ICAS-88-3.10.1

THE CAUSE AND CURE OF PERIODIC FLOWS AT TRANSONIC SPEEDS

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Abstract

Periodic flows at transonic Mach numbers have been a serious aerodynamic problem since the early days of flight at transonic speeds. The buffeting which occurs can cause serious discomfort to pilot and passengers and in severe cases may result in structural deformation or even failure. Civil transport aircraft are nowadays flying much closer to the speed of sound and military aircraft also spend a large proportion of their flying time in this potentially hazardous Mach number region. Consequently, it is very important to understand fully the cause of periodic flows at transonic speeds in order to be able to prevent their occurrence in new designs and to be able to apply cures to any problems in existing designs. This paper will present experimental results which describe in some detail the physics of the cause of periodic flows at transonic speeds and will also show results of several techniques which have successfully eliminated the problem. Results are given for the 14% thick Biconvex aerofoil and the NACA 0012 aerofoil. It is hoped these results will provide data which is detailed enough for useful comparison with theoretical results which to date are scarce.

Notation

a	Speed of sound
c	Model chord
f	Frequency
M_{CRIT}	Critical Mach number
M_{∞}	Free-stream Mach number
M_1	Mach number ahead of shock wave
$\bar{P}$	Rms pressure fluctuation
q	Free-stream dynamic pressure
t	Time
V	Free-stream velocity
V_s	Shock wave velocity
ω	Circular frequency ($2\Pi f$)
$(x/c)_s$	Non-dimensional shock wave position

I. Introduction

Unsteady transonic aerodynamic effects have been the subject of considerable research effort since the early days of high speed flight and there are still many areas where our understanding of the problems which occur is severely limited. These flows pose a particularly difficult challenge for both computational methods and for experimental investigation due to the very nature of transonic flow. This paper is an attempt to provide a clear physical understanding of the cause of one particular type of unsteady transonic flow by the careful use of experimental techniques and at the same time provide some detailed data for comparison with theory. Several techniques for curing the unwanted buffet will also be described.

The flow being considered is a two-dimensional periodic type of buffet which occurs typically at low angles of attack on some types of rigid aerofoil section. The main feature of the flow is a large amplitude (typically 0.2-0.3c) periodic shock wave oscillation on each surface of the aerofoil as shown in Figure 1. The shock wave motions are in anti-phase and so large changes in lift, drag and pitching moment can occur. The frequency parameter ($\omega c/V$) for this type of oscillation is approximately unity and if this should be close to an appropriate structural mode of a flight vehcile, structural failure could result. This type of flow should also be avoided in wind tunnels (eg struts, model supports, fairings, etc) where the noise spectrum of the working section will be adversely affected and could result in errors when measuring steady or unsteady aerodynamic features.

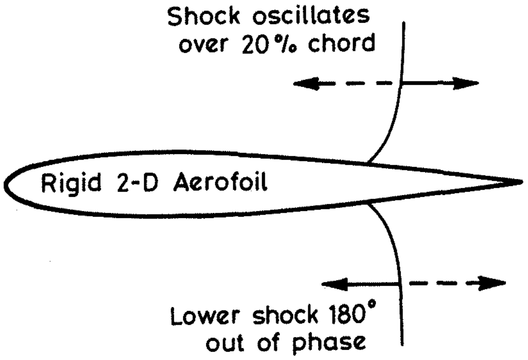


Figure 1. General features of periodic flow.

Mabey[1] and Mohan[2] have found useful information regarding the important parameters for sustained periodic flow in the transonic speed range. They can be summarised as follows:

1) Thickness/chord ratio greater than 0.10.
2) Both shock waves must be strong - typical Mach number ahead of the shock wave would be about 1.3.
3) Large trailing edge angle.
4) Shock wave position typically aft of x/c = 0.5.

The above conditions imply a high subsonic free-stream Mach number, typically 0.8<M<0.9. Lifting supercritical wings will in general not satisfy the conditions of 2) and 3) above but fairings, pylons and wind tunnel model/instrumentation support struts frequently satisfy all four conditions.

II. Experimental Details and Some Results

Tests were performed in the College of Aeronautics 19 cm x 23 cm continuous running transonic wind tunnel[6]. The new working section recently fitted to this wind tunnel simulates many of the geometric details of the proposed European Transonic Wind-tunnel (ETW) with its slots in the fully open two-dimensional configuration. The working section noise levels of this tunnel are typically less than 0.002 of the free-stream dynamic pressure making it well suited to unsteady aerodynamic experiments.

The aerofoils tested were the 14% thick Biconvex aerofoil and the NACA 0012 aerofoil as shown in Figure 2. The 14% Biconvex aerofoil is well known for its periodic flow,[2,3,4] in fact all Biconvex aerofoils with thickness/chord ratios greater than 10% can exhibit periodic flow.[1,5] NACA 0012 is another 'aerodynamic standard' which is known to exhibit periodic flow[2] and is commonly used (as is the Biconvex profile) for struts and fairings in transonic wind-tunnels.

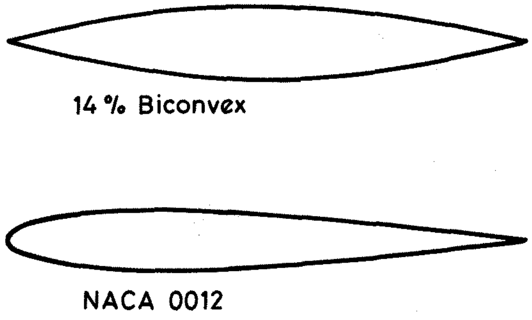
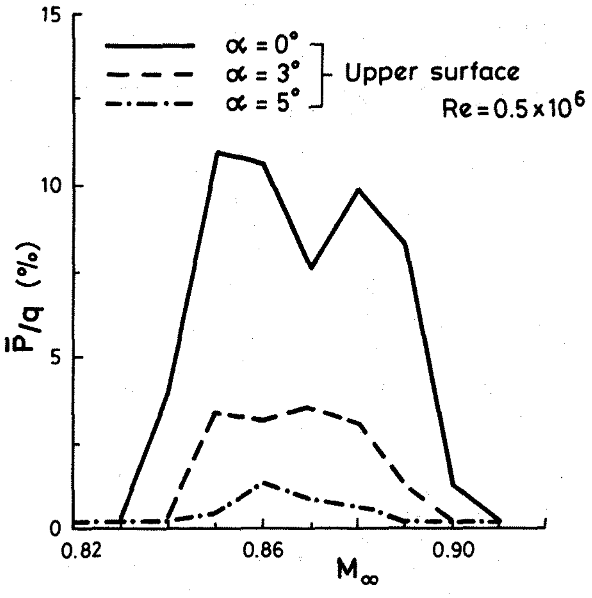


Figure 2. Aerofoil sections tested.

Results are presented for the Biconvex aerofoil at a nominal Reynolds Number based on model chord of 0.5×10^6 and for the NACA 0012 aerofoil at $Re = 1.0 \times 10^6$. All tests have had transition fixed. Table 1 shows the test programme in some detail, together with the Mach number range over which the periodic flow was found. For the case of the 14% Biconvex aerofoil it can be seen that the Mach number range of the periodic flow does not change much with incidence in the range 0 to 5 degrees but the strength of the pressure fluctuations as measured at $x/c = 0.8$ are seen to decrease significantly as shown in Figure 3(a).

AEROFOIL	$\alpha°$	$Re \times 10^{-6}$	TESTED MACH NO. RANGE	PERIODIC FLOW MACH NO. RANGE
14% BICON.	0	0.5	$0.81 < M_\infty < 0.91$	$0.84 < M_\infty < 0.89$
14% BICON.	1	0.5	$0.81 < M_\infty < 0.91$	$0.84 < M_\infty < 0.89$
14% BICON.	3	0.5	$0.81 < M_\infty < 0.91$	$0.85 < M_\infty < 0.89$
14% BICON.	5	0.5	$0.81 < M_\infty < 0.91$	$0.85 < M_\infty < 0.88$
NACA 0012	0	1.0	$0.7 < M_\infty < 1.0$	$0.93 < M < 0.95$
NACA 0012	5	1.0	$0.9 < M_\infty < 1.0$	NONE

TABLE 1 PERIODIC FLOW TEST PROGRAMME

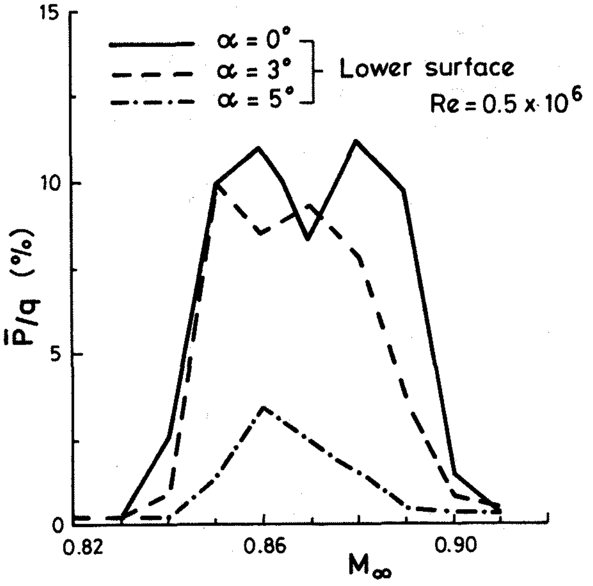


(a) 14 % Biconvex Aerofoil

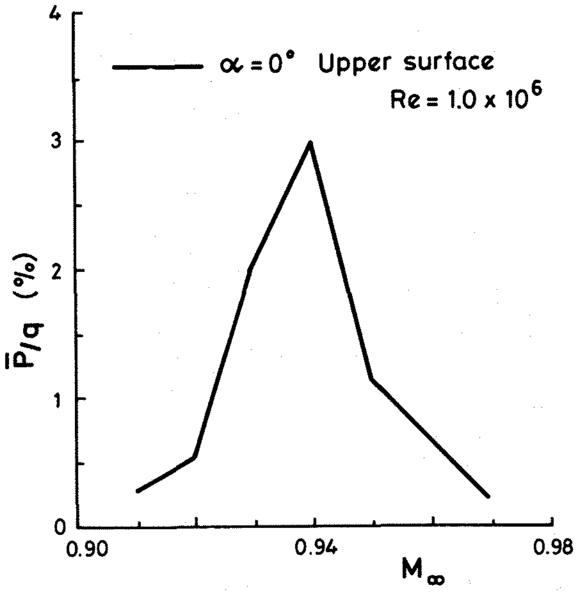
Figure 3. Pressure fluctuations at $x/c = 0.8$ v. Mach No. (Continued on page 3)

Typical variations in the surface pressure fluctuations $\bar{P}/q$ (at $x/c = 0.8$) with Mach number are shown in Figure 3(b) for NACA 0012 at zero degrees of incidence. The thicker Biconvex profile has a much stronger periodic flow with a surface pressure fluctuation of about 10% of the free-stream dynamic pressure, compared with only 3% for the NACA 0012 aerofoil. The Mach number range of the periodic flow is clearly higher for the thinner NACA 0012 aerofoil. The wind-tunnel noise level at these frequencies accounts for only 0.2% of the free-stream dynamic pressure. Figure 4 shows typical time histories of the surface pressure for the cases of attached flow, periodic flow and strong shock-induced separation. The periodic nature of the pressure fluctuation can clearly be seen in Figure 4(b). Note also the large but random fluctuations associated with the so called 'steady' shock-induced separation (Figure 4(c)).

The variation of shock wave position with Mach number is shown in Figure 5. The shock positions have been determined using several random spark exposures of the Schlieren system and



(b) 14% Biconvex Aerofoil



(c) NACA 0012 Aerofoil

Figure 3 Cont.

so do not necessarily capture the extremities of the oscillation. However, the Mach number range of the oscillation is well defined by this simple technique. Figure 6 shows the shock wave strength derived from mean pressure measurements using a conventional Scani-valve system. The oscillation begins when the Mach number ahead of the shock wave reaches about 1.2, rather less than the value of $M_1 = 1.3$ that one would expect for a 'steady' shock-induced separation[7].

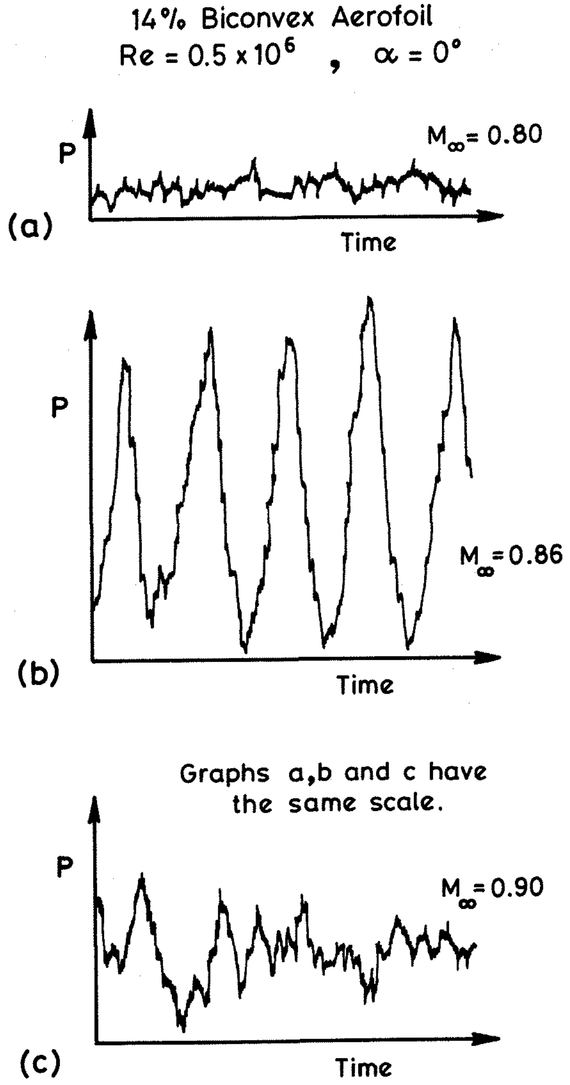


Figure 4. Pressure time histories at x/c = 0.8.

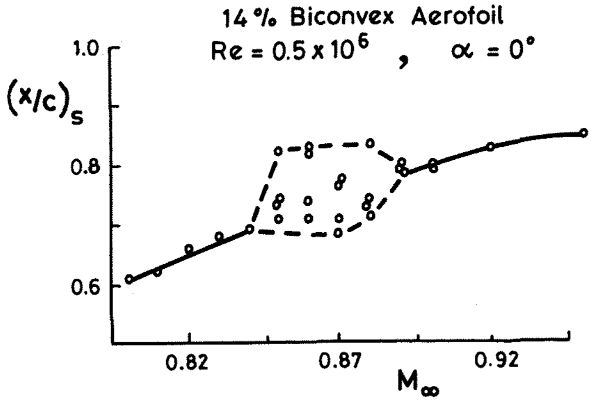


Figure 5. Shock positions taken from Schlieren photographs

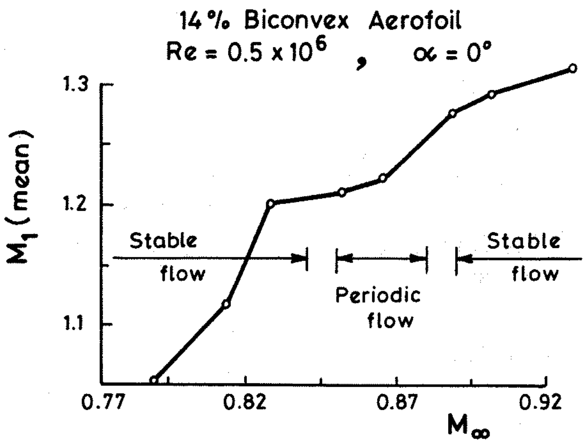
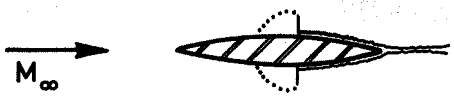


Figure 6. Shock strength from mean pressure measurements.

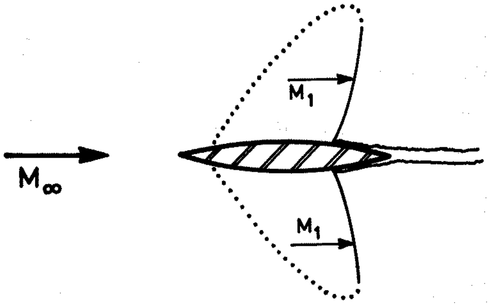
III. The Cause of Periodic Flows at Transonic Speeds.

Detailed study of the large amount of experimental data obtained in this investigation has resulted in the following being suggested as a mechanism which causes transonic periodic flow to occur:

Consider the flow development on a thick symmetric aerofoil at zero degrees of incidence as Mach number is increased from M_{CRIT}. A small supersonic region will develop just aft of the maximum thickness and will be terminated by a weak shock wave on each surface as shown in Figure 7(a). The flow will be attached, steady and symmetrical.

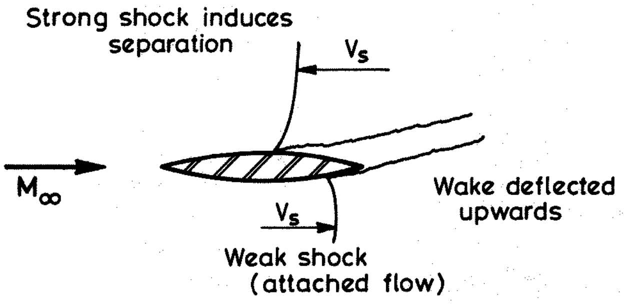


(a) M_∞ slightly greater than M_{crit}

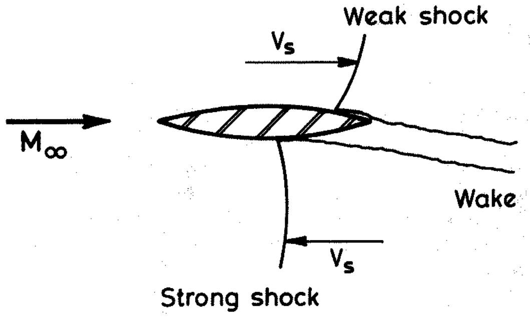


(b) High subsonic Mach number but shock strength $M_1<1.2$ (no seperation)

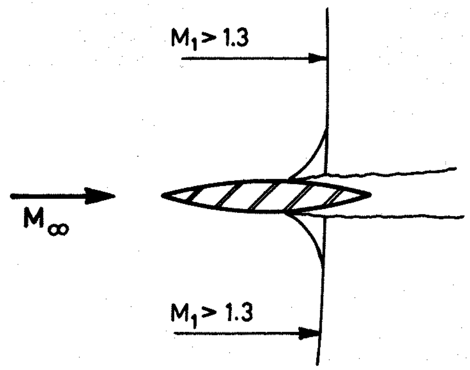
Figure 7. Shock wave development as Mach number increases.



(c) Periodic flow starts.



(d) 1/2 cycle after (c)



(e) Shock waves now too strong for re-attachment to take place during periodic flow cycle, oscillation stops.

Figure 7 Cont.

As Mach number is further increased the shock waves move aft and become stronger and the supersonic regions extend further out from the surface as shown in Figure 7(b). Providing the Mach number ahead of the shock M_1, is less than that required to promote separation, the flow will remain attached steady and symmetrical. Any unsteadiness measured aft of the shock wave will have a random frequency content and will have a broadband rms value of $\tilde{P}/q$ similar to that found in any attached turbulent boundary layer flow in the particular tunnel concerned.

Now consider what happens when a random disturbance reaches say the upper surface shock wave which now has a strength of say $M_1 = 1.2$. The disturbance is considered to be one which will move the upper surface shock wave forward at a speed V_s given by:

$$V_s = -c.d(x/c)_s/dt$$

The shock wave strength will now be made up of two components:

$$M_1 = M_{STEADY} + M_{UNSTEADY}$$

where

M_{STEADY} = Mach No ahead of shock wave for 'steady' case

$$M_{UNSTEADY} = -\frac{c.d(x/c)_s}{a.dt}$$

Clearly, if $M_{STEADY} = 1.2$ and the disturbance produces a value of $M_{UNSTEADY}$ greater than 0.1 then the flow will separate as the shock wave travels forwards, as shown in Figure 7(c) (using the criterion $M_1 > 1.3$ causes shock-induced separation[7]). When separation occurs on the upper surface it will cause a rapid upward deflection of the wake, similar to the rapid upward deflection of a trailing edge flap[8], due to the momentary gradient in the wake. As a result of the now asymmetric wake the lower surface shock wave will be pushed towards the rear. Due to its rapid motion towards the trailing edge the $M_{UNSTEADY}$ component of its strength will be negative so the shock wave strength will initially reduce (the shock wave may even disappear at this point in the cycle) and the lower surface boundary layer at this stage in the process will remain attached (Figure 7(c)).

These anti-phase motions of the shock waves have another important feature which must be considered. The forward going shock wave is moving into a slower supersonic region and when it has moved far enough forward it will become weak enough for the flow to re-attach on the upper surface. Similarly, the rearward travelling shock wave on the lower surface will be moving into a faster supersonic region (if it were to exist in a steady state) and it will eventually strengthen sufficiently to overcome the rearward motion caused by the upward wake deflection and boundary layer separation on the lower surface will follow. The combined result of the above 'steady' and 'unsteady' effects is that the wake is now deflected downwards (towards the separated flow) and the directions of the shock wave motions are now reversed, see Figure 7(d). The flow has now developed into a self-sustained, fixed frequency, limit-cycle oscillation. Other important features are the shock waves moving in anti-phase and the wake being displaced towards the surface on which the separation is taking place. The spectrum of surface pressure fluctuations (as measured just behind the mean shock wave location) will contain a large peak at the natural frequency of the periodic flow. Experiments have shown the frequency parameter for the periodic flow to be of order unity.

As the free-stream Mach number is further increased throughout the oscillatory range an upper limit is reached where re-attachment can no longer take place during the cycle and M_1 will at all times during the cycle be sufficiently strong to cause shock-induced separation, see Figure 7(e). The surface pressure fluctuations (measured behind the shock wave) will no longer contain a sharp peak at the periodic flow frequency but will now contain the random fluctuations inherent in a 'steady' shock-induced separation, see Figure 4(c).

Some of the features described above can be seen in the Schlieren pictures of Figure 8 which correspond to two anti-phase positions of the periodic flow cycle.

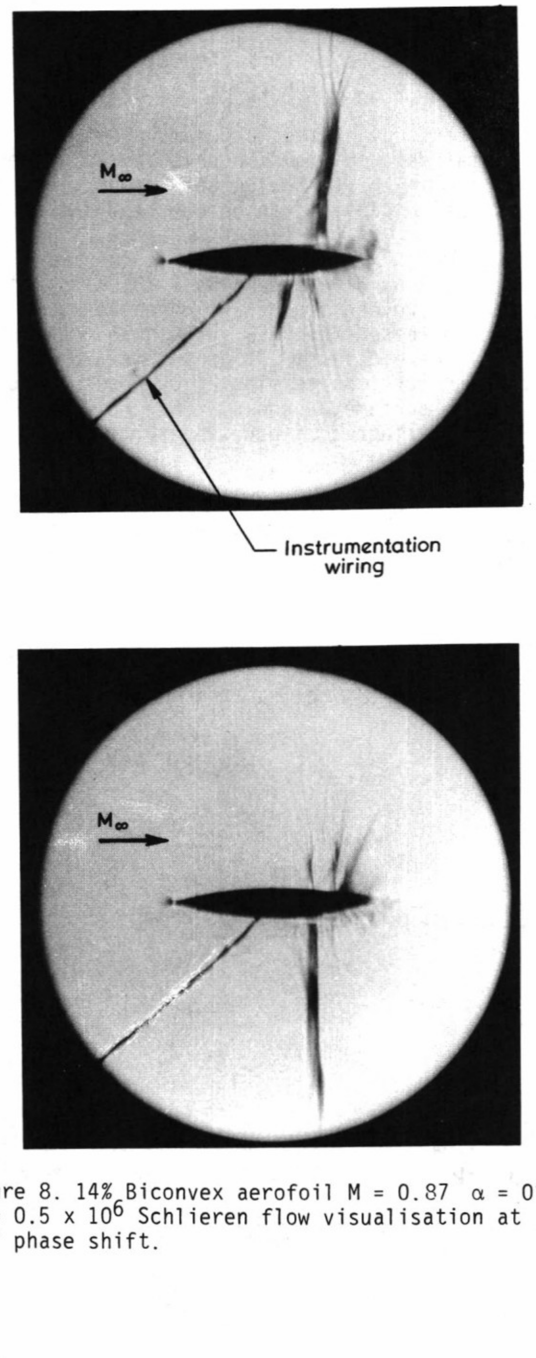


Figure 8. 14% Biconvex aerofoil M = 0.87 $\alpha = 0°$, Re = 0.5×10^6 Schlieren flow visualisation at 180° phase shift.

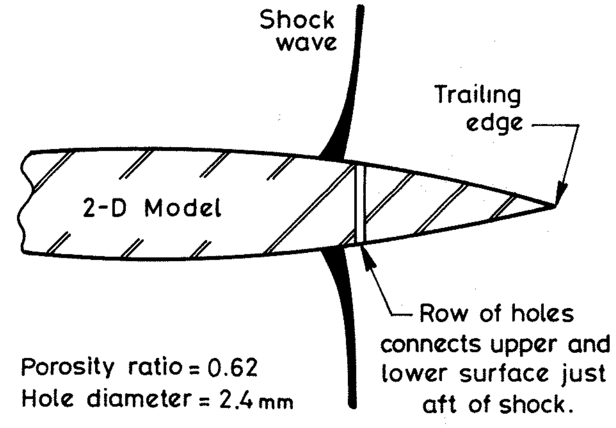
As stated previously, the computation of this periodic flow problem is a very difficult one. The flow is transonic and unsteady with large scale shock-induced separations and computations to date[9,10] have been made with the help of large powerful computing facilities. These calculations have successfully predicted the main features of the periodic flow as seen in this series of experiments, namely:

a) fixed frequency, limit cycle, anti-phase shock wave motions.
b) the forward going shock wave is strong and flow is separated behind the shock wave on this surface.
c) the rearward going shock wave is weak (may even disappear) and the flow is attached on this surface.
d) the wake oscillates up and down.

Prediction of the frequency parameter in the calculations of Girodroux-Lavigne and Le Balleur[10] is also in good agreement with experiment.

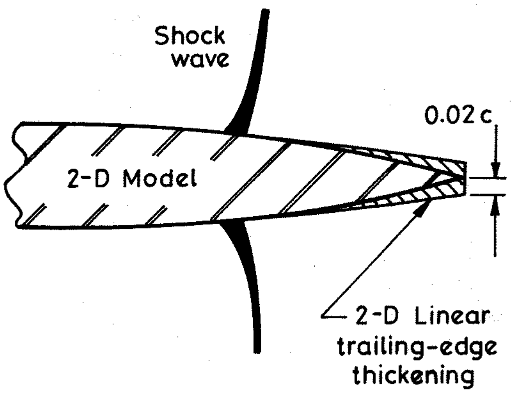
IV. The Cure of Periodic Flows at Transonic Speeds

Three quite different techniques have been employed in an attempt to find the most suitable cure to the periodic flow problem. Figure 9(a) shows the buffet breather proposed by Mabey[11]. This technique has been successfully used to suppress buffet on an aircraft fairing. The principle of the technique is to provide a degree of pressure communication between upper and lower surfaces just aft of the shock wave and so suppress the oscillation. The second cure, shown in Figure 9(b), is trailing edge thickening. Here the reduced trailing edge angle will reduce the strength of the shock waves and so delay (or eliminate) the periodic flow. A three dimensional variant of this, hereinafter referred to as trailing edge wedges, can be found on the control surfaces of the Bell X1 research aircraft. The third cure is a simple wire located just aft of the shock wave (on each surface) as shown in Figure 9(c). The objective here is to crudely fix the shock-induced separation position.

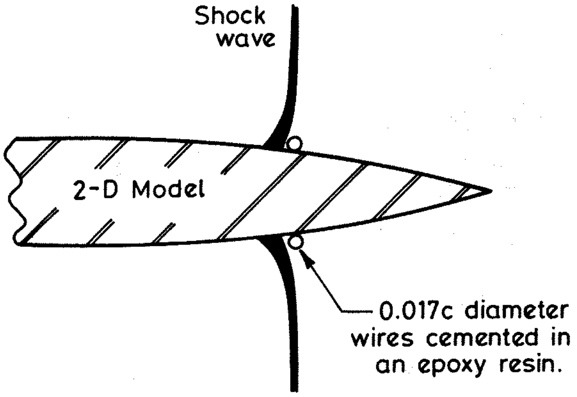


(a) Buffet breather.

Figure 9



(b) Trailing-edge thickening.



(c) Wires

Figure 9. Cures for periodic flow.

The test programme of these cures is shown in Table II, which includes results from the trailing edge wedges also. The actual reductions in $\bar{P}/q$ are shown in Figures 10, 11 and 12. The following points should be noted:

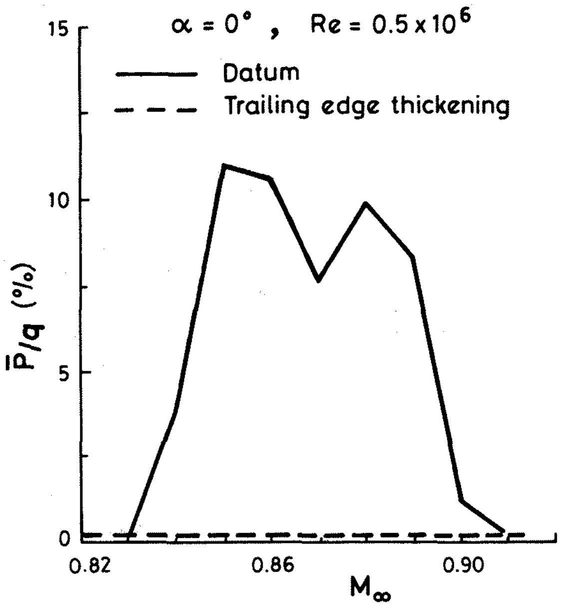
a) The buffet breather works well at zero degrees of incidence on both NACA 0012 (Figure 12) and the 14% Biconvex aerofoil (Figure 10a) and is still effective at suppressing the oscillations at 3 and 5 degrees of incidence on the Biconvex aerofoil (Figures 10b & c). In all these cases the separation position has been effectively fixed at the buffet breather location.

b) Trailing-edge thickening was successful at zero incidence on the Biconvex aerofoil (Figure 11a), the separation position being fixed at the start of the thickening. Trailing-edge wedges were also successful, but to a lesser degree (Figure 11b).

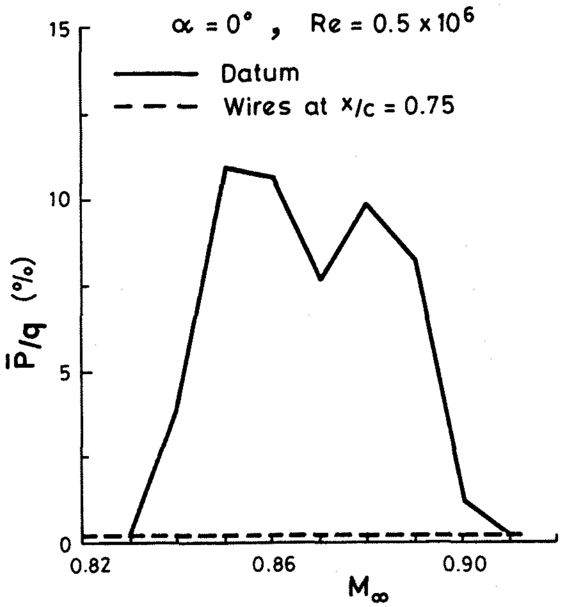
c) The wire resulted in a very stable flow with no measurable periodic component in the pressure fluctuation at x/c = 0.8 (Figure 11c). The separation position has been fixed at the wires and the wake observed in the Schlieren pictures[6] is significantly larger than for the other cures.

CURE	AEROFOIL	INCIDENCE
BUFFET BREATHER	BICONVEX	0
BUFFET BREATHER	BICONVEX	3
BUFFET BREATHER	BICONVEX	5
BUFFET BREATHER	NACA0012	0
T.E. THICKENING	BICONVEX	0
T.E. WEDGES	BICONVEX	0
TRIP WIRE	BICONVEX	0

TABLE II ATTEMPTED CURES FOR PERIODIC FLOWS

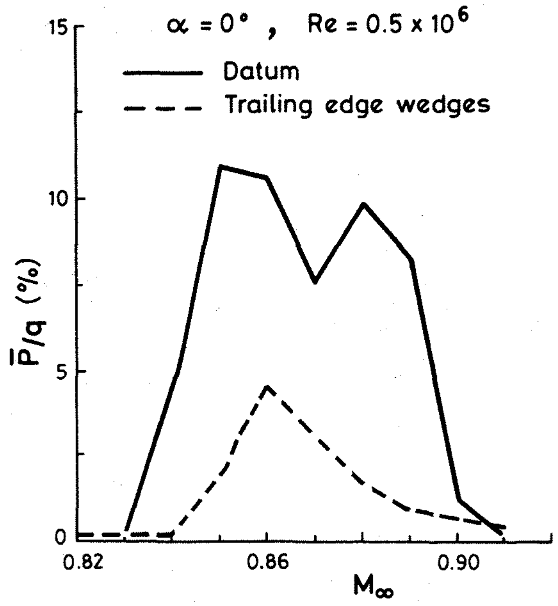


(a) Trailing edge thickening

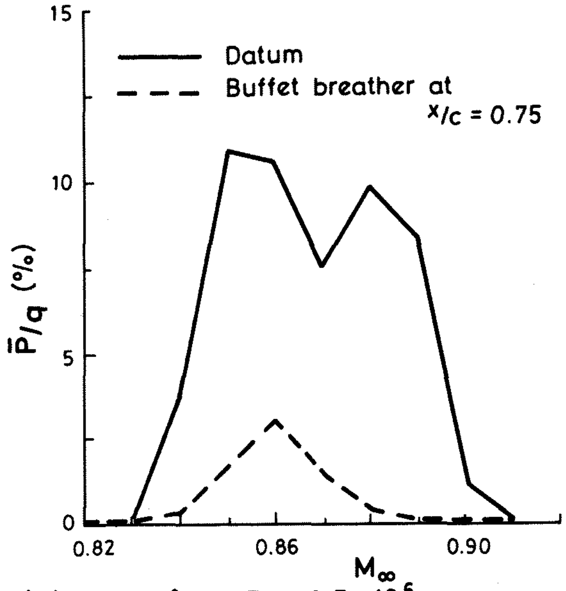


(c) Wires

Figure 10. 14% Biconvex aerofoil with buffet breather - pressure fluctuations at x/c = 0.8.

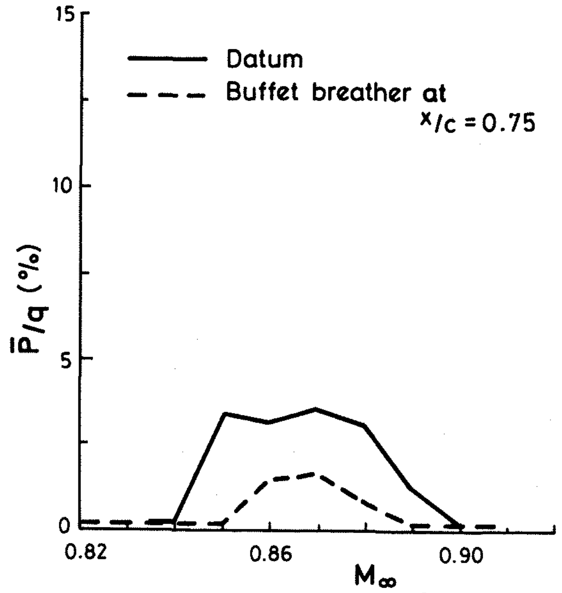


(b) Trailing edge wedges

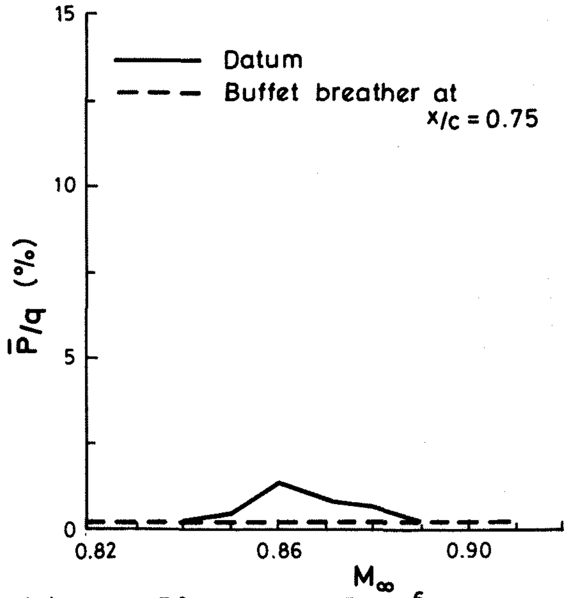


(a) $\alpha = 0°$, $Re = 0.5 \times 10^6$

Figure 11.



(b) $\alpha = 3°$, $Re = 0.5 \times 10^6$



(c) $\alpha = 5°$, $Re = 0.5 \times 10^6$

Figure 11. 14% Biconvex aerofoil with various cures at zero incidence - pressure fluctuations at x/c = 0.8.

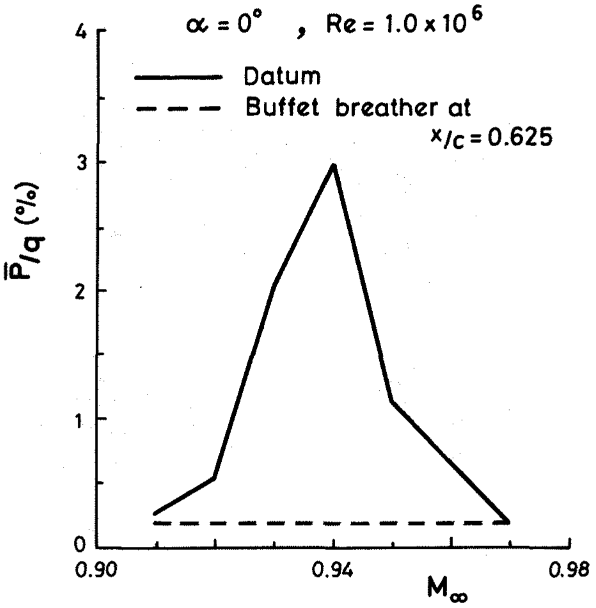


Figure 12. NACA 0012 aerofoil with buffet breather - pressure fluctuations at x/c = 0.8.

V. SUMMARY

The aims of the work reported here are twofold, namely:

1) to explain in physical terms what causes a periodic flow at transonic speed.

2) to provide suitable techniques which would cure the problem in a realistic situtation.

A general explanation of the first aim has been given which takes account of the following important features of the periodic flow:

a) Shock waves are 180 degrees out of phase.

b) Flow separates on alternate surfaces.

c) Wake oscillates up and down.

d) Shock wave oscillation is large amplitude, fixed frequency, limit-cycle.

e) Oscillation occurs only over a finite Mach number range.

f) Dynamic shock wave strengths have been included in the explanation.

The physical explanation has been illustrated using experimental data.

Several successful techniques have been applied to cure the oscillatory behaviour. The most suitable techniques tested for the cure of a periodic flow at transonic speeds on a non-lifting aerofoil are the 'buffet breather', trailing edge thickening or, if drag is not important, the 'wire'. The latter would be the simplest to apply in the case of an existing wind-tunnel strut or fairing but would cause a large drag penalty at all speeds.

The cure of periodic flows on lifting aerofoils would be best carried out by a re-design of the profile, making it thinner or changing its profile to avoid the conditions which give rise to periodic flow as detailed above in the introduction. However, 'buffet breathers' have proved effective at low and moderate incidences and could well be as effective at high incidence if their chordwise location was selected with care. This area requires further research since the surface holes will result in a drag penalty. Trailing edge thickening may well be effective at incidence but this has not been tested here.

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