Aerodynamic Characteristics of a Two-Dimensional Moving Spoiler in Subsonic and Transonic Flow

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An experimental study has been conducted in two dimensional flow to determine the steady and unsteady performances of a spoilerlike control surface Selected results obtained with a spoiler performing simple harmonic oscillations show that unsteady (first harmonic) pressure distributions and aerodynamic coefficients strongly depend on freestream Mach number, spoiler mean deflection, and frequency of the oscillations Typical transient pressures and transient loads recorded for a sudden and large change in spoiler angle indicate that large unsteady and significant nonlinear effects are generated by the motion of this type of control The possibility of a reversal of the control effectiveness is also demonstrated

Nomenclature

c = airfoil chord
C_h = hinge moment coefficient
C_L = lift coefficient
C_{L1}/δ_i = unsteady lift coefficient (magnitude of first harmonic)
C_m = pitching moment coefficient
C_p = pressure coefficient
Cp_1/δ_i = unsteady pressure coefficient (magnitude of first harmonic)
f = frequency
k = frequency parameter $\pi fc/U_\infty$
M_∞ = freestream Mach number
U_∞ = freestream velocity
x = chordwise coordinate
α = airfoil angle of attack
δi = amplitude of spoiler oscillations
δm = spoiler mean deflection
δsp = spoiler deflection
ψ_1 = phase angle relative to the spoiler motion

Introduction

THERE has recently been a renewed interest in the aerodynamics of spoilers because of their potential usefulness in active control technology applications Actually, spoilers are aerodynamic control devices with a high degree of effectiveness which can provide rapid lift variations required by gust alleviation or turbulence reduction systems

Documentation in this particular field is noticeably scarce and a literature survey shows that, except for Refs 1 and 2, all recent work published on this subject is concerned with aerodynamic phenomena associated with statically deflected spoilers In view of this, a basic experimental study was carried out in two-dimensional flow in order to enhance knowledge of unsteady effects generated by the deflection of a spoilerlike control surface This project is part of a more general research program on unsteady aerodynamics undertaken at the Office National d' Etudes et de Recherche Aerospatiales (ONERA) some years ago [3 5]

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The specific objective of the work described in this paper was to determine the performances of an oscillating spoiler Therefore, emphasis was placed on the measurement of oscillatory pressure distributions and aerodynamic coefficients. Preliminary results of the time-dependent aerodynamic response following a rapid change in spoiler angle were also obtained

Experimental Setup

Model and Wind Tunnel

The experiments were performed on a supercritical airfoil (16% in thickness ratio and 0 18 m in chord), fitted with a flap and a full span plain type spoiler, in the 0.78×0 56 transonic windtunnel S3 at the ONERA/Modane Test Center The test section had upper and lower perforated walls, each having an open ratio of approximately 9 7%

The spoiler relative chord was 0 15 c and its hinge line was located at $x/c = 0$ 52 on the airfoil upper surface (Fig 1) In order to achieve high stiffness and low inertia, this spoiler was made from carbon fiber. It was driven by two hydraulic rotary actuators placed outside the test section These actuators were controlled by servovalves, which were in turn activated either by a sinusoidal or an arbitrary waveform generator Harmonic oscillations of 1 deg could be obtained for frequencies up to about 150 Hz Larger amplitudes (up to 5 deg) could be achieved at lower frequencies. The system could also be used for a fast and accurate setting of the spoiler static deflection (up to 40 deg)

Airfoil surface steady pressures were measured with a row of 80 pressure taps located at the mid cross section (five located on the spoiler upper surface and two on the spoiler lower surface) Unsteady pressure measurements were obtained with 34 small differential pressure transducers installed in the model and connected to surface orifices by the shortest possible passage (two on the spoiler upper surface, two on the spoiler lower surface) (see Fig 1) Great care was taken to ensure a constant pressure on the reference side of these transducers In addition, the spoiler was equipped with one accelerometer and two torsion gage bridges bonded to its shaft

It must be noted that the objective of the present work was not to obtain data fully representative of the flow around the same model in free atmosphere In fact, the evaluation of tunnel steady and unsteady interference effects, especially when separated zones are present, represents a considerable task that is beyond the scope of the present study Nevertheless in a previous study concerning the case of an oscillating trailing edge flap (same airfoil in the same wind tunnel) it was checked that there were no significant dif ferences on unsteady pressure distributions obtained either with solid or perforated upper and lower walls as long as the corresponding steady pressure distributions were identical for both configurations

Data Acquisition

The S3 wind tunnel standard data acquisition system was used for steady measurements, but acquisition and processing of unsteady data were accomplished with a separate system especially designed for this type of test A detailed description of this data acquisition system can be found in Ref 6

For harmonic tests, the sampling frequency was adjusted to eight times the spoiler oscillation frequency and measurements were taken over 64 periods Fourier analysis was thus performed on 512 points

For nonharmonic tests, measurements of pressure outputs for ten successive identical spoiler motions were recorded on magnetic tapes, and, in this case, data reduction was performed after the tests.

Test Program

The main objective of this study was to investigate the influence of the following parameters on oscillatory pressure distributions and aerodynamic coefficients: freestream Mach number from 0 30 to 0 80; spoiler mean deflection from 0 to 20 deg; frequency of oscillations, from about 10 to 150 Hz (i e , a frequency parameter $k=\pi fc/U_\infty$ from 0.05 to 0 85 at $M_\infty=0$ 30 and from 0 05 to 0.375 at $M_\infty=0$ 73); and amplitude of oscillations from 1 to 5 deg

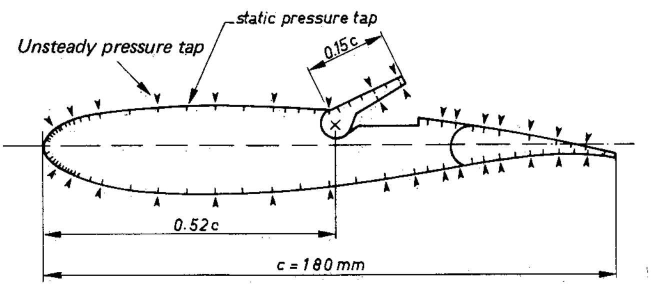

Fig 1 Wind tunnel model

Furthermore, a first attempt was made to measure the time-dependent pressures and loads following a large and fairly rapid change in spoiler angle (1 to 20 deg or 20 to 1 deg in 64 or 16 ms)

All the tests reported herein were performed for an airfoil angle of attack equal to zero for a trailing edge flap angle equal to zero and for a stagnation pressure equal to 1 7 10^5 Pa (giving a Reynolds number of 1 9 10^6 at $M_\infty=0$ 30 and 4 7 10^6 at $M_\infty=0$ 73).

Transition was fixed at $x/c=0$ 075 on both the upper and lower surface of the airfoil Transition trips were 1 mm wide and made of carborundum grit and 0 089 mm in height

Results in Steady Flow

Pressure Distributions

Figure 2 shows the pressure distributions obtained for a freestream Mach number of 0 30 and seven different values of the spoiler angle between 0 and 20 deg (For the sake of clarity, pressure coefficients on the lower surface of the spoiler are not plotted)

These results are very typical of the effect of a deflected spoiler on pressure coefficients Thus, only the main features of the flowfield will be described

On the upper surface, upstream of the spoiler, changes in pressure distributions become apparent only for spoiler angles of about 4 to 6 deg The figure well illustrates the growth of the separation bubble aft of the spoiler and the change in location of the reattachment point; for $\delta sp \leq 6$ deg, the flow reattaches to the airfoil surface, while for $\delta sp > 8$ deg, the separated flow region extends beyond the airfoil trailing edge For large values of δsp (e g , $\delta sp=20$ deg) the pressure distribution is characterized by a region of nearly constant pressure aft of the spoiler trailing edge

On the lower surface, for values of δsp less than about 8 deg, there is hardly any change in pressure distribution But for $\delta sp > 8$ deg, the suction in the separated flow region aft of the spoiler, through the trailing edge condition reduces the lower surface pressures For a freestream Mach number of 0 73 (Fig 3), it can be noted that the separation bubble reaches the trailing edge and that changes in both upper and lower surface pressure distributions are obtained for lower values of the spoiler deflection when compared to the low speed case On the lower surface, for $\delta sp=8$ deg, the flow

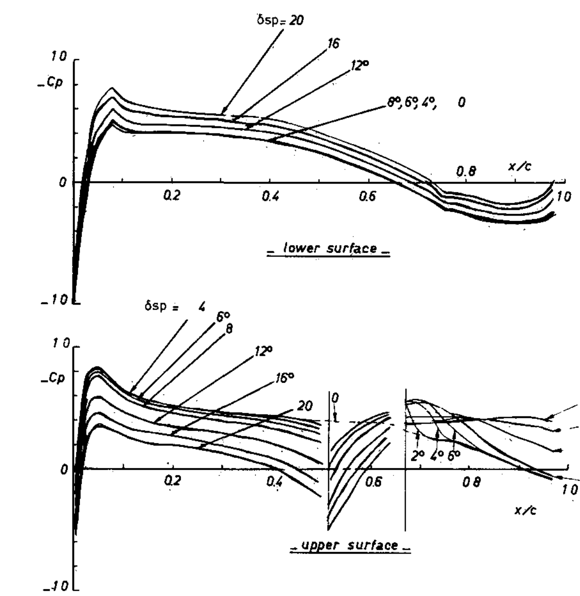

Fig 2 Effect of spoiler deflection on pressure distributions; $M_\infty=0$ 30

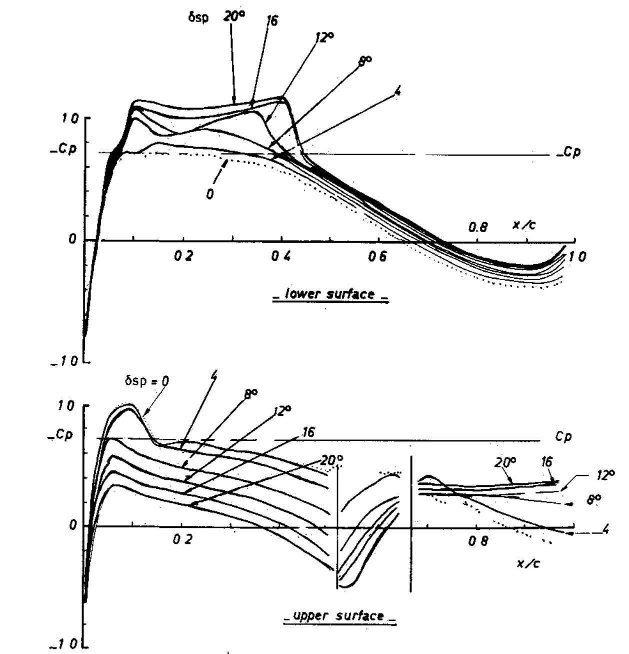

Fig 3 Effect of spoiler deflection on pressure distributions; $M_\infty=0$ 73.

suddenly decelerates near $x/c=0\;15$ and gradually accelerates up to a shock wave located about $x/c=0\;40$ The first compression tends to disappear for larger values of δsp When δsp increases from 16 to 20 deg, the shock location is nearly constant but its strength increases Nevertheless, for this particular freestream Mach number, no boundary layer separation is observed

Figure 4 shows some airfoil pressure distributions obtained for a spoiler deflection of 10 deg and several freestream Mach numbers between 0 30 and 0 80 The figure indicates that for this particular value of δsp, the lower surface shock wave causes boundary-layer separation for $M_\infty \geq 0\;78$ On the upper surface, upstream of the spoiler (except for $M_\infty = 0.78$ and $M_\infty = 0\;80$), the Mach number has only a moderate in fluence on pressure distributions On the contrary, down stream of the spoiler, the pressure level strongly depends on this parameter

Comparison with Preliminary Computation

The set of data previously discussed was used to calculate quasisteady results (the limit for $k \to 0$) for comparison with purely unsteady results This data base will also be used to validate theoretical methods that are being developed at ONERA. In fact, the fluid mechanical phenomena associated with the use of spoilers are of a formidable complexity and, at the present time, even in steady flow, the treatment of this problem is far from being completely solved Until quite recently, steady spoiler prediction methods were developed for low freestream Mach numbers assuming inviscid flow models (see Ref 7, for example) In these past two years, some progress has been made toward incorporating wake mixing effects into the theoretical model [8]

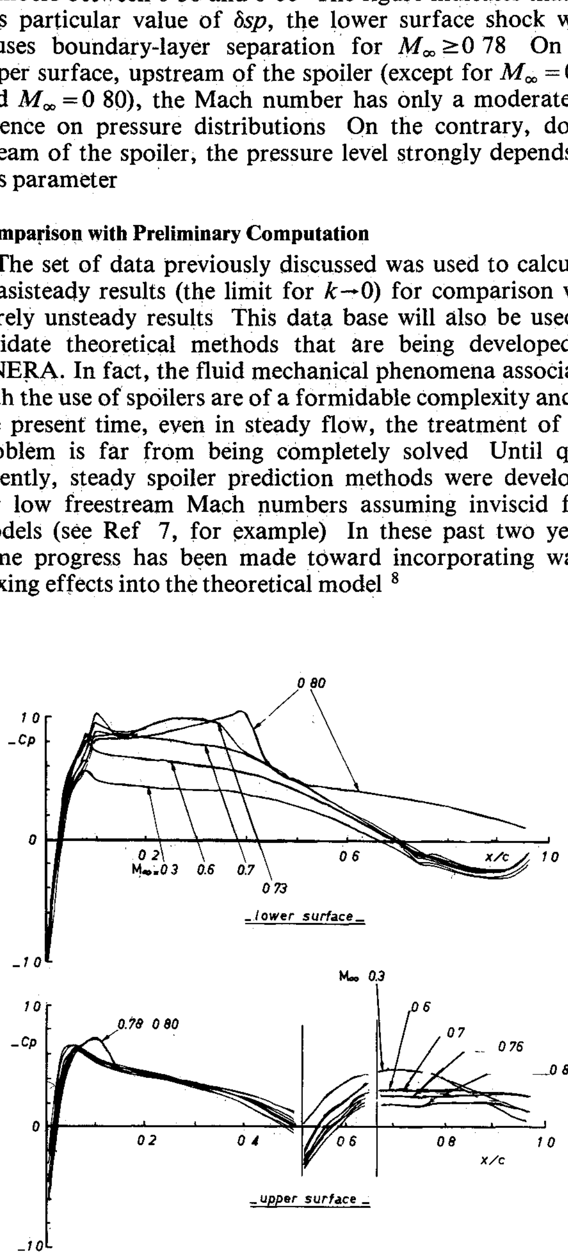

Fig 4 Effect of Mach number on pressure distributions; $\delta sp = 10$ deg

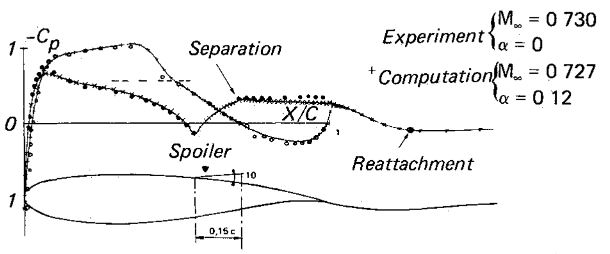

Fig 5 Computed pressure distribution on airfoil with deflected spoiler

Figure 5 shows an example of a first attempt at predicting the spoiler steady effectiveness in transonic flow including viscous effects The code used in the present study is an ex tension of a method used for the computation of strong viscous inviscid interaction (including separation) around steady transonic airfoils [9] The computation was carried out assuming that the spoiler was a simple flat plate and using the corrected values of the freestream Mach number and in cidence as given by a wall correction program based on pressure measurements along both top and bottom wind tunnel walls The spoiler geometry is materialized by an equivalent injection condition at the wall and by a sudden separation of the boundary layer at its tip The results in Fig 5, obtained in the case of a fully turbulent flow, proved very encouraging although complete validation of the model would require more detailed investigation involving several other test cases

Aerodynamic Coefficients

Figure 6 shows the variations of the steady aerodynamic coefficients (lift, pitching moment, and spoiler hinge moment) with respect to δsp for three particular values of the freestream Mach number: 0 30, 0 60, and 0 73 These coefficients were calculated by integrating the pressure coefficient curves presented above (Control surface rotation as well as pressure measurements on the spoiler lower surface

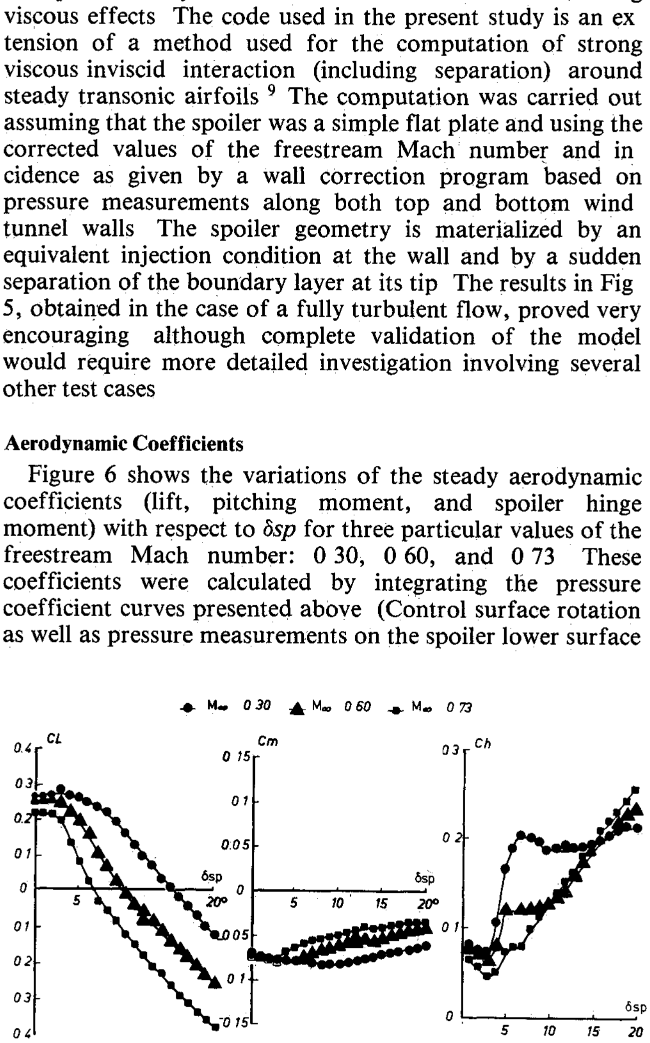

Fig 6 Effect of spoiler deflection on aerodynamic coefficients

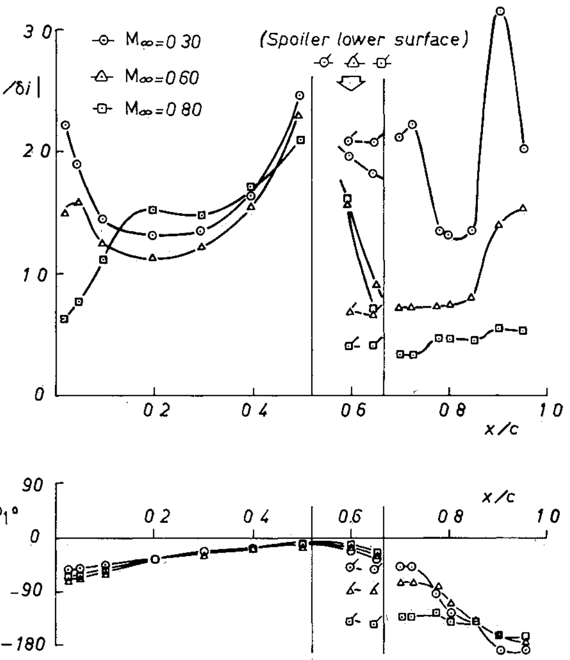

Fig 7 Effect of freestream Mach number on unsteady pressure coefficients; $\delta m = 10$ deg, $\delta i = 1$ deg, $k = 0\;15$, upper surface

were taken into account) This figure indicates that the behavior of the three sets of curves is very different depending on the range of spoiler deflection considered

For small values of δsp, there is no significant decrease in lift (a small increment is even obtained in the case $M_\infty = 0$ 30) The existence of such a region of poor response for small deflection is very typical of this type of control It is interesting to note that this behavior corresponds to angle settings for which the flow reattaches aft of the spoiler In this case, it can also be noted that the airfoil pitching moment tends to increase and that the magnitude of the closing hinge moment is low and tends to decrease

For large values of δsp, lift decreases gradually Nevertheless, for the particular configuration studied in these experiments, the variations of C_L with respect to δsp cannot be considered as linear In this range of δsp, the pitching moment decreases and there is a large increase in the spoiler hinge moment especially at the lowest Mach number

Results for Spoilers in Simple Harmonic Motion

The spoiler is driven at a frequency f with an amplitude δi around a mean deflection δm:

$$\delta = \delta m + \delta i \sin \omega t$$

At any point on the profile, the pressure coefficient oscillates periodically around a mean value C_{p_m}, so that $C_p(t)$ can be described by a Fourier series; that is,

$$C_p(t) = C_{p_m} + |C_{pl}| \sin(\omega t + \psi_l) + |C_{p_2}| \sin(2\omega t + \psi_2) +$$

In this paper, the description of the results will be limited to the first harmonic which usually predominates over higher harmonics Results (referred to as "unsteady" or "oscillatory" pressure distributions) are presented in terms of chordwise variation of both the magnitude reduced by the motion amplitude ($|C_{pl}/\delta_i|$) and the phase angle relative to the spoiler motion (ψ_l).

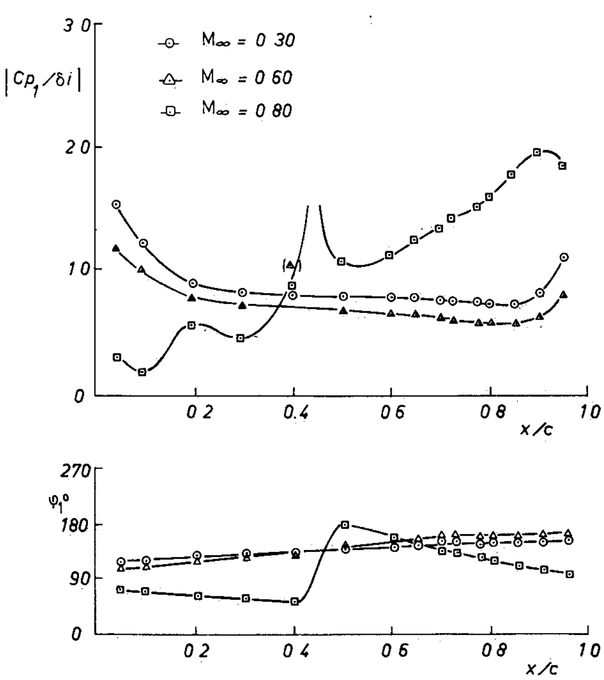

Fig 8 Effect of freestream Mach number on unsteady pressure coefficients; $\delta m = 10$ deg, $k = 0$ 15, lower surface

Unsteady Pressure Distributions

Examples of upper surface unsteady pressure distributions measured for three different freestream Mach numbers are presented in Fig 7 It can be seen that upstream of the spoiler and on the spoiler, the present curves are qualitatively very similar to the curves obtained in the case of an oscillating trailing edge flap We note a first maximum of $|C_{p_l}/\delta_i|$ in the neighborhood of the airfoil leading edge and a second maximum at the hinge line of the moving control On the spoiler itself, the magnitude of the oscillatory pressure

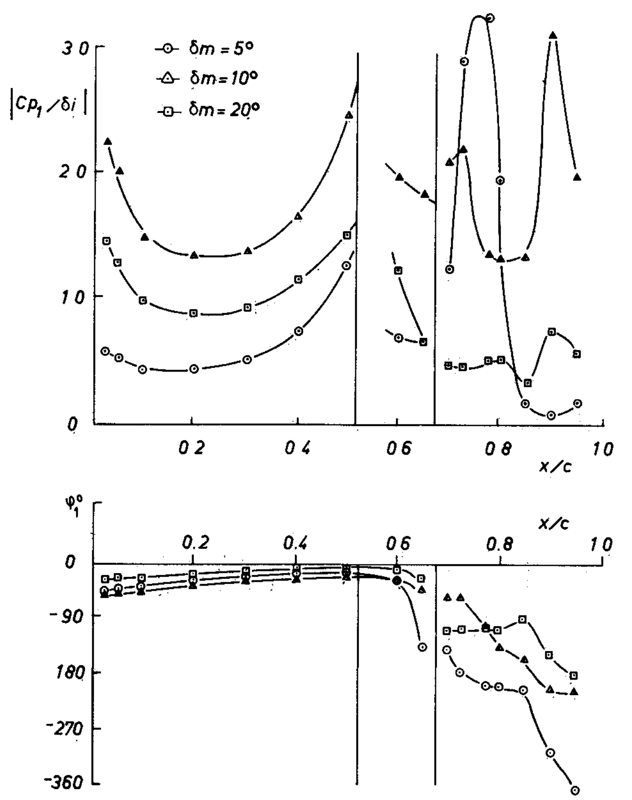

Fig 9 Effect of mean spoiler deflection on unsteady pressure coefficients; $M_\infty = 0.30$, $k = 0$ 15, $\delta_i = 1$ deg, upper surface.

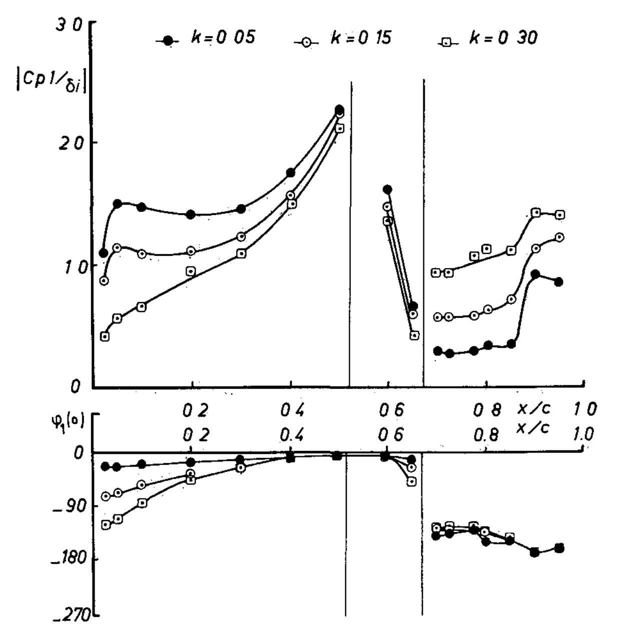

Fig 10 Effect of reduced frequency on unsteady pressure coefficients; $M_\infty = 0$ 73, $\delta m = 10$ deg, $\delta_i = 1$ deg, upper surface

decreases rapidly from the hinge line to the trailing edge In the leading edge region, the magnitude is diminished as the freestream Mach number is increased Very low values can be achieved when the flow is locally supersonic; this is the case for $M_\infty = 0\ 80$ The figure indicates also that a change in freestream Mach number has little effect on phase angles; for a given value of M_∞, we note a nearly linear variation of ψ_I with chordwise distance, except in the vicinity of the spoiler trailing edge

Aft of the spoiler, the magnitude of the oscillatory pressure strongly depends on the Mach number or, more precisely, on the type of flow in this region When separation extends beyond the airfoil trailing edge, relatively low and nearly constant $|C_{p_I}/\delta_i|$ are achieved On the contrary, when the flow reattaches to the airfoil surface, the curves slow very irregular behavior and a localized pressure peak corresponding to the oscillation of the reattachment point is obtained

Figure 7 also indicates that some intermediate situation may be obtained as well However, it is clear that a complete understanding of the flow in this region would require a very detailed investigation including, for example, flow visualizations and turbulence measurements. (One must also bear in mind that the flow pattern in this region might depend on the exact geometry of the spoiler as well) Likewise, it is interesting to note that both the magnitude and the phase angle of the oscillatory pressure measured on the spoiler lower surface are equal to the values obtained on the airfoil im mediately downstream of the spoiler Thus, for the sake of clarity such points have been omitted in the following figures

On the airfoil lower surface (Fig 8), when the flow is subsonic everywhere, the magnitude of the oscillatory pressure gradually decreases with chordwise distance up to about $x/c = 0\ 85$ and then increases in the region close to the trailing edge At $M_\infty = 0\ 80$, the oscillation of the shock wave generates a large pressure peak (sometimes difficult to localize in spite of the presence of 16 transducers) and a sudden jump in the phase angle Downstream of the shock wave the boundary layer separates (see Fig 4) and rather high oscillatory pressures are obtained

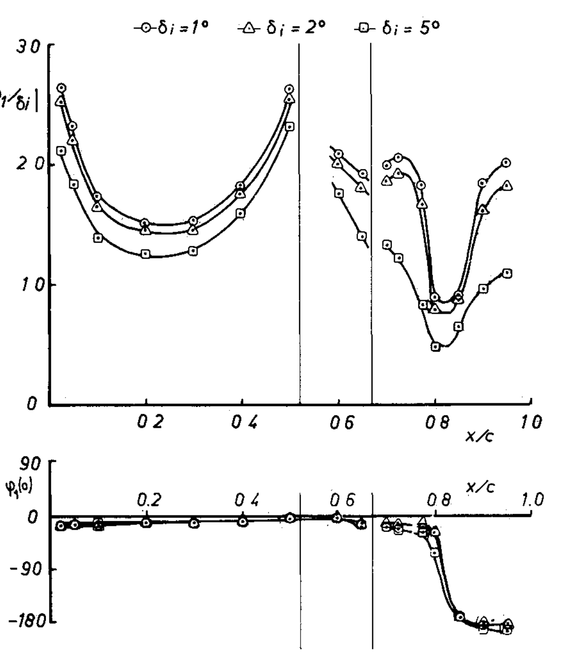

Fig 11 Effect of oscillation amplitude on unsteady pressure coef ficients; $M_\infty = 0\ 30$, $k = 0\ 05$, $\delta m = 10$ deg, upper surface

Effect of Other Parameters

Figure 9 demonstrates that the spoiler mean deflection has a large effect on airfoil unsteady pressure distributions It can be observed that, upstream of the spoiler, the largest am plitudes of the oscillatory pressure are obtained; in this particular case, for the intermediate value of δm, i e , $\delta m = 10$ deg, while minimum phase lag corresponds to $\delta m = 20$ deg For $\delta m = 5$ deg, the low values of $|C_{p_I}/\delta_i|$ measured are consistent with the already mentioned fact that poor spoiler effectiveness is achieved for small spoiler angles Figure 9 also illustrates the change in location of the peak of $|C_{p_I}/\delta_i|$ associated with the flow reattachment process aft of the spoiler A typical effect of the frequency parameter on oscillatory pressure distributions is presented in Fig 10 It can be seen that an increase in frequency leads to an important increase in phase lag relative to the spoiler motion (especially in the region near the leading edge), and to a large decrease in magnitudes upstream of the spoiler Aft of the spoiler, an opposite effect is observed A detailed analysis of the com plete set of data demonstrated that very similar trends were obtained for most other configurations Nevertheless, it will be shown below that a different behavior may sometimes occur in cases of small spoiler mean deflections

The effect of changing the spoiler oscillation amplitude was examined for several combinations of the flow parameters M_∞, δm, and k An example of unsteady pressure distributions is shown in Fig 11 for three values of δ_i, a frequency parameter of 0 05, and a freestream Mach number of 0 30 It is clear from these results that even in in compressible flow, the magnitude of the first harmonic of the oscillatory pressure ($|C_{p_I}|$) cannot be considered as exactly proportional to δ_i In the present case, power spectra of some pressure signals (not shown here) further indicated that the magnitude of the second harmonic of the oscillatory pressure was about 10% of the magnitude of the first harmonic For a similar situation with $\delta m = 5$ deg, a value up to 50% has even been observed

It must be emphasized that in the case of an oscillating trailing edge flap and for identical values of the various parameters (M_∞ k and δ_i) almost perfect linearity of the pressure response was obtained [3 5]

Unsteady Lift Coefficient

The variations of the unsteady lift coefficient (obtained by numerical intergration of the chordwise oscillatory pressure distributions discussed above) with spoiler mean deflection

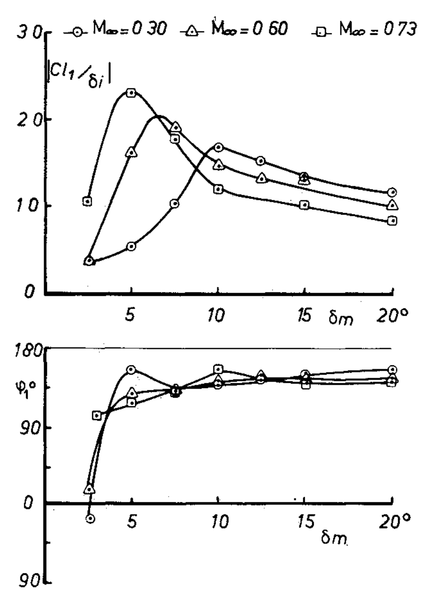

Fig 12 Effect of spoiler mean deflection and Mach number on unsteady lift; $k = 0\ 15$, $\delta_i = 1$ deg

are shown in Fig 12 for Mach numbers of 0 30, 0 60 and 0 73 These data were all obtained for a value of the frequency parameter of 0 15 and for an oscillation amplitude of 1 deg The figure shows that as δm is increased from 2 5 to 20 deg, the magnitude of the oscillatory lift first increases rapidly, reaches a maximum, and then decreases gradually The value of the maximum of $|C_{L1}/\delta_i|$, as well as the value of δm at which this maximum occurs, greatly depends on the freestream Mach number For moderate and large values of δm the phase lag relative to the spoiler motion is about 50 deg (it should be remembered that due to the sign convention $\Delta C_L < 0$ for $\delta_p > 0$, hence the physical reference for phase angles is 180 deg) whereas for small values of δm, phase lags of the order of 180 deg are encountered This means that, in such cases, during the opening part of the motion, the airfoil lift increases Thus, unsteady, as well as steady, effectiveness reversal can be encountered with this type of control surface

The unsteady lift coefficient at $M_\infty = 0$ 30 is plotted in Fig 13 against the spoiler mean deflection δm for three values of the frequency parameter k (0 05, 0 15, 0 60) together with the quasisteady values These were obtained simply by calculating the derivative with respect to δsp of the corresponding steady lift curve as shown in Fig 6 Figure 13 demonstrates that an increase in the frequency parameter results in a large reduction in spoiler effectiveness and a large increase of phase lag relative to the spoiler motion Consequently, the quasisteady approximation, which fairly well reproduces the trends observed at low frequency ($k = 0$ 05), soon becomes useless for larger values of k Figure 13 also indicates that the particular behavior (effectiveness reversal) at small spoiler settings is strongly dependent on the frequency parameter

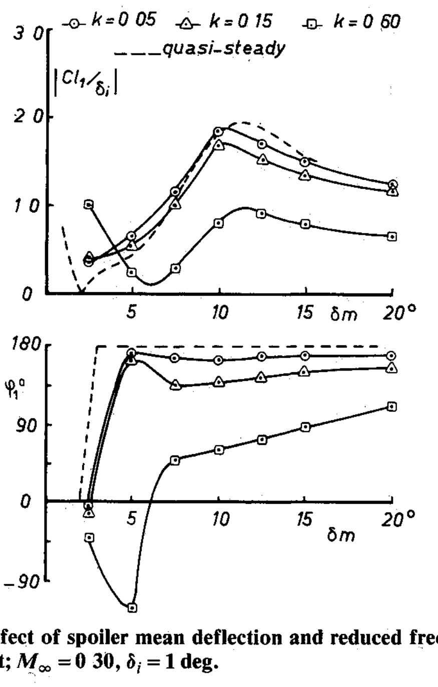

Fig 13 Effect of spoiler mean deflection and reduced frequency on unsteady lift; $M_\infty = 0$ 30, $\delta_i = 1$ deg.

Preliminary Results for a Large and Rapid Change in Spoiler Angle

The fact that the system behaves in a markedly nonlinear fashion renders any study in the frequency domain in complete In view of this, a preliminary study of the time dependent response following a large and rapid change in spoiler angle was made

For these tests, the specified time dependent control input was:

$$\delta = \delta_I \quad \text{for } t < t_I$$

$$\delta = \delta_I + \frac{\delta_2 - \delta_I}{2} I\left(1 - \cos\pi \frac{t - t_I}{t_2 - t_I}\right) \quad \text{for } t_I \leq t \leq t_2$$

$$\delta = \delta_2 \quad \text{for } t > t_2$$

This deflection law provides a smooth variation of the control angular velocity and can be easily imposed on the mechanical part of the system Since the data acquisition system and software had not been developed for this type of tests, only a few cases were studied and the emphasis was placed on the qualitative aspect of the results rather than on the quantitative aspect.

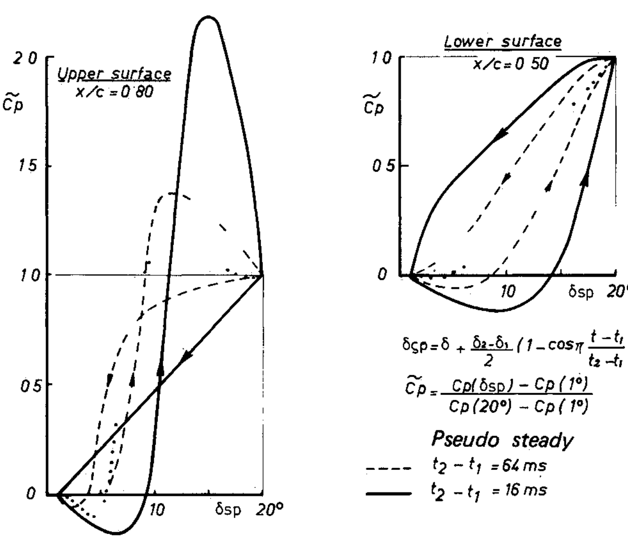

Fig 14 Typical pressure response for static and dynamic spoiler motion; $M_\infty = 0$ 30

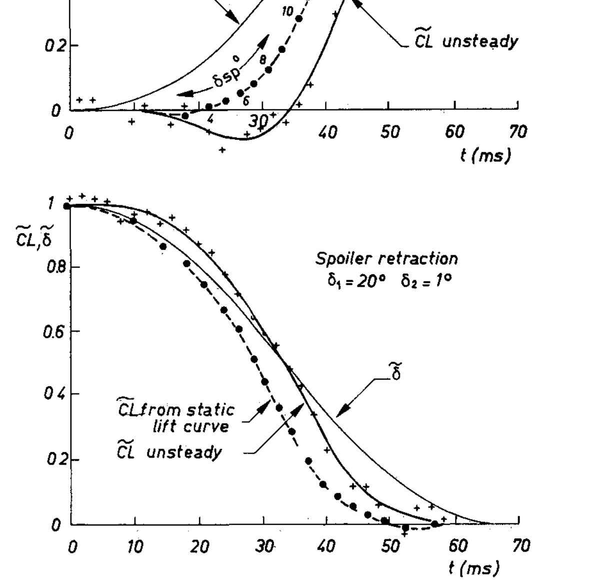

Fig 15 Time dependent lift for static and dynamic spoiler motion; $M_\infty = 0$ 30

Figure 14 shows the measured response of two particular pressure transducers that were obtained at a freestream Mach number of 0 30 in the case of a spoiler extension ($\delta_1 = 1$ deg, $\delta_2 = 20$ deg) and of a spoiler retraction ($\delta_1 = 20$ deg, $\delta_2 = 1$ deg) Two values of the rise time were considered: $t_2 - t_1 = 64$ ms ($\simeq 36\,\hat{t}$ where $\hat{t}$ is the time it takes the freestream to travel a distance of one chord) and $t_2 - t_1 = 16$ ms ($\simeq 9\hat{t}$) The data are presented in nondimensional form $\tilde{C}_p = [C_p(\delta) - C_p(1\ \text{deg})]/[C_p\ (20\ \text{deg}) - C_p\ (1\ \text{deg})]$ as a function of the spoiler angle δsp For comparison, we also plotted on the same figure the curve (referred to as "pseudosteady") obtained simply by assuming that the pressure coefficient at any instant of time is equal to the steady state value associated with the instantaneous spoiler angle

Figure 14 gives a good illustration of the unsteady and nonlinear character of the pressure response A very large hysteresis loop is obtained, and it can be observed that at the beginning of the opening motion there is a sign reversal in the pressure variation. Both trends are particularly obvious for the shortest rise time, i e , $t_2 - t_1 = 16$ ms It is also clear that the suction (which corresponds to a large value of $\tilde{C}_p$) associated with the development of the separated region aft of the spoiler can achieve very high values when the control is rapidly deflected

Figure 15 shows the time dependent nondimensional lift variation obtained at $M_\infty = 0\ 30$ and for a rise time of 64 ms The figure demonstrates that a significant adverse lift effect and an important time lag are associated with the spoiler extension even in the case of a moderate rate of rotation (312 deg/s) This particular behavior (already observed on pressure traces) is thought to be due to the formation of a strong vortex at the spoiler tip However, a detailed understanding of the phenomena involved is far from being complete When a retraction of the spoiler is involved, the results are very different in the sense that the unsteady lift variation follows the "pseudosteady" variation with a nearly constant time delay and that no adverse lift effect is encountered

Concluding Remarks

Wind tunnel tests have been made to determine the unsteady effectiveness of a spoilerlike control surface In a first set of experiments, the emphasis was placed on the study of harmonic oscillations of the spoiler Information was obtained concerning the influence of several parameters on magnitude and phase of both oscillatory pressures and lift In particular, it was shown that the results strongly depend on freestream Mach number, spoiler mean deflection, and frequency of oscillation In a second set of experiments, transient pressures and transient lift following a specified rapid and large change in spoiler angle were recorded The experimental results demonstrate the complexity of the flow pattern associated with the motion of this type of control and indicate, in particular that large unsteady and important nonlinear effects are present; the possibility of a reversal of the control unsteady effectiveness was also observed Such features would certainly create considerable difficulties in a feedback control system design.

Acknowledgments

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