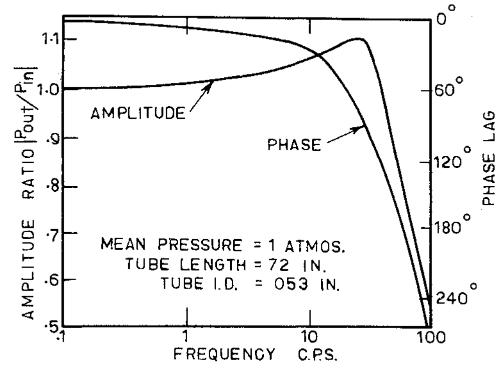

Fig. 5 Transfer function for the pressure tube-scanning valve combination.

monitoring the mean pressure in the plenum tube. At tunnel speeds of 103 and 51.1 fps, the jet momentum coefficients were 0.14 and 0.58, respectively. It should be noted that, because the jet flap consists of discrete jets, its momentum coefficient is taken as the average value across the span.

Steady tests were performed at 103 fps ($C_j = 0.14$) and at 51.1 fps ($C_j = 0.58$) with the jet exit holes rotated 7.3° and 18.1° from the airfoil chordline. Another test series was performed at 103 fps and 13.2° rotation of the exit holes, with a reduced jet exit hole spacing, viz., 0.019-in. diam holes 0.125 in. apart. The jet momentum coefficient was 0.14. This last test was repeated with the trailing edge modification shown in Fig. 6.

V. Results

Accuracy

During the tests the errors in pressure measurement were mostly caused by the random fluctuations from tunnel turbulence. This was studied by taking pressure measurements with the plenum tube oscillating but the jet turned off. Over the test frequency range the signal-to-noise ratio varied from 8:1 down to 4:1. After the correlation technique was applied the turbulent fluctuations caused errors varying with frequency from 2% to 5% in pressure amplitude and 1° to 4° in phase. Other small errors may have been introduced by slight distortion of the sinusoidal motion of the plenum tube. These were minimized by extracting only the fundamental from all displacement and pressure signals.

Pressure Distributions

Local differential pressure distributions over the airfoil are shown in Figs. 7–10. The differential pressure distributions for steady jet deflection are given in Fig. 7. Typical oscillatory pressure distributions, induced by mechanical oscillation of the plenum tube, are presented in Figs. 8 and 9 in terms of components of pressure coefficient in phase and out of phase with the plenum tube rotational position. The

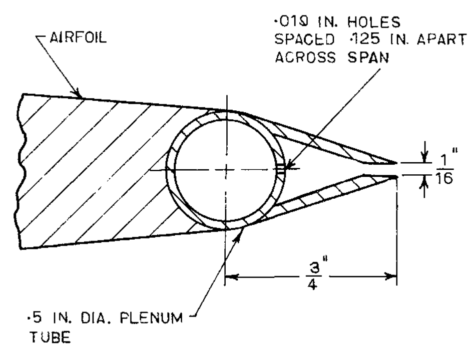

Fig. 6 Trailing-edge fairing.

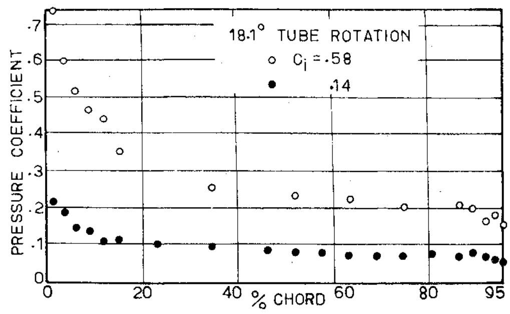

Fig. 7 Steady differential pressure distributions.

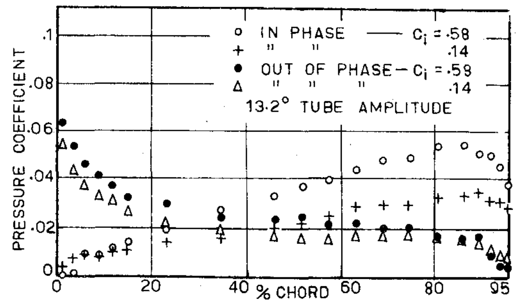

Fig. 9 Differential pressure distributions at 22 cps.

amplitudes of oscillatory pressures induced by fluidic actuation of the jet flap are shown in Fig. 10. Further results can be found in Ref. 14.

The pressure distributions, induced by mechanical oscillation of the jet flap, were integrated to obtain the lift coefficients and their phase relative to the plenum tube position. Both the jet induced pressure lift and the total lift are presented in Fig. 11.

VI. Discussion of Test Results

Oscillatory Tests

The test results consistently show a lift magnitude which decreases with increasing frequency. Both the jet induced pressure lift and the total lift are found to always lag the jet deflection by an angle which reaches a maximum and then decreases with increasing frequency. These findings differ markedly from Spence's theoretical result which predicts a lift magnitude remaining constant up to a reduced frequency of one, but increasing rapidly with further increase in frequency. In further contrast Spence finds the lift to lead the jet deflection by an angle increasing with frequency (Fig. 8 of Ref. 5).

The only other investigation of which the authors are aware is the water tunnel test by Kaplan and Lehman.[7] Although the jet momentum coefficients used were much lower than those of the present tests, the trends are quite similar, viz., decreasing lift magnitude with increasing frequency, and lift phase lags with maxima at a reduced frequency of about 0.36.

This contradiction between theory and experiment is difficult to resolve at this time. It seems reasonable to expect the oscillatory jet behavior to approach that of a mechanical flap at sufficiently low frequencies. Application of the well-known Theodorsen analysis[15,16] then shows for an airfoil-oscillating flap combination, with hinge line at 85% chord, that the lift magnitude decreases appreciably over the frequency range of the present tests and produces lift which lags the flap deflection by as much as 11° at a reduced frequency of 0.35.[14]

Only limited information can be obtained from the tests of a fluidically actuated jet flap because phase angles and jet deflection angles were not measured. The oscillatory pressure amplitudes, at $C_j = 0.58$, were about 2–3 times greater than those obtained for the mechanically actuated jet flap. At $C_j = 0.14$, only slightly greater (10%–20%) pressure amplitudes were measured.

Steady Tests

The measured steady total lift coefficients per unit deflection angle are appreciably lower than those obtained from Dimmock's tests and Spence's theory. It is felt that this is attributable to two differences in jet nozzle configuration, viz., the present use of discrete jets, and a larger trailing-edge radius. By halving the spacing of the jets the lift coefficient at $C_j = 0.14$ was increased 17%. Furthermore, by adding the trailing-edge fairing shown in Fig. 6, the lift coefficient was increased by 76%.

VII. Considerations for Lift Control on Practical Aircraft Systems

Gust Response Controller

The use of jet flaps for the fast-acting lift control needed for gust alleviation has been suggested in the literature.[5,6] However, the authors know of no work analyzing the feasibility of a practical airplane application. Obviously there is a need for more information on the unsteady aerodynamic characteristics of jet flaps before they can be considered for a practical gust control system. This is particularly apparent for the high subsonic and transonic speed range. Although wind-tunnel tests have shown good steady jet flap effectiveness up to and far into the transonic Mach number range,[6] there is neither theoretical nor experimental work available for the oscillatory case. It is therefore difficult to evaluate the potential of jet flap control systems for modern large subsonic aircraft.

A possible scheme for gust response control is shown in Fig. 12. An auxiliary airfoil with a trailing-edge jet flap could be mounted between pylons at a suitable chordwise and spanwise location on either the upper or lower surface of the main wing. If an aircraft is to use jet flaps for high lift augmentation, then these or others at the trailing edge of the main wing could be used for gust alleviation.

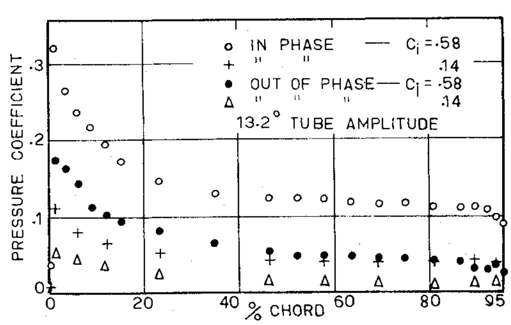

Fig. 8 Differential pressure distributions at 1 cps.

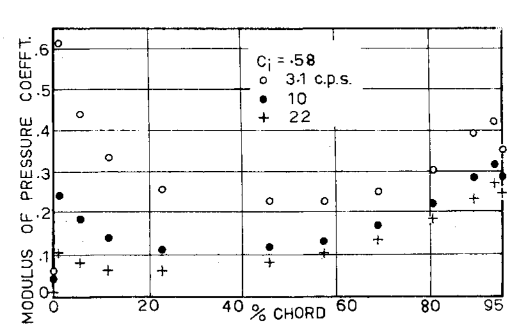

Fig. 10 Differential pressure distributions with fluidic actuation.

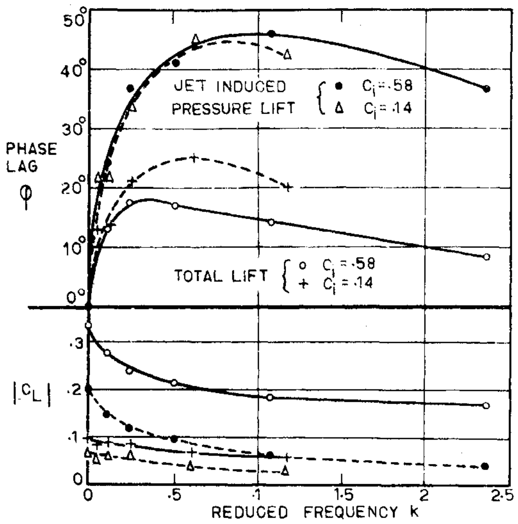

Fig. 11 Measured lift coefficient (amplitude $|C_L|$ and phase lag φ) at 13.2° amplitude of plenum tube oscillation.

Shaker for Flight Flutter Testing

The principle of the oscillating jet flap lends itself to an efficient means of exciting the structural modes of an aircraft during flight flutter tests. For large aircraft the technique[17] most popular in the United States is based on the use of small oscillating airfoils near the wing and stabilizer tips, to excite the aircraft over a range of frequencies from about 0.5 to 25 cps. In order to reduce the mass of these airfoils and their hydraulic actuation equipment to an acceptable level, sacrifices in reliability and performance must be made. By using a fluidically actuated airfoil-jet flap combination, mounted between pylons near the wing and stabilizer tips in the manner described under "Gust Response Controller," oscillatory lift forces could be generated with a minimum of additional mass and without the wear and inertia problems associated with rapidly moving parts. Air from the engines, or from a small auxiliary engine-compressor unit, could be supplied to the jet flap in the manner described under "Gust Response Controller."

Shaker for Aeroelastic Model Testing

It is desirable to excite the modes of wind-tunnel flutter models in much the same way as in full-scale flutter testing. However, the design of sufficiently lightweight mechanically driven systems is difficult for small models. A miniaturization of the airfoil-jet flap shaker system, previously described for flight flutter testing, offers an attractive solution.

VIII. Airstream Oscillator

Model and Gust Probe

Tests were performed to investigate the practicality of the fluidically actuated jet flap system as an efficient airstream

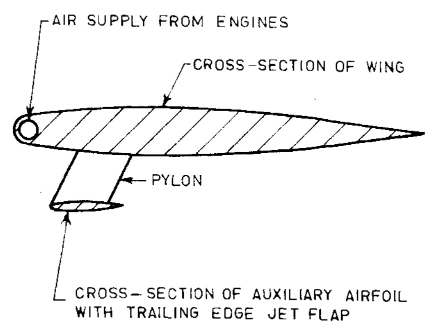

Fig. 12 Feasible installation for the control of wing response.

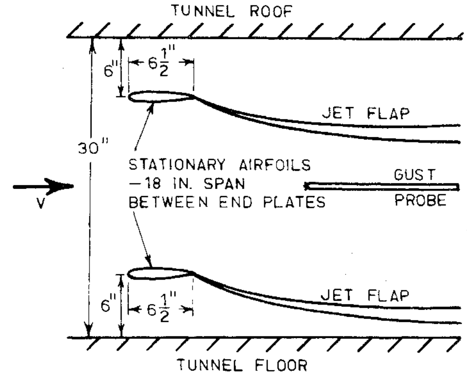

Fig. 13 Schematic diagram of airstream oscillator.

oscillator. The need for such a system for wind-tunnel dynamic response studies has been recognized for several years.[18–21] Therefore the configuration shown in Fig. 13 was tested in the Research Low Speed Wind Tunnel (Sec. III). Two symmetric airfoils with 6.5-in. chord were held at zero angle of attack close to the roof and the floor of the tunnel. The airfoils spanned the full 18 in. between the end plates, as shown. Each was fitted along its trailing edge with a fluidically actuated jet flap system identical in all respects to that described in Sec. III and Fig. 4. The two jet flaps could be switched synchronously (either both up or both down) at frequencies up to 15 cps by a rotary pneumatic valve located outside the tunnel. This valve might ultimately be replaced

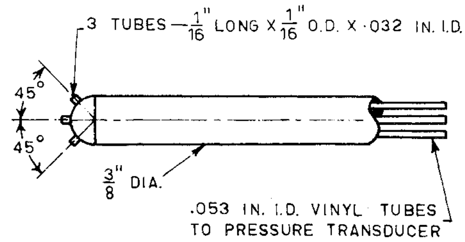

Fig. 14 Gust probe.

by a fluidic amplifier with greatly increased upper frequency limit, simplicity and reliability.

The induced local changes of flow direction, in planes normal to the airfoil chord planes, were measured with the gust probe shown in Fig. 14. The center tube could be used to measure local total head and the two outer tubes were connected with 6-ft lengths of 0.053-in. i.d. vinyl tubing to either side of the diaphragm of a pressure sensitive transistor. The pressure difference between the two outer tubes indicated the local instantaneous flow direction. A tuned 1.5 Hz band width filter was used to extract the fundamental from the transducer output signal. The probe was calibrated by first deflecting it statically in a uniform stream. Next the frequency re-

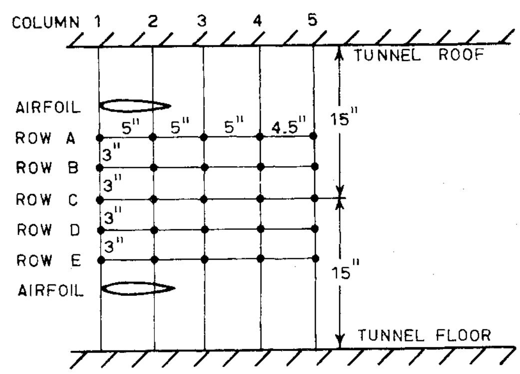

Fig. 15 Location of gust measurement stations.

Table 1 Amplitude (in deg) of local changes of flow direction at 1.5 cps

Row	Column number 1	2	3	4	5
A	5.8	7.8	9.1	3.9	3.3
B	2.9	3.9	5.7	4.4	4.4
C	1.6	2.6	4.4	3.9	3.3
D	1.6	2.6	4.2	4.2	3.6
E	3.2	3.6	5.2	4.2	3.6

sponse of the tube-transducer combination was measured and used to correct the outputs of the pressure transducer. This calibration of the probe is adequate for these preliminary tests.

Results and Discussion of Airstream Oscillator Test

The amplitudes of oscillation of the local flow direction were measured at 25 points in the vertical plane at the airfoil midspan (Fig. 15). Measurements were also taken at the corresponding points in vertical planes 5 in. either side of the midplane. The tunnel speed was 63 fps and the momentum coefficient of each jet flap was 0.45. The jet flaps were oscillated at 1.5, 4, and 10 cps—only the mechanical limitations of the rotary valve prevented tests at higher frequencies. The amplitudes of local changes in flow direction in the plane at midspan are shown in Tables 1 and 2. Results in the other two planes are not presented—except for approximately 15% decrease in the amplitude of fluctuations, the behaviour is similar to that in Tables 1 and 2. During the test, it was observed visually that the lower jet flap was not oscillating with as large an amplitude as the upper jet flap. This can be seen in the results presented in Tables 1 and 2. The flow was considerably less two-dimensional at locations further downstream of those presented here. However, it is believed that these results indicate a useful region of suitably uniform oscillating flow—viz., between the chord planes of the airfoils and from near their midchords to about four chord lengths downstream.

Quite large oscillations were generated throughout the flowfield. In areas penetrated by the jet the flow oscillations were markedly distorted. Clearly more extensive design and testing are needed but these preliminary results show that the jet flap principle offers considerable promise as an efficient airstream oscillator.

IX. Concluding Remarks

Jet flaps used as fast acting lift controllers were studied experimentally to assess their feasibility as a means of gust alleviation. The effects, on a two-dimensional airfoil-jet flap combination, of the strength and the frequency of oscillation of the jet flap were measured in incompressible flow. The results were obtained by measuring oscillatory pressures at many locations on the model with a rather unconventional technique which eliminates the expense and the calibration of a large number of transducers. Two jet flap actuation schemes were investigated, viz., mechanical rotation of the jet nozzles, and fluidic switching of the jet flap by control jets at the trailing edge of the airfoil. Because of their extreme simplicity and reliability, fluidically actuated jet flaps show much potential for development.

Table 2 Amplitude (in deg) of local changes of flow direction at 10 cps

Row	Column number 1	2	3	4	5
A	2.9	5.9	8.7	7.8	8.1
B	1.2	3.9	6.0	5.0	4.4
C	1.1	2.9	4.8	4.4	4.2
D	0.9	3.1	4.6	4.6	5.1
E	1.1	3.9	6.0	6.2	6.9

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