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Control-Surface Buzz

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Summary.

The term buzz, as used here, refers to a class of control-surface oscillations sometimes encountered during flight at transonic or low supersonic speeds. Essentially these are self-excited oscillations in a single degree of freedom—namely rotation of the flap about its hinge.

It is shown that buzz can be associated with several régimes of flow and it is likely that the mechanism of excitation is different for each type. At least one form of instability can be related to negative aerodynamic damping predicted theoretically and does not depend on boundary-layer effects. Other forms of buzz depend on the occurrence of shock-induced separation ahead of the flap hinge, or on the presence of shock waves at the surface of the flap itself.

The parameters that determine buzz characteristics are discussed, together with the available information relevant to the prevention of buzz in practice.

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1. *Introduction.*

Undoubtedly today the most important example of single-degree-of-freedom flutter of aircraft is control-surface buzz. The history of the subject starts about the year 1945 when aileron vibration of a novel type was encountered during flight at high subsonic speed. Wind-tunnel investigations identified the trouble with a form of aerodynamic excitation requiring only a single degree of freedom, namely rotation of the control surface about its hinge. It appeared that the phenomenon was associated with the formation of a shock wave at the surface of the wing and that a backwards and forwards motion of this accompanied the oscillation of the flap[1, 2]. It also became clear that the occurrence of the flutter depended primarily on the flight Mach number rather than on the equivalent air speed. Thus we have the concept of a critical Mach number for buzz in place of a flutter critical speed. The actual mechanism of a buzz oscillation has never been clear. Theory based on the assumption of potential flow over a thin aerofoil can predict negative aerodynamic damping of a flap both for very low frequencies at subsonic speeds and for more practical frequencies over a range of supersonic Mach numbers. But this type of instability could hardly account for the oscillations encountered at Mach numbers of 0·8 or less. However, it has become apparent that more than one variety of buzz can occur. Indeed, it appears that buzz can be associated with several types of flow régime, the particular buzz likely to be encountered depending mainly on the wing section, the incidence and the Mach number.

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2. *The Types of Flow for which Buzz can Occur.*

The occurrence of buzz under various régimes of flow may be illustrated by reference to Figs. 1 and 2 which have been obtained from wind-tunnel experiments with two-dimensional aerofoils having freely-hinged flaps. In these experiments the leading edges of the aerofoils were roughened to produce a turbulent boundary layer which was more representative of full-scale Reynolds numbers. Fig. 1, which refers to a symmetrical aerofoil having a thickness to chord ratio of 10% and a 9 in. chord, shows buzz occurring over three distinct ranges of Mach numbers A, B and C. The lowest critical Mach number for buzz is a little above the critical Mach number at which the flow becomes supersonic locally at the surface of the aerofoil and is found to be associated with a shock at the surface of the aerofoil ahead of the hinge line causing separation of the boundary layer; for incidences very close to zero, the first onset of buzz occurs with shock-induced separation present at both upper and lower surfaces of the aerofoil (*see* Fig. 3a); for higher incidences buzz occurs with shock-induced separation at the upper surface only (Fig. 3b). Oscillation of the flap is coupled with backwards and forwards movement of each shock wave, but its excursion does not extend onto the flap itself. The region of stability S_1 appears to be associated with the presence of a lower-surface shock at the vicinity of the hinge.

The second region of instability is associated with the regions of local supersonic flow extending rearwards onto the surface of the flap, (Fig. 3c) and also appears to involve separations induced by shock waves. Flap oscillations are again coupled with movement of the shock waves. Both types of oscillation have limit cycles with amplitudes up to $\pm 10°$, or more, but whereas the oscillations corresponding to region A are almost sinusoidal, those in region B, although periodic, are found to be not always harmonic, a property which is believed to be associated with the presence of severe non-linearities in the hinge-moment curve for this particular aerofoil. At high incidences the two regions of instability A and B appear to be superimposed to provide a single region in which the flap is unstable, but through which, with increasing Mach number, a change occurs in the character of the oscillation.

With further increase of Mach number a second region of stability S_2 is encountered which is associated with the shock waves having moved rearwards to the trailing edge, thus corresponding to local supersonic flow everywhere over the flap. Still further increase of Mach number to a value greater than unity (Fig. 3e), leads to region C, in which the oscillation, for small amplitudes at least, does not appear to involve shock-wave or boundary-layer effects. Unfortunately it was not possible to explore the region between $M = 1 \cdot 03$ and $M = 1 \cdot 4$, but the flap was found to be stable at the latter Mach number. We may note that for this aerofoil the lowest critical Mach number for region A is independent of the manner in which it is approached. That is, the instability ceased during a gradual decrease of speed at the same Mach number as it commenced during an increase of speed. The upper boundary of region A and the boundaries of the second region, B, however, exhibited some hysteresis.

The results of experiments with an aerofoil having a thickness to chord ratio of 4% and a 9·4 in. chord are shown in Fig. 2. If the flap is not disturbed by external means, instability first occurs during a gradual increase of Mach number when boundary B_2 is reached, and this condition corresponds to one or both of the main regions of local supersonic flow over the aerofoil having extended rearwards onto the flap (Fig. 3c). Once started, the oscillation will continue until the Mach number is lowered to boundary B_1. Between boundaries B_1 and B_2 the flap is stable for small disturbances, but buzz will be initiated if the flap is given a disturbance sufficient to lead to a region of supersonic flow forming locally at the convex corner formed by the deflected flap (Fig. 3d). During buzz, the shock waves at the surface of the flap move backwards and forwards in synchronism with the flap motion. Unlike the occurrence with the thicker aerofoil, no buzz is encountered with the thinner aerofoil which could be associated solely with the existence of shock-induced separation ahead of the hinge line. The thinner aerofoil is found to exhibit spontaneous oscillatory instability up to the highest transonic speed reached in the tunnel, $M = 1 \cdot 13$. At this speed the main supersonic regions have extended as far as the trailing edge (Fig. 3e), and the type of buzz is probably similar to that encountered in region C with the thicker aerofoil. No examination was made in the region between $M = 1 \cdot 13$ and $M = 1 \cdot 4$, but at the latter Mach number the flap is stable, as with the thicker aerofoil.

It seems clear from the behaviour of the two aerofoils that buzz can be associated with at least three basically different flow conditions namely:

(1) Flap in subsonic flow; boundary-layer separation induced by a shock wave situated at the surface of the aerofoil ahead of the hinge. Figs. 3a and 3b.

(2) Mixed supersonic and subsonic flow over the flap with a shock wave at one or both surfaces between the hinge line and the trailing edge. Separation has been observed but this may not be an essential feature. Figs. 3c and 3d.

(3) Supersonic flow locally over the entire flap with the main shock waves attached to the trailing edge. This type of buzz would be expected to correspond to the negative damping of the flap predicted by potential-flow theories. Fig. 3e.

Other evidence of the existence of more than one region of buzz is provided by the experiments of Martz[3] with a delta wing having a full-span control surface. His measurements of the aerodynamic damping of the flap are shown, in an abridged form, in Fig. 4. It would seem possible that the three regions of instability encountered in these measurements might correspond to the three types of buzz already described.

3. *The Types of Buzz with Shock Waves at the Surface of the Aerofoil or Flap.*

Considerable discussion has revolved around the physical mechanisms of those oscillations which are not predicted by potential-flow theories. The type associated with shock-induced separation ahead of the hinge line was the type first encountered in flight and rather more attention has been devoted to finding an explanation of this type than to the understanding of the type associated with shock waves at the surface of the flap.

3.1. *Shock Wave Ahead of Hinge Line.*

The early wind-tunnel investigations of buzz showed that a phase difference existed between the motion of the shock wave over the surface of the wing and the motion of the flap. It was also realized that shock-induced separation was probably playing an important part. At an early stage in the history, analyses were put forward independently by Smilg[4] and by Erickson and Stephenson[1]. Both theories involved an aerodynamic hinge moment which lagged behind the motion of the flap[5] and both identified the phase lag with a time lag in the flow changes resulting from a movement of the flap. In the Erickson-Stephenson approach, the observed phase lag in the motion of the shock wave was regarded as the amount the aerodynamic restoring force lagged behind the flap. Indeed a time lag in the movement of the shock was to be expected due to the appreciable time required for the pressure changes resulting from the flap motion to propagate forwards through the region of high-speed flow. Based on the calculated time lag an 'aerodynamic frequency' was derived and criteria were suggested concerning the moment of inertia, elastic hinge stiffness and additional damping necessary to prevent buzz. On the other hand, Smilg considered the possibility of the time lag being due to several additional causes including boundary-layer separation. The aerodynamic hinge-moment damping and stiffness terms applying under potential-flow conditions were retained in magnitude but suffered a phase delay identified with the time lag in the flow. A stability criterion and an estimation of the additional damping necessary to suppress buzz were then developed. It would be difficult to justify either of these methods on a strictly rigorous basis and, it would seem, that only qualitative agreement with measurements has been obtained.

An experiment of Phillips and Adams[6] in low-speed flow showed that a self-excited oscillation of a flap could take place in the absence of any shock wave if the flap were mechanically coupled to a spoiler protruding a variable amount above the aerofoil surface ahead of the flap. The spoiler in causing boundary-layer separation could be regarded as representing a strong shock wave. When the spoiler was not coupled to the flap but fixed at a constant height above the surface, buffeting, rather than a regular oscillation, of the flap occurred; when the height of the spoiler was coupled with the movement of the flap, a self-excited oscillation occurred. Two important points may be noted. Firstly the fact that in the simulated buzz there was no phase lag between the spoiler and the flap would suggest that in real buzz, the phase lag in the shock wave was not an essential feature. Secondly the experiment suggested that the real buzz oscillation involved a mutual coupling between the shock-induced separation and the flap. Furthermore it has been shown by Lambourne[7] that the backwards and forwards motion of the shock is coupled with a cyclic change of shock strength, and that this in itself can lead to a cyclic change in the severity of the shock-induced separation in synchronism, but not necessarily in phase, with the flap. An upward-moving flap is coupled with a forward-moving shock of high strength which causes severe separation, a downward-moving flap with a weak rearward-moving shock causing little or no separation. A flap oscillation can also occur at low speeds provided the aerofoil is at an incidence close to the critical incidence at which the flow begins to separate from the leading edge. In this case the flap motion is coupled with a cyclically varying separation from the leading edge. In both cases the severity of the separation appears to be related to the direction of motion of the flap and this suggests a mechanism which depends on the incremental hinge moment due to separation being able to do work on the flap. Thus from the experimental evidence we have a plausible physical explanation of the observed oscillations occurring with shock-induced separation ahead of the hinge. On the other hand, the recent theoretical work of Eckhaus[8] for the flow condition with shocks ahead of the hinge has predicted the existence of a region of negative damping even in the absence of boundary-layer effects. Indeed his calculated critical Mach numbers have shown good agreement with experimental observations.

A rather different approach arises from the theoretical and experimental work of Trilling[9], Fiszdon and Mollo-Christensen[10] which has suggested that the shock-wave boundary-layer interaction for a rigid aerofoil has its own characteristic periodicity which, when a flap is present, might possibly lead to buzz. It will be noted that the idea of a characteristic periodicity bears some similarity to the theory put forward by Erickson and Stephenson. However, the idea of a periodicity inherent in the flow is not in accord with observations of flap oscillations which indicate that the frequency is determined by the aerodynamic, inertia and hinge-stiffness characteristics of the flap.

Although the mechanism of the buzz oscillation is not yet fully understood it is possible from general experience and documentary evidence[1, 2, 4, 7, 11, 12, 13] to draw the following conclusions regarding the type of buzz associated with shock-induced separation ahead of the hinge line:

(1) The critical Mach number for buzz correlates with a criterion for the critical onset of shock-induced separation. (A rather sudden decrease of the pressure near the trailing edge of an aerofoil is found to signal the onset of shock-induced separation effects[14].)

(2) The critical Mach number for buzz falls with increasing incidence.

(3) The critical Mach number for buzz is not greatly altered by a change in the elastic hinge stiffness.

(4) At constant Mach number, the buzz frequency is approximately given by

$$\omega = \sqrt{\frac{C + C_A}{I}}$$

where I is the moment of inertia of the flap, C is the elastic hinge stiffness, and C_A is an aerodynamic hinge stiffness which is approximately equal to the slope of the hinge-moment curve for static deflections, i.e.,

$$C_A \propto (\tfrac{1}{2}\rho V^2)\frac{dC_H}{d\eta}.$$

(5) The oscillation has a stationary amplitude which depends on the elastic hinge stiffness and moment of inertia of the flap. Changes which increase the buzz frequency would be expected to decrease the amplitude. (Experiments by Saito[12] have suggested that at constant Mach number and constant hinge stiffness, the product of the stationary amplitude and the frequency is a constant.)

3.2. *Shock Wave at Surface of Flap.*

Unfortunately little is known about the cyclic phenomena occurring during the type of buzz with shock waves at the surface of the flap. Boundary-layer separation at the flap has been observed and would seem to be an essential feature for some examples, but it appears that this may not be generally true and that instability can occur in the presence of shocks without separation, as suggested theoretically by Coupry and Piazzolli[15]. The existence of limit cycles and the observed fact that the stability of a flap can depend on the magnitude of the initial disturbance suggests a non-linear mechanism of oscillation distinct from the negative-damping type of instability as, for instance, predicted for some conditions of potential flow.

4. *Potential-Flow Negative Damping of Flap.*

Negative damping of a flap under two-dimensional conditions is predicted by potential-flow theory for certain ranges of Mach number and reduced frequency. It is convenient in the present connection to use a reduced frequency $\omega c_F/V$ based on c_F, the chord of the flap, rather than on the aerofoil chord. The reason for this is that the more important regions of negative damping are associated with sonic and supersonic flow and under these conditions the calculated air loads due to rotation of the flap are independent of the extent of the fixed portion of the aerofoil ahead of the flap; this follows from the assumptions made in the theory of an infinitely thin aerofoil at zero incidence. In other words the flap oscillating about its hinge is in theory identical to an isolated aerofoil pitching about the leading edge. Plotted as Mach number vs. reduced-frequency diagram, Fig. 5 provides a general survey of the regions of negative damping of a flap hinged at its leading edge. The curves shown are based on the calculations of Runyan[16] for subsonic speeds, of Nelson and Berman[17] for sonic speeds and for supersonic speeds on the calculations of Garrick and Rubinow[18], and Huckel and Darling[19]. It may be noted that for incompressible speeds and for low subsonic speeds, negative damping is predicted only for very low values of reduced frequency. For supersonic speeds, negative damping is predicted for the region $1 \cdot 0 < M < \sqrt{2 \cdot 0}$ and, within this range, the region of negative damping extends to frequency values which, from the practical viewpoint, are high.

In considering the theoretical predictions of the amount of aerodynamic damping it is convenient to use the non-dimensional damping coefficient $B_A/\rho V c_F{}^3 s_F$. Here B_A, specified as a moment per unit angular velocity measured in rad per sec, represents the aerodynamic negative damping or, with a change of outlook, the amount of positive viscous damping which would be just sufficient to 'kill' an instability.

Fig. 6, to which further reference will be made later, shows the variation of $B_A/\rho V c_F{}^3 s_F$ with reduced frequency for sonic speed and for two supersonic Mach numbers based on the numerical results of Refs. 17, 18 and 19.

It is perhaps necessary to emphasize that the theoretical predictions refer to an aerofoil and flap of infinitesimally small thickness under two-dimensional conditions. The inclusion of flap thickness in the theory would be expected to modify the predictions in a manner similar to the effect of aerofoil thickness on pitching damping so that the upper limit of the Mach number range for negative damping would be extended.

A reduction in the region of negative damping due to a decrease in aspect ratio has been noted by Berman[20] and also by Landahl[21] who has further shown that the damping will always be positive for an outboard control if its aspect ratio is less than 4·5 or for an inboard control if its aspect ratio is less than 3·5.

5. *The Parameters that Influence Buzz.*

It is appropriate at this stage to consider in a general way the influence of various parameters on buzz. This is conveniently approached by way of dimensional analysis.

The buzz characteristics of a wing and flap depend on the geometry of the system, the wing incidence and flap angle, and on a number of other quantities which experience shows can be restricted to the following:

M	Mach number
ρ	air density
V	air velocity
I	moment of inertia of flap
C	elastic hinge stiffness of flap (moment per radian)
B	viscous damping added to flap system (moment per unit angular velocity)
L	typical linear dimension of system.

From these seven quantities we can obtain the following four non-dimensional parameters:

M	Mach number
$\left(\frac{I}{\rho L^5}\right)$	'density' parameter
$\left(\frac{C}{\rho V^2 L^3}\right)$	'stiffness' parameter
$\left(\frac{B}{\rho V L^4}\right)$	'damping' parameter.

Thus for a series of geometrically similar systems, the values of these four non-dimensional parameters determine whether or not buzz *can* occur under a specified condition. Whether or not buzz *actually* occurs depends, in some cases, on the presence of disturbances of sufficient magnitude, as already pointed out in Section 2.

We can now make some general observations regarding the effects of various parameters.

Mach Number.

A necessary condition for buzz to occur is that the Mach number shall lie within a certain region. That is

$$M_1 < M < M_2$$

where M_1 and M_2 are the limits of the critical region.

Density and Stiffness Parameters.

The occurrence of buzz due to potential-flow negative damping is possible only for values of the frequency parameter, $(\omega c/V)$, below a critical value which itself depends on Mach number. It is not yet known whether a similar critical value of the frequency parameter applies to each of the other forms of buzz. Clearly, if the elastic stiffness of the flap could be increased indefinitely, buzz would not then occur*, and it would seem justifiable in the absence of evidence to the contrary to suggest that it is beneficial to the avoidance of all forms of buzz for the frequency parameter to be high. Relating the characteristic frequency of the flap under conditions of flow to the flap inertia and total hinge stiffness we have

$$\omega = \sqrt{\frac{C + C_A}{I}}$$

where the aerodynamic stiffness,

$$C_A = \rho V^2 L^3 k$$

and

$$k \propto \frac{dC_H}{d\eta},$$

the slope of the hinge-moment curve. The frequency parameter can then be related to non-dimensional density and stiffness parameters as follows,

$$\left(\frac{\omega c}{V}\right)^2 \propto \left(\frac{\rho L^5}{I}\right) \left(\frac{C}{\rho V^2 L^3} + k\right).$$

It can be seen that a low value of I the flap inertia, and high values of the stiffnesses C and k, are

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* Two possibilities present themselves. Either there is a critical value of the stiffness parameter above which no buzz is possible; or the stationary amplitude of the buzz oscillation tends to zero as the stiffness parameter tends to infinity.

always beneficial. The effectiveness of increasing the elastic stiffness depends on the relative magnitude of this stiffness in comparison with the aerodynamic stiffness.

The influence of air density is best considered for a number of separate cases in each of which the added damping, B is zero.

(*a*) *Flap with no elastic stiffness* (*i.e.*, $C = 0$).—The buzz properties depend on only the two parameters

$$M \text{ and } \left(\frac{I}{\rho L^5}\right).$$

On the supposition that a high value of the frequency parameter is beneficial we may conclude that a high value of the air density is an advantage. Thus it would appear that an undamped and elastically unrestrained flap could, for constant Mach number and constant incidence, exhibit buzz at high, but not at low, altitude.

(*b*) *Flap with aerodynamic balance* (*i.e.*, $k = 0$).—We now have

$$\left(\frac{\omega c}{V}\right)^2 \propto \frac{CL^2}{IV^2} \propto \frac{CL^2}{Ia^2M^2}$$

where a is the speed of sound. In this case, since the value of a falls with increasing altitude we may expect a tendency for buzz to be first encountered at low altitudes.

(*c*) In the general case when $C \neq 0$ and $k \neq 0$ the effect of air density depends on the relative magnitudes of the elastic and aerodynamic stiffnesses.

Damping Parameter.

We must expect differences between the action of a damper on potential-flow negative-damping type of buzz and on the other types of buzz. For the negative-damping type, the behaviour of the flap for small displacements is governed by a linear differential equation and the occurrence of buzz depends on the sign of $(B + B_A)$, the combined damping, where $-B_A$ is the negative aerodynamic damping. Thus to prevent this type of buzz, the added damping must numerically exceed the aerodynamic damping. In theory, additional damping less than this value can have no effect on the occurrence of buzz except to reduce the rate at which the amplitude grows.

On the other hand the type of buzz involving shock waves and flow separation appears to involve non-linear features which lead to a limit cycle. In this case it seems likely that the application of increasing additional viscous damping would firstly lead to a decreasing amplitude of oscillation and later to a complete cessation at some critical value of the damping.

Since it is beneficial to the avoidance of buzz for the parameter $(B/\rho VL^4)$ to be large, it is an advantage, in this respect, for the velocity and the air density to be low, and thus for the altitude to be high. However, the effect of altitude on the stiffness parameter must also be considered and when this is done no general conclusion regarding the effect of altitude on buzz can be drawn except for the condition $C \gg C_A$; in which case, for constant incidence, buzz is more likely to occur at low altitude.

6. *Methods Aimed at Avoiding Buzz.*

The methods of curing buzz most frequently resorted to with aeroplanes are the addition of dampers, or the provision of very high hinge stiffnesses by the use of irreversible or power-operated controls. Methods in which the aerodynamic characteristics of the wing or flap are modified in an *ad hoc* manner have been tried from time-to-time with varying success. In general it may be expected that any change which delays or modifies the occurrence of separation, or modifies the position of the shock waves will cause an alteration in the buzz characteristics corresponding to these particular flow features.

The influences of various parameters on buzz have already been discussed in Section 5. We come now to consider, on the basis of wind-tunnel and rocket results the manner in which the characteristics of buzz respond in practice to various modifications. It is, however, worth remarking that it has frequently been found that buzz when encountered with aeroplanes, as distinct from that reproduced in wind tunnels, is rather 'touchy' to small and not always obvious changes. Thus it has been found that trouble would occur with some, but not all, aircraft of a production line; in other cases buzz has appeared only after an aircraft has been in service for some time. Similar sensitivity does not appear to have been found in wind-tunnel tests with models.

Mass Balancing.

Unlike control-surface coupled flutter, buzz is not sensitive to mass balancing. Due to an increase in inertia and a corresponding decrease in frequency, the addition of balance masses may increase the severity of buzz. If classical coupled flutter can be avoided by other means, mass underbalance may be beneficial to the avoidance of buzz not only by keeping the inertia low, but also because the flap can under suitable conditions receive some damping from the coupling with a wing motion (i.e., wing bending or wing torsion).

Increase of Elastic Hinge Stiffness or Decrease of Flap Inertia.

Each of these changes results in an increase in the flap frequency appropriate to the conditions of flow, and in general, as already discussed, this would appear to alleviate buzz. It appears that the elastic stiffness would need to be increased to a high value to avoid buzz entirely. Measurements of Wyss and Sorensen[22] for a two-dimensional aerofoil with a 25% chord flap show large amounts of aerodynamic negative damping up to a value of the reduced frequency $\omega c_F/V = 0 \cdot 18$, whilst potential-flow theory for low supersonic speeds predicts negative damping up to a value of $\omega c_F/V$ as high as $0 \cdot 65$.

Additional Damping.

The application of a damper to the control surface is perhaps the most effective method of curing buzz. Unfortunately from the available information it is not possible to provide a reliable specification of the amount of damping required to suppress buzz. In view of the sparseness of the experimental information it is convenient to consider that which exists in relation to theoretical predictions based on two-dimensional potential flow as shown in Fig. 6, although it is possible that the experimental results refer to buzz involving shock waves or separation. One point shown in the diagram has been obtained from Ref. 22 mentioned above and corresponds to a damping coefficient

$$\frac{B}{\rho V c_F{}^3 s_F} \doteqdot 4 \text{ rad}^{-1} \text{ for } \frac{\omega c_F}{V} = 0 \cdot 15.$$

The measurements of Martz[3] for a flap attached to a delta wing provide values in each of the three unstable regions shown in Fig. 4. The largest amount of negative damping measured in the test corresponds to a value

$$\frac{B}{\rho V c_F{}^3 s_F} \doteqdot 2 \cdot 5 \text{ rad}^{-1} \text{ for } M = 0 \cdot 95 \text{ and } \frac{\omega c_F}{V} = 0 \cdot 08$$

but it will be seen from Fig. 4 that the curve is falling precipitously in this region.

Effect of Sweepback.

The introduction of sweepback to the trailing edge and hinge line of a flap would be expected to raise the critical Mach number for buzz and possibly to reduce the range of Mach number over which buzz occurs. Tests[23] have shown that increasing the angle of sweep Λ for a particular wing-aileron combination results in the critical Mach number for buzz being increased by the factor $\sqrt{\sec \Lambda}$.

Vortex Generators.

Vortex generators by delaying the onset of shock-induced separation can delay the onset of buzz due to this cause. Careful positioning may be necessary to ensure that these devices are effective.

Spoilers on Surface of Wing or of Flap.

Buzz due to shock-induced separation can sometimes be prevented by spoilers attached to the wing surface. To be effective it is essential for the spoilers to be placed downstream of the shock waves so that the regions of separated flow which the spoilers produce can reduce the coupling between the movement of the flap and the movement of the shock waves.

Spoilers attached to the surface of the flap have been found effective when the shocks are ahead of the flap. They may also be beneficial in cases where the shocks are at the surface of the flap.

Flaps with Blunt Trailing Edges.

Flaps with blunt trailing edges (*see* Fig. 7) have been used to cure the reversal of control effectiveness that can occur at transonic speeds when the shock waves move onto the flap. Although it has been reported[24] that some reduction in the severity of buzz follows from an increase of trailing-edge thickness, it seems that buzz cannot always be avoided by this means. Since thickening of the trailing edge leads to an increase in the slope of the static hinge-moment curve, it can be expected that, for a constant flap inertia, thickening will increase the buzz frequency and thus for this reason may be beneficial.

The splitter-plate configuration[25] shown in Fig. 7b offers a modified form of blunt trailing edge. It is believed that this has proved to be effective in flight although wind-tunnel tests have provided evidence to the contrary.

LIST OF SYMBOLS

a	Speed of sound
B	Viscous damping applied to flap; moment per unit angular velocity
B_A	Aerodynamic damping, (specified as for B above)
C	Hinge stiffness (elastic), moment per radian
C_A	Hinge stiffness (aerodynamic), moment per radian
c_F	Chord of control surface
C_H	Hinge-moment coefficient
I	Moment of inertia of control surface about its hinge
L	Typical linear dimension of wing or flap
M	Mach number
s_F	Span of control surface
V	Velocity
η	Angular deflection of control surface
Λ	Angle of sweepback
ρ	Air density
ω	Frequency (rad/sec)

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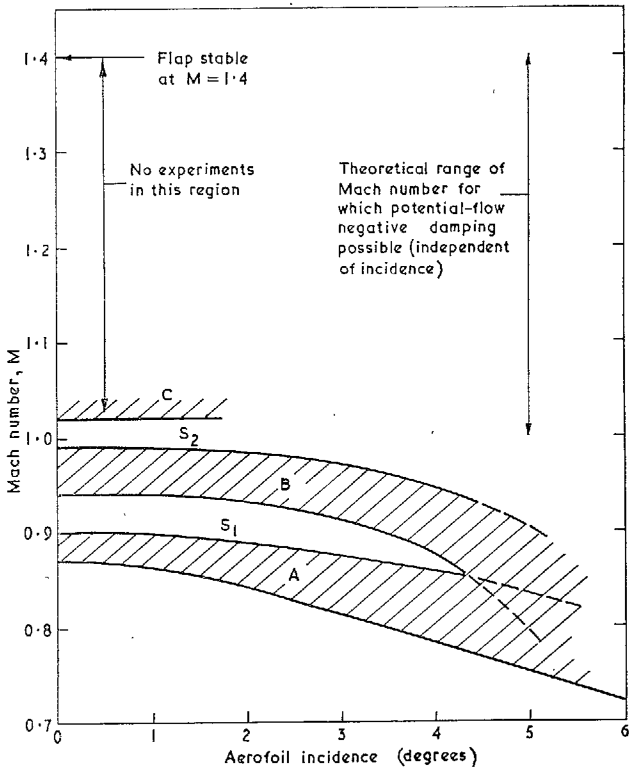


FIG. 1. Experimental buzz regions for a two-dimensional aerofoil and flap. Thickness to chord ratio 10%. Hinge at 0·75 chord. Frequency parameter $\omega c_F/V = 0\cdot 1$ approx.

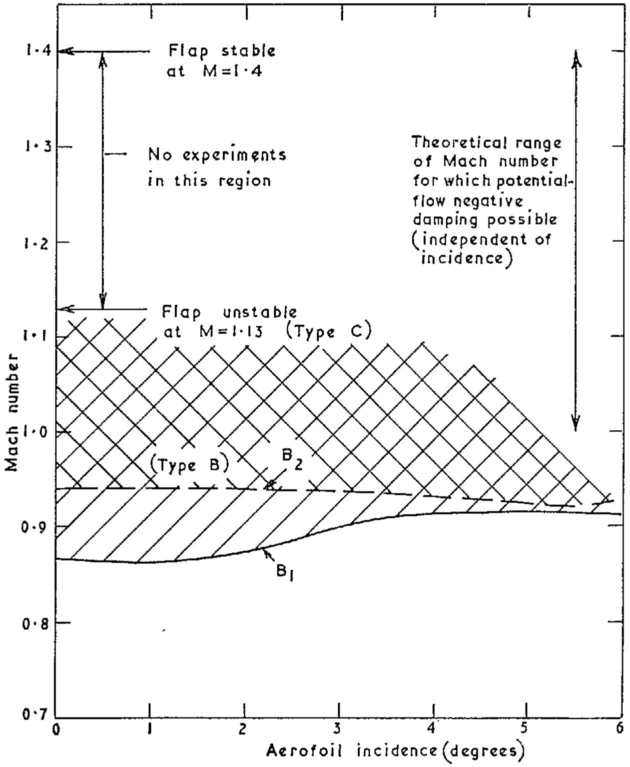


FIG. 2. Experimental buzz regions for a two-dimensional aerofoil and flap. Thickness to chord ratio 4%. Hinge at 0·7 chord. Frequency parameter $\omega c_F/V = 0\cdot 2$ approx.

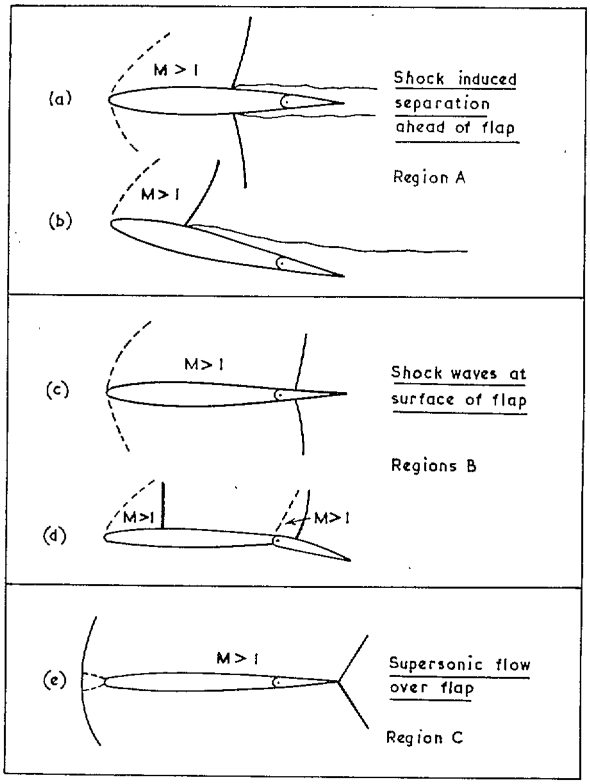


FIG. 3. Aerodynamic conditions for which buzz may occur, in relation to the regions shown in Figs. 1 and 2 (*schematic*).

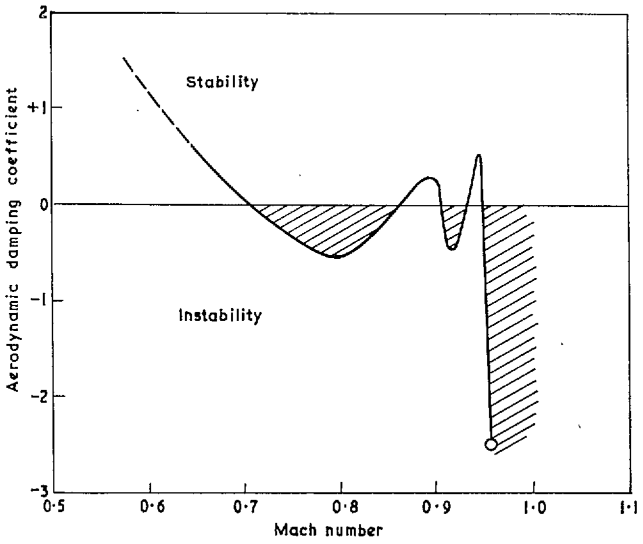


FIG. 4. Measurements of control-surface instability (based on Ref. 3).

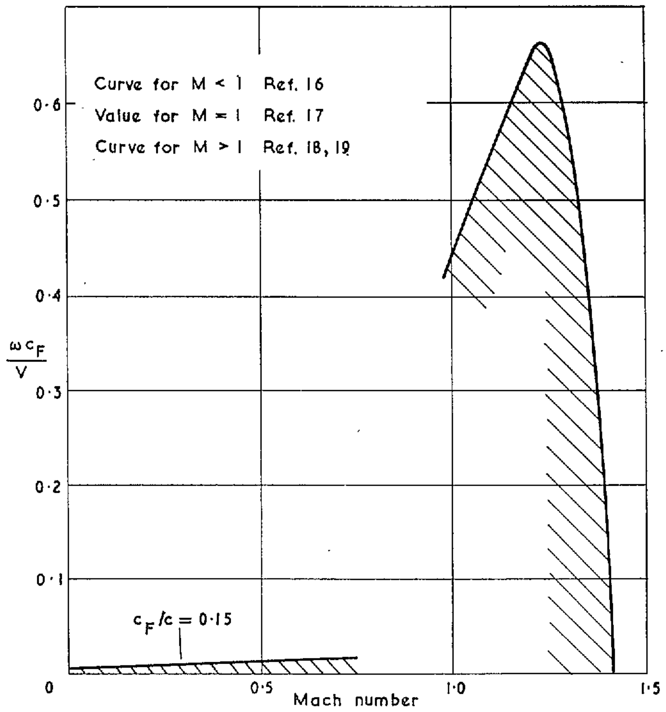


FIG. 5. Theoretical conditions for negative damping of flap in two-dimensional flow.

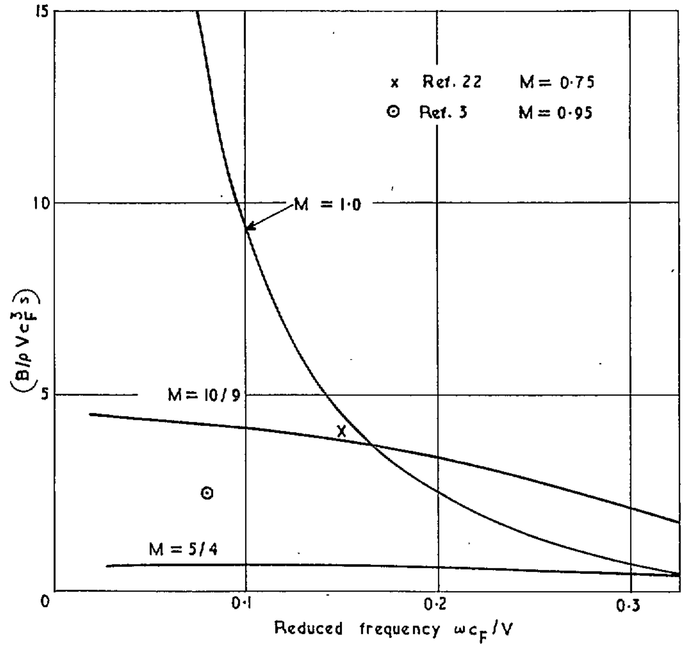
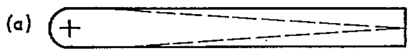


FIG. 6. Damping required to suppress buzz. Theoretical curves for two-dimensional sonic and supersonic flow and two values deduced from measurements at subsonic speeds.



Flap with blunt trailing edge

Flap with splitter plate

FIG. 7. Flap modifications.

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