Transonic Buffet of a Supercritical Airfoil with Trailing-Edge Flap

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A supercritical airfoil with a trailing-edge flap was tested at the High Reynolds Number Two-Dimensional Test Facility of the National Aeronautical Establishment. Buffet boundaries at various flap angles were determined from the divergence of the indicated normal-force fluctuations. The test was performed quite deep into the buffet régime of the airfoil, and spectral analyses of the unsteady normal force showed shock-wave oscillations of approximately 50–80 Hz for Mach numbers between 0.612 and 0.792. The drag of the airfoil was measured from wake probes, and the drag penalties for the large flap angles were quite significant. This study illustrates the use of trailing-edge flaps for buffet alleviation at transonic conditions.

Nomenclature

b = model span
C_D = drag coefficient from wake integration
C_D' = function when integrated over width of the wake gives total drag
C_L = lift coefficient from balance measurement
$C_{L_{max}}$ = maximum lift coefficient
C_{L_α} = lift-curve slope
C_N = fluctuating normal-force coefficient from balance measurement
C_N' = rms value of normal-force coefficient
C_p = pressure coefficient
$C_{p_{TE}}$ = trailing-edge pressure coefficient
c = chord length
M = Mach number
M_D = drag rise Mach number
M_{DES} = design Mach number
N_{rms} = rms value of normal force from balance measurement
q_∞ = freestream dynamic pressure
t = maximum thickness of airfoil
w = thickness of wake
x = distance measured in flow direction from airfoil leading edge
y = distance traversed by wake probe, perpendicular to flow direction
α = angle of incidence
δ = flap angle

Introduction

BUFFETING is the dynamic response of an aircraft as a result of aerodynamic excitation arising from random loading on the wing when the flow separates. For supercritical airfoils, flow separation can occur at the shock wave or at the trailing edge. The separated flow region behind the shock usually starts out as a bubble and grows downstream as buffet becomes more severe until the flow is completely separated. On the other hand, trailing-edge separation moves upstream until it reaches the shock wave. There are instances when both types of separation occur simultaneously and the two separated regions eventually merge.[1]

A number of studies[2-4] on buffet characteristics have appeared in recent years, and prediction methods of buffeting response are also available.[5-9] For the aircraft designer, the buffet onset boundary provides important information to enable him to specify the cruise condition of the aircraft. For buffet associated with trailing-edge separation, a theoretical prediction method has been proposed.[10,11] However, for shock-induced separation, the method is not applicable, and usually wind-tunnel tests are necessary to define the buffet onset boundary. Trailing-edge pressure divergence is not a reliable indicator of buffet onset in such circumstances, since the pressure will not be affected until the separation bubble reaches the trailing edge. At the National Aeronautical Establishment (NAE), buffet onset is measured from the divergence of the fluctuating normal force measured from a balance output. This has been found to give reliable results for buffet onset associated with both types of flow separation.

Some earlier studies of conventional airfoils with flaps[12,13] show that buffet boundaries can be raised appreciably by increasing the flap settings. Trailing-edge flaps are found to be more effective than leading-edge flaps for providing large lift increments and as a means for buffet control. To gain more insight into the effects of flaps on buffet intensities and delay of buffet onset at transonic conditions, a wind-tunnel investigation of a supercritical airfoil with a trailing-edge flap was carried out. An understanding of the effects of a flap on the characteristics of the separated flow is useful in assessing the deployment of a trailing-edge flap as a passive means for buffet alleviation.

The investigation was made in the NAE High Reynolds Number Two-Dimensional Test Facility[14] using an airfoil designed by de Havilland Aircraft of Canada. The airfoil was used in a previous joint NAE-de Havilland research and development program aimed at improvements in design that would reduce wing section drag. The design conditions for this airfoil were for a cruise Mach number of 0.72 and lift coefficient of 0.6.

This paper gives a brief description of the model and experimental procedures. Results that illustrate the effects of a trailing-edge flap on the buffet characteristics of this airfoil are presented. The details of this study are reported in Refs. 15 and 16. The conclusions derived from this investigation are applicable to other supercritical airfoils.

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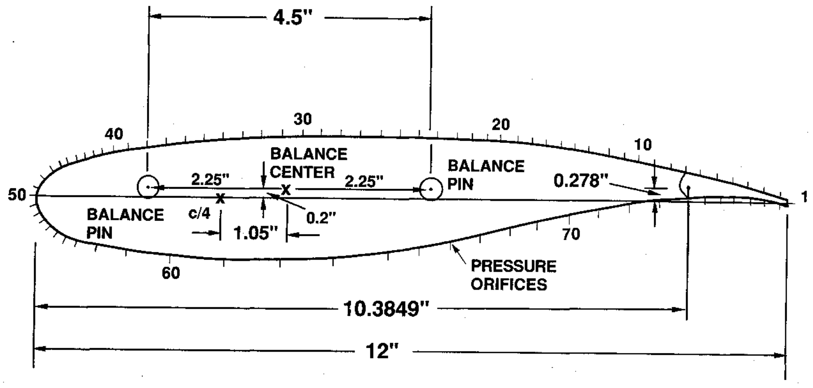

Fig. 1 Schematic of supercritical airfoil with 16% thickness-to-chord ratio.

Model and Instrumentation

The airfoil (Fig. 1) studied was basically the same model as the one used in the investigation reported in Ref. 17, but with the addition of a trailing-edge flap. It was made of aluminum having a chord of 12 in. and a span of 15 in. The maximum thickness-to-chord ratio was 16%. The flap was approximately 14% chord, and the trailing-edge thickness was 0.1% chord. There were 79 pressure orifices on the model surface for static pressure measurements: 43 of them were located on the airfoil upper surface and 23 on the lower surface. On the flap, there were 13 pressure orifices with 6 on either side and one at the trailing edge. Their locations on the airfoil are shown in Fig. 1. The drag of the airfoil was obtained using a traversing wake rake with pitot probes at four spanwise locations, which were located approximately 18 in. downstream of the airfoil trailing edge. In this experiment, only the two centrally located probes were used, and their average was taken for drag measurements.

The lift and pitching moment were determined from a sidewall balance. In addition to the steady-state values of the balance outputs, the fluctuating quantities were also measured. In this paper, the rms value of the normal force is presented in nondimensional form given by

$$C_N' = N_{\text{rms}}/q_\infty bc \tag{1}$$

Spectral analyses of the balance outputs were also performed. The signal was sampled at 1.6 kHz and analyzed digitally on a computer using the IEEE routine PMPSE[18] to give power spectra and autocorrelation functions. A transform size of 256 and a signal duration of 2 s were chosen in the analyses.

The force balance was very stiff, and both the lowest frequencies of rigid-body airfoil heave and fixed-fixed wing bending were much larger than the peak excitation frequencies observed under buffet conditions, which increased from approximately 50 Hz at $M = 0.612$ to 80 Hz at $M = 0.792$. In wind-off test, the response of the balance to impulse excitation was measured, and four natural frequencies were detected at 140, 215, 320, and 360 Hz. They were all greater than the buffet excitation frequencies. A typical plot of the response transfer function showing the vibration modes is given in Fig. 2.

Distributed suction was applied through porous plates to regions of the tunnel side walls in the vicinity of the model. The amount of suction was selected so that any three-dimensional effects would be minimized.

All of the tests were performed at a chord Reynolds number of approximately 20×10^6 with free transition. At design conditions, flow visualization using a thin film of oil containing a dye that fluoresced in ultraviolet light showed transition to occur on the upper surface at less than 5% chord from the leading edge. The Mach numbers in this investigation varied between 0.612 and 0.792, and the flap angle settings were $\delta = 0$, 4, 8, 14, -4, and -8 deg. The standard convention of

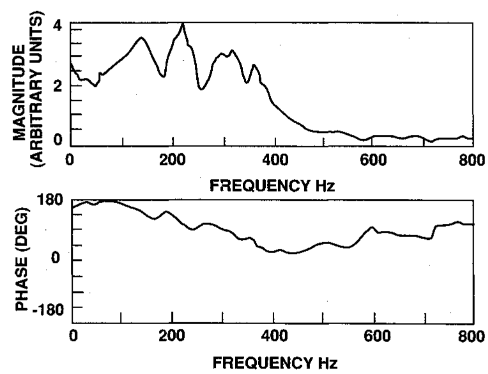

Fig. 2 Transfer function of force balance response to impulse excitation.

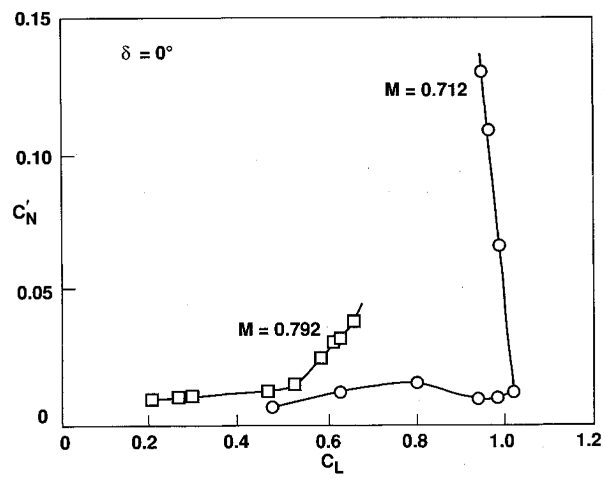

Fig. 3 Normal force fluctuations vs lift coefficients for $\delta = 0$ deg at $M = 0.712$ and 0.792.

positive flap deflection in the downward position and negative in the upward position was adopted. The maximum value of the angle of incidence was 10 deg.

Results and Discussion

Buffet Boundaries

In Refs. 15 and 16, the C_L vs α curves show that, for M greater than M_D, a maximum value of C_L is not usually observed. Instead, the C_L curve increases initially with α but gradually tapers off without reaching a maximum. However, below M_D, a $C_{L_{\max}}$ is detected.

The C_N' are plotted vs C_L for two M in Fig. 3 for $\delta = 0$ deg. It is interesting to note that, for the higher Mach numbers, i.e., $M = 0.772$ or greater for this airfoil, a very rapid increase in C_N' (as shown in the graph for $M = 0.712$) is not detected. The slopes of the curves do not become negative since there is no $C_{L_{\max}}$ in the C_L vs α curves in the range of incidence tested. To determine the C_L at buffet onset, the procedure is to obtain a smooth C_N' vs C_L curve either by use of a spline or fitting manually. The C_L at buffet is then determined by noting the point on the curve with a slope $dC_N'/dC_L = 0.1$. This value is arbitrarily chosen. The results are found to be consistent and in good agreement with those determined using the trailing-edge pressure divergence criterion for those flow conditions where it is applicable. Figure 4 shows the variations of C_N' and $C_{p_{TE}}$ with α for $M = 0.722$ and $\delta = 0$ deg. The values of α at buffet onset determined from trailing-edge pressure divergence and the present method are indicated. The slope $dC_N'/d\alpha$ is related to dC_N'/dC_L by the following expression

$$\frac{dC_N'}{d\alpha} = C_{L_\alpha}\frac{dC_N'}{dC_L} \tag{2}$$

where C_{L_α} is obtained from steady lift vs α curves. Experience at NAE in testing supercritical airfoils shows that it is more convenient to use the fluctuating normal force from a balance to determine buffet onset. Installation of a pressure transducer close to the trailing edge is cumbersome and not feasible for airfoils with thin trailing edge. Also, it is often necessary to obtain trailing-edge pressure data over a wide range of incidence below buffet onset to define a baseline to locate α when trailing-edge pressure divergence occurs.

For conventional airfoils, it is often possible to designate in the buffet regime regions of mild, moderate, or heavy buffeting. For supercritical airfoils, buffet onset occurs so close to $C_{L_{\max}}$ for M near or less than M_{DES} that it is not too meaningful to assign a degree of severity, except when M is greater than some value, i.e., M_D for this particular airfoil. Figure 5 shows the buffet onset boundary at $\delta = 0$ deg together with curves for different degree of severity expressed in terms of constant C_N'. These curves lie below the buffet onset boundary for Mach numbers less than a value of about 0.72. This is due to the behavior of the C_N' variations with C_L (Fig. 3), where for $M < 0.72$ a decrease in C_L is detected when C_N' increases above its value at buffet onset. For higher M the curves lie above the buffet onset boundary, since C_N' increases with C_L monotonically. Also shown in Fig. 5 are the values of $C_{L_{\max}}$ for those values of M where a maximum in C_L can be detected.

The buffet boundaries for various flap settings are shown in Fig. 6. It is seen that the curves can be raised appreciably, and there are large increments in lift with positive changes in δ. The C_L at buffet onset decreases rapidly for $M > M_{DES}$. At

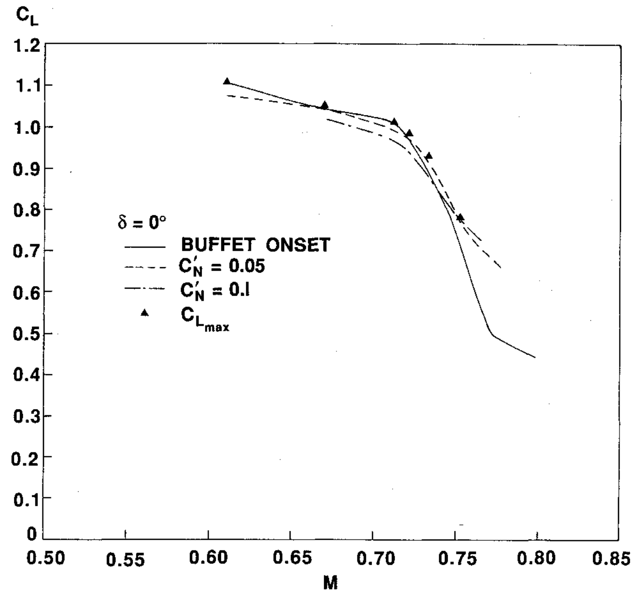

Fig. 5 Buffet boundary at $\delta = 0$ deg.

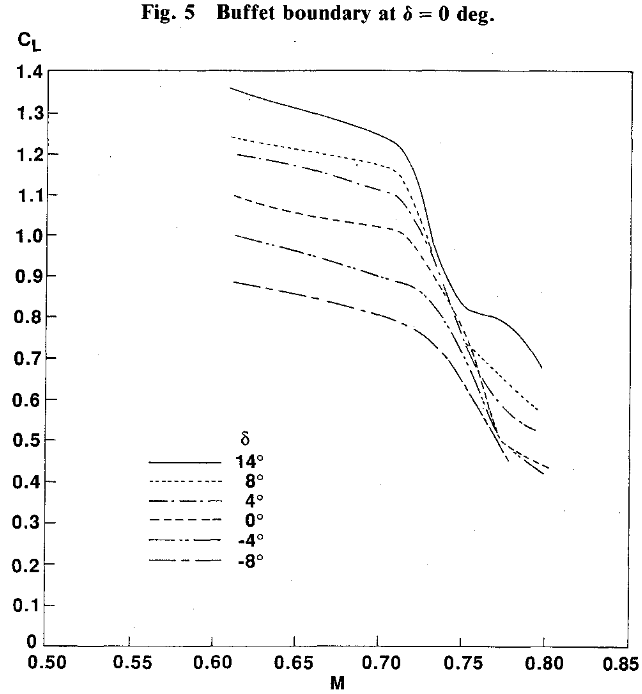

Fig. 6 Buffet boundaries for various values of flap angles.

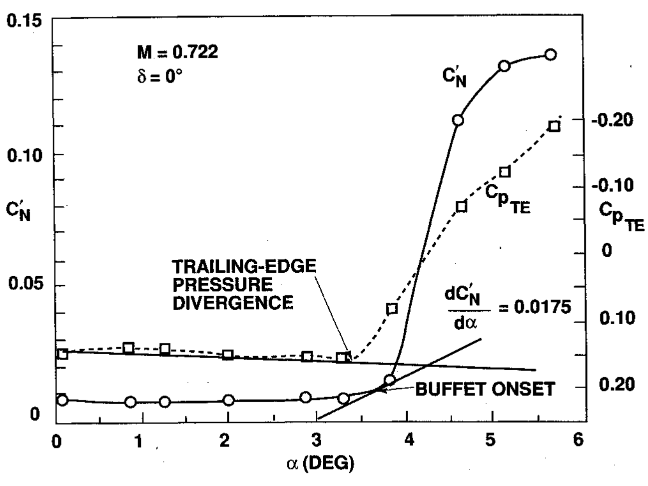

Fig. 4 Comparison of buffet onset determined from divergence of indicated normal-force fluctuations and trailing-edge pressure.

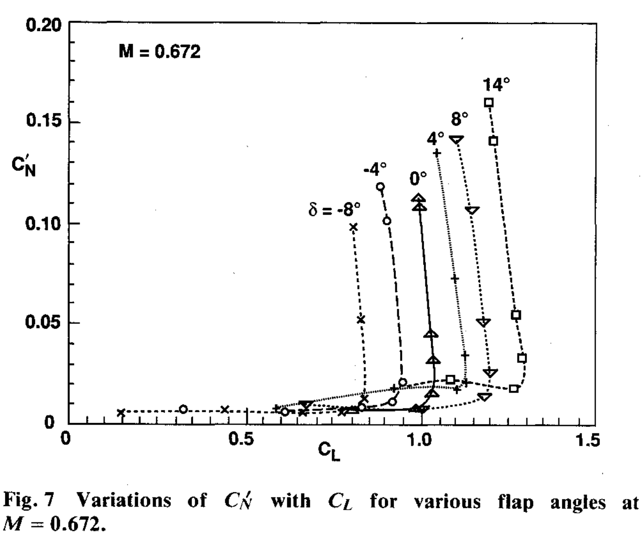

Fig. 7 Variations of C_N' with C_L for various flap angles at $M = 0.672$.

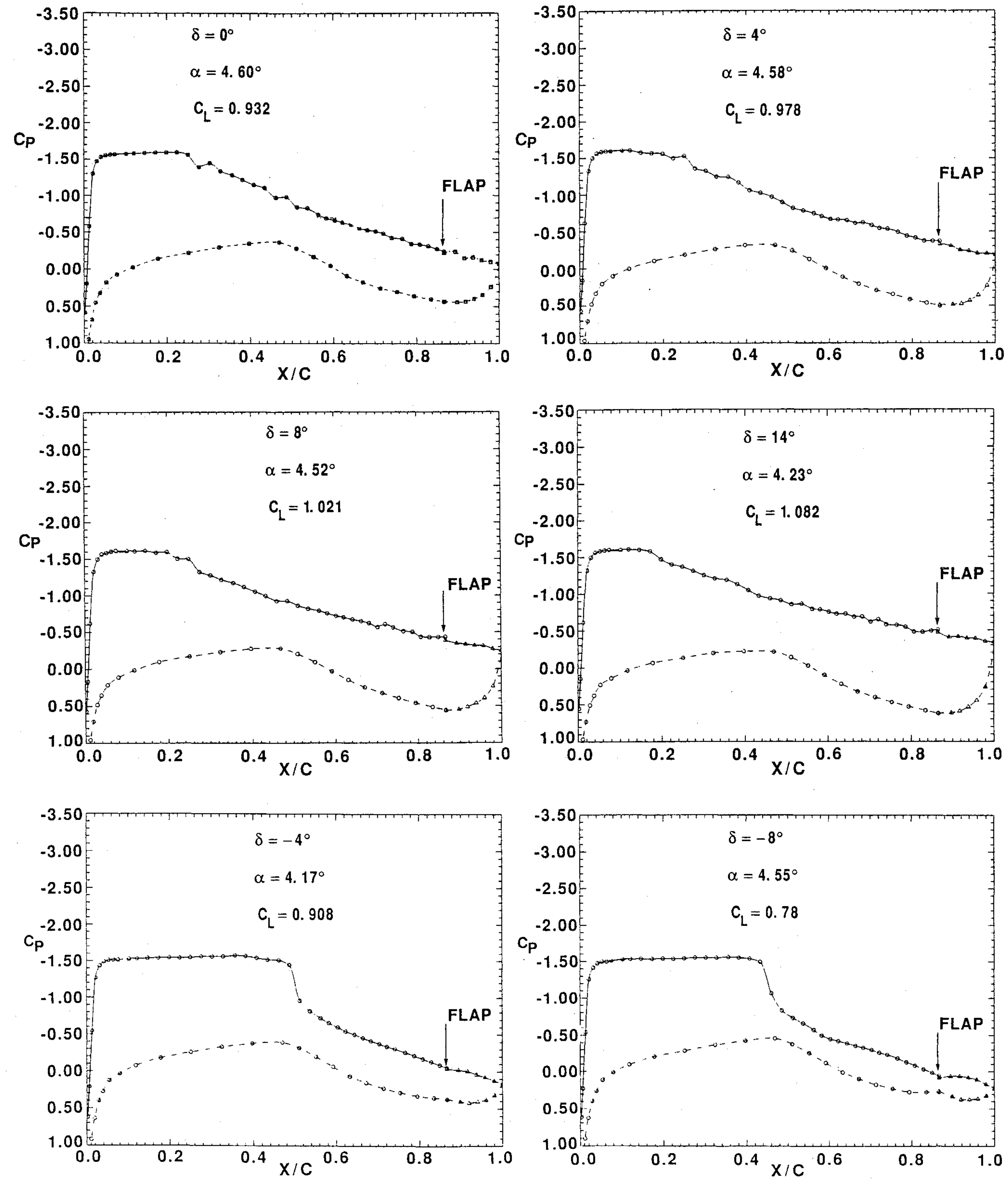

Fig. 8 Surface pressure distributions at $M = 0.723$ and α of about 4.5 deg.

$M = 0.75$, which corresponds to M_D at design C_L, this airfoil shows only small gains in the buffet boundary by the use of flaps. Further increases in M again show an increase in the lift before encountering buffet. At low M, i.e., $M = 0.672$, the buffet boundaries at $\delta = 4$ and 8 deg appear to be closer together than the other curves with the same increment in δ. Examination of results such as C_L vs α, shock locations,[15,16] and C_N' vs C_L (Fig. 7) shows that this behavior may be a characteristic of this particular airfoil and is not due to the manner in which the buffet onset boundary is determined.

Pressure Distributions on Airfoil Surface at Design Mach Number

Static pressure measurements were obtained from 50 and 29 pressure orifices on the upper and lower model surfaces, respectively. The C_p distributions for the airfoil near M_{DES} are shown in Fig. 8 for α of about 4.5 deg. It was difficult in the tests to keep both α and M constant. The values of α for $\delta \geq 0$ deg are well into buffet regime, whereas that for $\delta = -4$ deg is slightly greater than the buffet onset value. For $\delta = -8$ deg, α is just outside the buffet boundary. For other values of the M, the C_p distributions show the shock to be more unsteady at the lower values of M, and more detailed results are given in Refs. 15 and 16.

Power Spectra of Normal Forces from Balance Measurements at Design Mach Number

The IEEE computer program PMPSE[18] was used in spectral analyses of the normal-force outputs from the balance. Figure 9 shows the results using a fast Fourier transform block size of 256 and signal length of 2 s. The sampling frequency was 1.6 kHz. The test conditions for this figure correspond to those in Fig. 8. For $\delta = -8$ and -4 deg, the airfoil is, respectively, below and just above the buffet boundary. No distinct peaks are detected for these two flap angles because the trailing-edge pressure is either not diverged, or, in the -4 deg case, the separated flow region is very small and the shock wave is practically steady. For $\delta \geq 0$ deg the spectra of C_N show distinct peaks at approximately 70 Hz for this M. Similar results were obtained in a previous investigation[3] of the BGK no. 1 airfoil, and they were identified as being caused by shock-wave oscillations.

Drag Measurement

The drag polar was determined from wake measurements, and at the design C_L, M_D (using a criterion based on a value of slope of $dC_D/dM = 0.1$) was 0.75.

At the design $C_L = 0.6$, C_D vs M is plotted in Fig. 10. Below M_D, small flap angles ($\delta = \pm 4$ deg) do not increase the drag significantly. However, the 8- and 14-deg flaps appear to have quite a large drag rise. For off-design conditions ($C_L = 0.8$), Ref. 16 shows that the drag increase for negative flap angles is much larger than that for positive δ.

Wake Profiles

Some representative results for the wake profiles are given in Fig. 11. The growth of the wake with different flap settings at $M = 0.723$ and α of about 4.5 deg is shown for a wake traverse 1.75 in. from the tunnel centerline. The distance y traversed by the wake probe is normalized with respect to the airfoil chord. The C_D' on the horizontal scale is proportional to the total pressure drop. The integral of C_D' over the width of the wake gives the total drag. For this value of α, the airfoil is experiencing buffet, except for $\delta = -8$ deg, which is very close to the onset boundary. The profiles are very unsteady as the airfoil operates beyond the buffet onset. The C_D' shown are between values that occur in one pressure scan. The duration of a scan depends on the width of the wake and the traversing speed but will not exceed a maximum value of 2.4 s.

As an indication of the growth of the wake, w is measured and normalized with respect to t. The value of w is determined from the wake profile at a value of C_D' equal to 1% of its maximum. The effect of flap setting is shown in Fig. 12 for $M = 0.723$. Positive flap angle increases w/t, whereas negative δ gives a smaller value of w/t. At this M, the wake thickness increases quite uniformly over the range of incidence covered in the test.

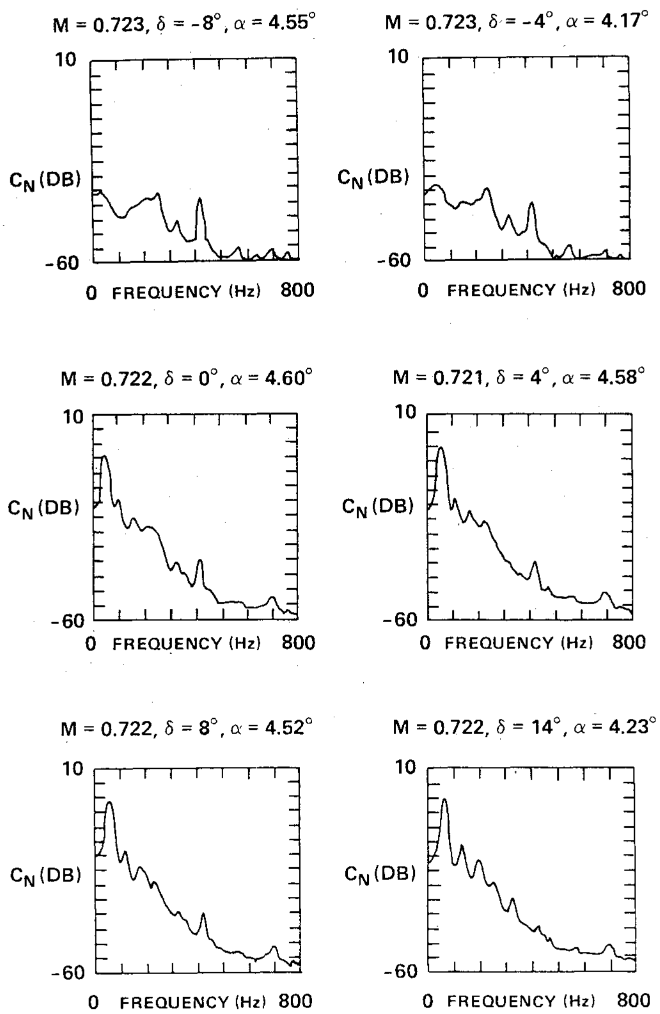

Fig. 9 Power spectra of normal forces from balance measurements.

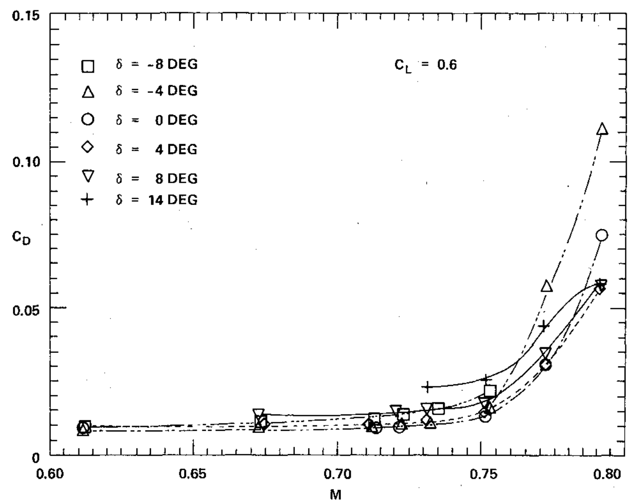

Fig. 10 Drag coefficient vs Mach number at design lift for various flap angles.

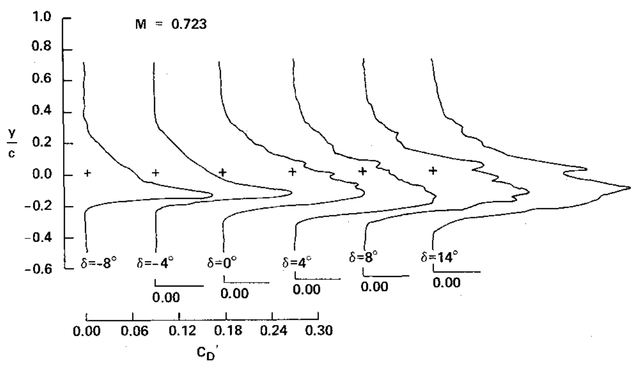

Fig. 11 Wake profiles at $M = 0.723$ and α of about 4.5 deg.

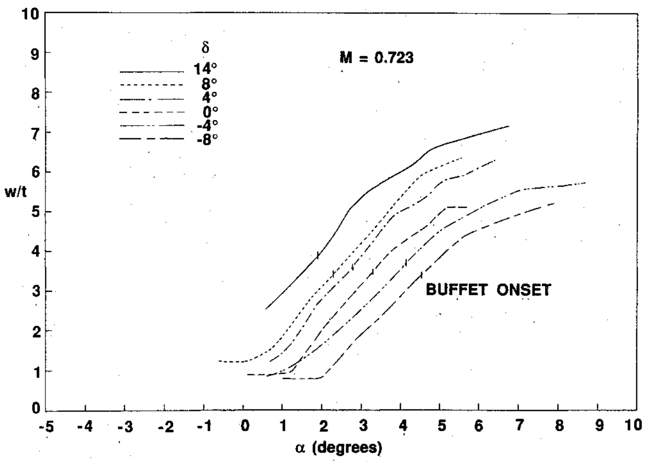

Fig. 12 Wake thickness vs angle of incidence at $M = 0.723$ for various flap angles.

Conclusions

A supercritical airfoil with a trailing-edge flap was investigated in the NAE High Reynolds Number Two-Dimensional Test Facility at a chord Reynolds number of approximately 20×10^6. The investigation was made quite deep into the buffet régime, and the effects of flap deflection on lift increment and buffet severity were analyzed. The results can be summarized as follows:

1) The onset of buffet can be determined quite accurately from plots of C_N' vs C_L at values of C_L where the slope of the curve is 0.1. This value for the slope is found to give consistent results that agree quite well with values derived from the criterion using the trailing-edge pressure divergence for flow conditions where buffet onset is primarily due to trailing-edge separation.

2) Buffet boundaries can be raised appreciably by employing positive trailing-edge flap deflections. Unlike conventional airfoils, where regions of mild, moderate, or heavy buffeting can be classified, the buffet onset boundaries for supercritical airfoils for $M < M_{DES}$ occur very close to and, in some cases, correspond to $C_{L_{max}}$. Identifying regions of different degree of severity is often impossible. This suggests that the design condition for supercritical airfoils should be farther away from the buffet boundary than the usual criteria used for conventional airfoil would indicate.

3) Spectral analyses of the balance normal-force outputs show shock oscillations at about 50–80 Hz between $M = 0.612$ and 0.792. Slightly inside the buffet régime, the magnitudes of the fluctuating normal force have quite large values near the "elbow" of the buffet onset curve. As M increases to higher values, the fluctuations in normal force decrease and the shock waves become more steady.

4) At the design $C_L = 0.6$, small flap angles do not increase the drag significantly for $M < M_D$. For off-design conditions ($C_L = 0.8$), the drag rise is much larger for negative flap angles than for positive angles of the same magnitude. The wake profiles show large unsteady fluctuations at conditions beyond the buffet onset boundary. Near M_{DES}, positive flap angles increase the wake thickness, whereas negative angles have the opposite effect. The growth of the width of the wake is quite uniform over the range of angle of incidence covered in the test.

References

[1]Pearcy, H. H., Osborne, J., and Haines, A. B., "The Interaction Between Local Effects at the Shock and Rear Separation—a Source of Significant Scale Effects in Wind-Tunnel Tests in Airfoils and Wings," AGARD CP-35, Sept. 1968.

[2]Roos, F. W., "Some Features of the Unsteady Pressure Field in Transonic Airfoil Buffeting," *Journal of Aircraft*, Vol. 17, Nov. 1980, pp. 781–788.

[3]Lee, B. H. K. and Öhman, L. H., "Unsteady Pressures and Forces During Transonic Buffeting of a Supercritical Airfoil," *Journal of Aircraft*, Vol. 21, June 1984, pp. 439–441.

[4]Benoit, B. and Legrain, I., "Buffeting Prediction for Transport Aircraft Applications Based on Unsteady Pressure Measurements," AIAA Paper 87-2356, Aug. 1987.

[5]Cunningham, A. M., Jr., Waner, P. G., Jr., Watts, J. D., Benepe, D. B., and Riddle, D. W., "Development and Evaluation of a New Method for Predicting Aircraft Buffet Response," AIAA Paper 75-69, Jan. 1975.

[6]Lee, B. H. K., "A Method for Predicting Wing Response to Buffet Loads," *Journal of Aircraft*, Vol. 21, Jan. 1984, pp. 85–87.

[7]Lemley, C. E. and Mullans, R. E., "Buffeting Pressures on a Swept Wing in Transonic Flight—Comparison of Model and Full Scale Measurements," AIAA Paper 73-311, March 1973.

[8]Butler, G. F. and Spavins, G. R., "Preliminary Evaluation of a Technique for Predicting Buffet Loads in Flight from Wind-Tunnel Measurements on Models of Conventional Construction," AGARD CP-204, Sept. 1976.

[9]Mabey, D. G., "Prediction of the Severity of Buffeting," AGARD LS-94, Feb. 1978.

[10]Redeker, G. and Proksch, H. J., "The Prediction of Buffet Onset and Light Buffet by Means of Computational Methods," AGARD CP-204, Sept. 1976.

[11]Thomas, F. and Redeker, G., "A Method for Calculating the Transonic Buffet Boundary Including the Influence of Reynolds Number," AGARD CP-83, April 1971.

[12]Friend, E. L. and Sefic, W. J., "Flight Measurements of Buffet Characteristics of the F-104 Airplane for Selected Wing-Flap Deflections," NASA TN D-6943, Aug. 1972.

[13]Monaghan, R. C. and Friend, E. L., "Effects of Flaps on Buffet Characteristics and Wing-Rock Onset of an F-8C Airplane at Subsonic and Transonic Speeds," NASA TM X-2873, Aug. 1973.

[14]Öhman, L. H., "The NAE High Reynolds Number 15″ × 60″ Two-Dimensional Test Facility," National Research Council of Canada, NAE-LTR-HA-4, Pt. I, April 1970.

[15]Lee, B. H. K. and Tang, F. C., "An Experimental Study of Transonic Buffet of a Supercritical Airfoil with Trailing Edge Flap," National Research Council of Canada, NAE-AN-54, Sept. 1988.

[16]Tang, F. C. and Lee, B. H. K., "Wind Tunnel Investigation of the Buffet Characteristics of a Supercritical Airfoil with Flap at a Reynolds Number of 20 Million," National Research Council of Canada, NAE-LTR-HA-5 × 5/0179, Aug. 1988, Vols. 1–3.

[17]Eggleston, B., Poole, R. J. D., Jones, D. J., and Khalid, M., "Thick Supercritical Airfoils with Low Drag and Natural Laminar Flow," *Journal of Aircraft*, Vol. 24, June 1987, pp. 405–411.

[18]Rabiner, L. R., Schafer, R. W., and Dlugos, D., "Periodgram Method for Power Spectrum Analysis," *Programs for Digital Signal Processing*, edited by The Digital Signal Processing Committee, IEEE Acoustic, Speech and Signal Processing Society, IEEE Press, New York, 1979.