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MARCH-APRIL 1968 J. AIRCRAFT VOL. 5, NO. 2

Some Contributions on a Control-Surface Buzz at High Subsonic Speeds

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A type of control-surface buzz occurring at high subsonic speeds where the shock waves form upstream of the flap is investigated. Experiments are made with a two-dimensional, airfoil-flap combination model at Mach numbers ranging from 0.78 to 0.81. First, measurements are taken of the amplitudes of the flap angle at the limit cycle of buzz and of the unsteady aerodynamic hinge moment for small oscillations using a free oscillation method. Second, optical observations of the flow around the model during the growth of buzz are made by means of a high-speed schlieren cinematography. The effects of frequency parameter and Reynolds number on the buzz characteristics are studied. It is shown that the separated flow behind the shock is responsible for the onset of the instability. On the basis of the present experimental results, a semi-empirical method of obtaining the unsteady pressure distribution over the surface of an airfoil at high subsonic speeds including shock wave is discussed and a possible mechanism of the onset of buzz is proposed. Furthermore, a method depending on the use of an air jet issuing from the upper surface of the airfoil was successfully devised in order to prevent the onset of this type of instability.

Nomenclature

a_1 = local speed of sound immediately upstream of shock
c, c_F = chord length of airfoil and flap
h_β = aerodynamic stiffness derivative of unsteady hinge moment $[= \rho V^2 c_F{}^2(h_\beta + i\nu h_{\dot\beta})\beta e^{i\omega t}]$
$-h_{\dot\beta}$ = aerodynamic damping derivative of unsteady hinge moment
$\mathbf{H}$ = total unsteady hinge moment derivative vector = $h_\beta + i\nu h_{\dot\beta}$
$\mathbf{H}_o$ = unsteady hinge moment derivative vector for hypothetical nonseparated flow
$\Delta\mathbf{H}$ = incremental hinge moment derivative vector due to flow separation
$|\Delta\mathbf{H}|$ = magnitude of $\Delta\mathbf{H}$
H_o = stagnation pressure of freestream
M_1 = local Mach number of flow immediately upstream of shock
M = Mach number of freestream
p_o = static pressure of shock-free distribution at mean position of shock
p_1, p_2 = static pressures of flow immediately upstream and downstream of shock
R = Reynolds number based on chord length of airfoil
t = time
u_s = velocity of forward movement of shock
V = air velocity
x, x_s = distance along chord from leading edge
β = flap angle

Received June 5, 1967; revision received September 11, 1967. This paper is an extract from part of the author's doctoral thesis submitted to the University of Tokyo. The author is indebted to R. Kawamura, K. Washizu, and J. Shioiri, University of Tokyo, for their criticism, helpful guidance, and encouragement during the course of the research. The experimental work was carried out at the Aerodynamics Division, the National Physical Laboratory, England, with the collaboration of L. Woodgate, while the author stayed at the NPL in 1964–1965 as a guest worker. The author also wishes to thank L. Woodgate, N. C. Lambourne, and H. H. Pearcey of NPL for their cordial assistance and valuable discussions in completing this paper.

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β_{max} = amplitude of flap angle at limit cycle
δ = height of shear layer
ν = frequency parameter = $\omega c_F/V$
ρ = air density
ϕ_L = phase lag of height of shear layer with respect to flap
ϕ_S = phase lag of shock movement with respect to flap
ϕ_H = phase lag of ΔH with respect to that for steady flow
ϕ_1 = phase lag of p_o/H_o with respect to flap
ϕ_2 = phase lag of shock movement in hypothetical nonseparated flow with respect to p_o/H_o
ϕ_3 = phase lag of shock movement in actual separated flow with respect to that in hypothetical nonseparated flow
ω = circular frequency

Introduction

RECENT investigations of control-surface buzz have revealed the various aspects of this instability.[1-3] It was shown by Lambourne that there exist at least three types of instability for two-dimensional flow, each depending upon its flight regime.[1,2] The present author showed that the supersonic potential flow over the surfaces of the flap is responsible for the onset of the third type of buzz occurring at low supersonic speeds.[3] However, for the first two types of buzz at high subsonic speeds, the mechanism of the onset is not yet exactly known. This paper is concerned with the first type of buzz occurring at high subsonic speeds where the shock waves form upstream of the flap.

The early wind-tunnel investigations of buzz showed a phase difference (lag) between the motion of the shock over the surface of the airfoil and that of the flap.[4] It was also realized that shock-induced separation was probably playing an important part.[5] Most of the past theories characterized this type of buzz as a time-lag oscillation. These theories were based on either or both of the following two characteristics of flow which were thought to be directly associated with each of the observations just mentioned.[4-6] One is the characteristic time delay represented by the time interval during which the pressure signal caused by the motion of the flap travels upstream to the shock through nearly sonic flow. Another is the hysteresis effects of the separated flow which may exist when changes in shock strength resulting from the motion of the flap induce corresponding changes in the downstream separated flow.

It was found by Lambourne, however, that the Mach number critical for the onset of buzz agrees with that for the onset of effects of shock-induced separation of the boundary layer on the over-all flow around an airfoil.[1] He also drew attention, through optical observations of the flow during buzz, to the cyclic variation of the severity of the separation as coupled with the strength of the moving shock, and hence, with the position and the velocity of movement of the shock over the surface of the airfoil. Thus, an upward-moving flap was considered to be 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, giving rise to a possible mechanism of amplification of the motion of the flap.[2] Although the steps taken by Lambourne seem to suggest the correct way towards the understanding of the problem, it appears that the precise role played by the unsteady shock-boundary layer interaction in the buzz instability remains uncertain.

The purpose of this paper is to show the experimental results that have recently been obtained by the present author with this type of buzz, to present a semi-empirical method of obtaining the unsteady pressure distribution over the surface of an airfoil in high subsonic nonseparated flow including shock waves, and finally to propose a new explanation for the mechanism of the onset of this instability. It was expected, though not proved by the previous investigators, that this type of buzz would have "soft flutter" characteristics, and so, particular attention was paid to the study of the growth of buzz, namely, from the oscillation at small amplitudes up to the limit cycle. The existence of a stable limit cycle is one of the characteristics common to all the instabilities occurring in the three regions mentioned earlier. As far as the author is aware, however, almost all the previous investigations were confined to the study of the limit cycle of buzz. A more detailed description of the present investigation is found in Ref. 7.

Experiment

The experiment was divided into two parts, 1) measurements of the amplitudes of the flap angle at the limit cycle of buzz and of the unsteady aerodynamic hinge moment for small oscillations using a free oscillation method, and 2) optical observations of the flowfield around the airfoil during the growth of buzz by means of high-speed schlieren cinematography. The experiment aimed at finding the effects of frequency parameter and Reynolds number on the buzz characteristics, which were expected to be most important among various parameters that influence buzz.

Apparatus and Model

The 18- × 14-in. transonic wind tunnel at the National Physical Laboratory was used for the present experiment. The model was a two-dimensional, airfoil-flap combination having 10% thick RAE 102 section. The airfoil was rigidly fixed to the tunnel walls at a fixed incidence of 4 deg. The chord length of the airfoil was 4.5 in. and that of the flap 1.125 in. Three flaps of the same section profile, but with different values of moment of inertia about the hinge, were used. Each flap was alternatively attached to the main airfoil by means of a spring hinge of a thin steel plate that ensured a low system damping.

The test was made for Mach numbers slightly above the lowest critical for which buzz occurs, namely for M = 0.78, 0.79, 0.80, and 0.81, respectively. The stagnation pressure of the tunnel was varied from 1 to 2 atm, approximately, the corresponding values of the Reynolds number based on the chord length of the airfoil ranging from 1.6 to 3.2×10^6, approximately. Since the elastic stiffness of the spring hinge was designed to be small, the angular stiffness of the flap about its hinge was mainly aerodynamic, so that the change in stagnation pressure resulted in the change in values of both the Reynolds number and the frequency parameter. The leading edge of the airfoil was roughened with a band of carborundum grains to provide a turbulent boundary layer that is more representative of flight conditions. A method depending on the use of an air jet issuing from the upper surface of the airfoil was devised in clamping the flap before the test was made. The method proved to be quite effective in suppressing buzz oscillation for a limited range of Mach numbers above the critical. Thus, an air jet with a supply pressure ranging from 3 to 7 atm, approximately, depending on the stagnation pressure used, was ejected into the separated flow behind the shock wave through a row of small holes distributed at 0.534 c on the upper surface of the airfoil. By sudden cutoff of the air jet, spontaneous oscillations of the flap occurred. The supply and cutoff of the air jet could be done very rapidly, the time required being 2 or 3 msec, approximately. Figure 1 presents a direct shadowgraph of the flow around the airfoil with the air jet at M = 0.79 for which buzz would otherwise have occurred. The shock was present at the upper surface and upstream of the holes for the air jet for small deflections of the flap over the Mach number range tested, whereas it was absent at the lower surface except for large upward deflections of the flap. The precise role that the air jet plays in suppressing buzz is not known, but it will be referred to later in a discussion of the mechanism of the onset of buzz.

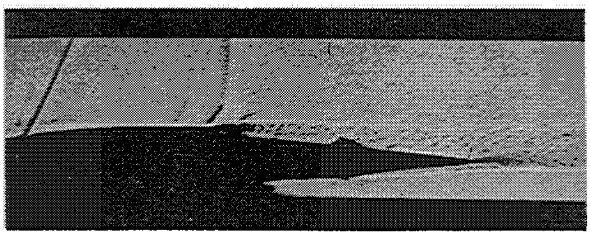


Fig. 1 Direct shadowgraph showing the flow pattern around airfoil with air jet at 4-deg incidence for M = 0.79 where buzz would otherwise have occurred.

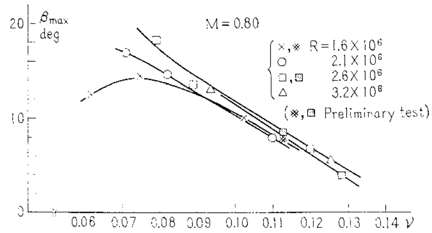


Fig. 3 Variations of limit-cycle amplitude of flap angle with frequency parameter at M = 0.80 for various values of Reynolds number.

The time history of the flap angle was obtained by an optical tracking system situated outside of the working section of the tunnel. Figure 2 is one of the original oscillograms showing the variations of the flap angle with the time. At small amplitudes less than 3 deg, approximately, the amplitude of the flap angle increased exponentially with the time. The frequency of oscillation was found to be almost constant during the growth of buzz up to the limit cycle. The unsteady aerodynamic hinge moment was then determined by measuring the frequency and rate of growth of the oscillating flap angle less than 3 deg.

Experimental Results

With gradually increasing speed, buzz occurred spontaneously at the Mach number slightly below 0.78. This value of the Mach number was found to agree with that for the trailing-edge pressure divergence.[1] The experimental results are shown for M = 0.78 and 0.80 only, since these are considered to be most representative.

Amplitudes of flap angle at the limit cycle

Figure 3 shows the variations of the limit-cycle amplitude of the flap angle with frequency parameter at M = 0.80 for various values of the Reynolds number. It is clear from the graph that the effect of frequency parameter is very large. With increase of this the amplitude of the flap angle decreases, the curves indicating that it will tend to be zero at ν = 0.14, approximately. At small frequency parameters the values reach ±19 deg. It is also shown that an increase of the Reynolds number resulted in an increase of the amplitude of the flap angle, particularly at small frequency parameters.

Unsteady aerodynamic hinge moment derivative

As is seen in Fig. 2, it is found that this type of buzz has "soft flutter" characteristics, namely, the oscillations grow spontaneously from small values. Figure 4a shows the variations of the aerodynamic damping derivative of unsteady hinge moment with frequency parameter for oscillations of small amplitude at M = 0.80. Here again, the effect of frequency parameter is found to be pronounced. The numerical values of the negative aerodynamic damping derivative decrease with increase of the frequency parameter and increase with increase of the Reynolds number. Figure 4b shows the variations of the aerodynamic stiffness derivative of unsteady hinge moment with frequency parameter. The results indicate that the variations of the stiffness derivative with frequency parameter are also very remarkable, although the values of the frequency parameter are not so large. The effects of Reynolds number are only seen at small frequency parameters, but not of the small order. The characteristic variations of unsteady aerodynamic hinge moment with frequency parameter are more clearly seen in Fig. 5, where the vector representation for unsteady hinge moments at the atmospheric pressure for M = 0.78 and 0.80 is given. The curve with crossed symbols in Fig. 5 gives the hinge moment derivative vector for M = 0.75 where buzz did not occur, the values of the frequency parameter corresponding to those for M = 0.78 and 0.80. This curve for M = 0.75 was obtained by Wight with a similar airfoil of 9 in. in chord length at 36- × 14-in. tunnel using a forced oscillation method, the amplitude of the flap angle being 3 deg, approximately.[8] It is worth noting that at Mach numbers where buzz occurred, the magnitudes of the unsteady hinge moment derivative vector were found to exhibit extraordinarily large changes with frequency parameter, whereas the phase lags of the vectors with respect to the steady ones are of the order of 20 deg.

Flow observations by high-speed cinematography

High-speed ciné films showing changes in the flow pattern around the airfoil during the growth of buzz were obtained using a schlieren photographic method. Figure 6 presents

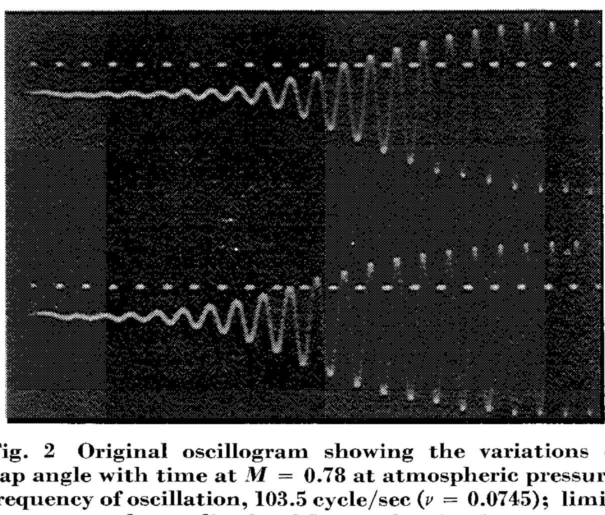


Fig. 2 Original oscillogram showing the variations of flap angle with time at M = 0.78 at atmospheric pressure; frequency of oscillation, 103.5 cycle/sec (ν = 0.0745); limit-cycle amplitude of flap angle, 13.7 deg.

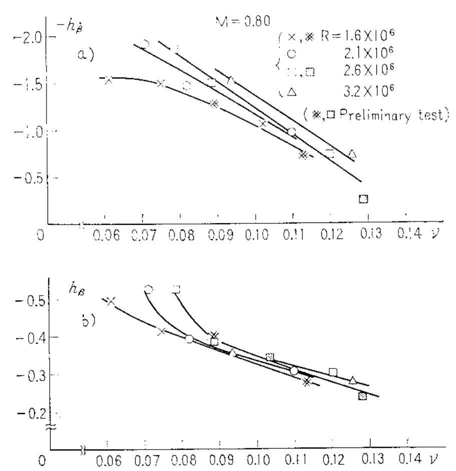


Fig. 4 Variations of the aerodynamic damping and stiffness derivatives of unsteady hinge moment with frequency parameter at M = 0.80 for various values of Reynolds number.

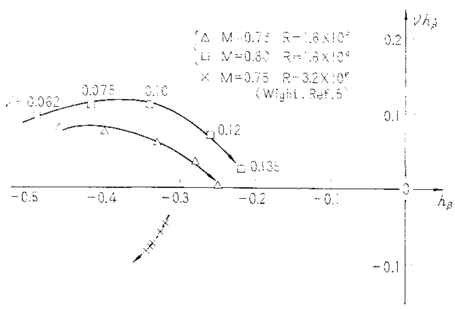
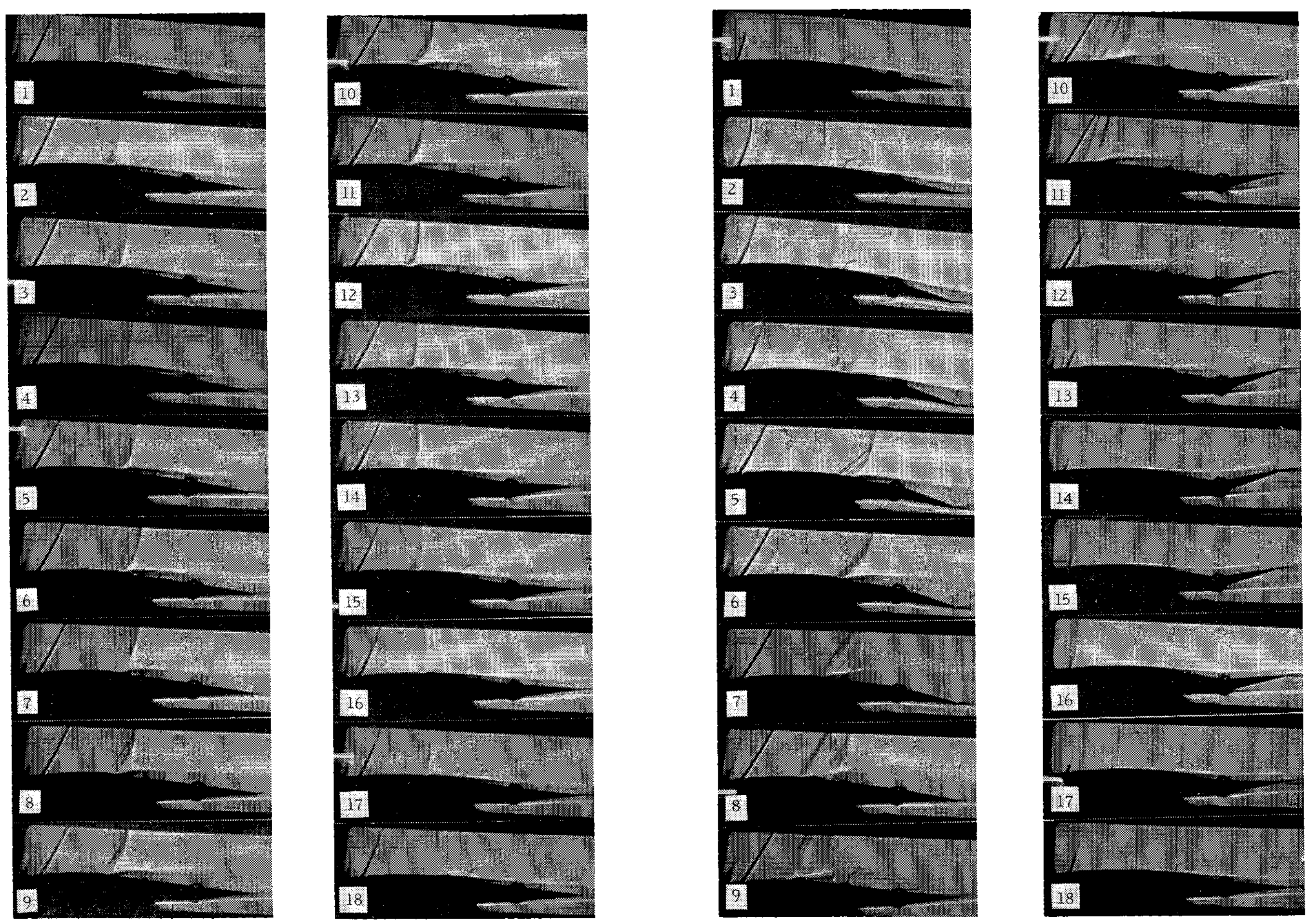


Fig. 5 Vector representation of the variations of unsteady hinge moment wth frequency parameter at M = 0.75, 0.78, and 0.80 at atmospheric pressure.

portions of the sequences of film for small and limit-cycle oscillations, whereas Fig. 7 gives the time history for the flap angle, the position of the shock wave, and the height of the shear layer for the corresponding small oscillation. Here, the height of the shear layer was measured at the position 0.2 c downstream of the moving shock; the height of the shear layer thus measured is considered to represent the instantaneous severity of the separation of the boundary layer at the foot of the shock.

The analysis of films has revealed important changes of the flow characteristics with respect to the flap. First, the large phase difference between the cyclic variations in the height of the shear layer and the flap motion appears to be a characteristic of this type of instability and would seem to be an essential feature of the mechanism of excitation. Secondly, it is well known that in steady flow, the slow-down in the rate of rearward movement of the shock with downward deflection of the flap is a characteristic of the onset of effects of shock-induced separation of the boundary layer on the over-all flow around an airfoil.[9] It is quite interesting to note, however, that according to Fig. 7, the movement of the shock is comparatively large and sufficiently linear with deflection of the flap in unsteady flow.

Figure 8 shows the variations with frequency parameter of the phase lags of the height of the shear layer and the position of the shock wave with respect to the flap for M = 0.78 and 0.80. The phase lag of the height of the shear layer is found to be very large and increase with the frequency parameter, whereas that of the position of the shock wave changes sign from negative (phase lead) to positive with increase of the frequency parameter; the effect of Mach number on these phase angles is absent. Close examination of the graph reveals that the difference between these two phase angles is constant and nearly equal to 90 deg. In other words, the changes in the height of the shear layer are shown to be approximately in phase with the velocity of forward movement of the shock wave; the separation is most severe when the shock is moving forward with greatest velocity, and vice versa with the shock moving rearward with greatest velocity. Although the range of the frequency parameter covered in this experiment was narrow, it will be guessed that the relation mentioned previously holds for some range of the frequency parameter larger than, say, 0.14, but with decrease of the frequency parameter to zero the relation breaks and both of the phase angles tend to be zero.



a) Small oscillation (films correspond to the time interval Δt in Fig. 7) **b) Limit cycle**

Fig. 6 High-speed schlieren films showing changes of the flow pattern around airfoil during the growth of buzz at M = 0.78 at atmospheric pressure.

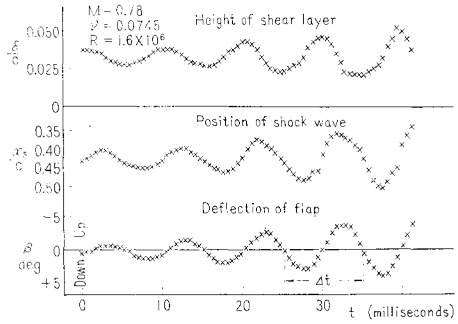


Fig. 7 Time history of flap angle, position of shock wave and height of shear layer for small oscillations at M = 0.78 at atmospheric pressure; frequency of oscillation, 103.5 cycle/sec.

Summary of Experimental Results

Important results obtained in the present experiment may be summarized as follows: 1) large phase lag of the height of the shear layer with respect to the flap, 2) height of the shear layer in phase with the velocity of forward movement of the shock, 3) phase lead of the shock movement with respect to the flap for buzz with small frequency parameters, 4) disappearance of the slow-down in the rate of rearward movement of the shock in unsteady separated flow, 5) rapid change in magnitude of the unsteady hinge moment derivative vector with the frequency parameter, 6) rather small phase change of the unsteady hinge moment derivative vector in contrast to large phase change of the height of the shear layer, and 7) effects of Reynolds number on buzz characteristics with a turbulent boundary layer.

Discussions on the Mechanism of Onset of Buzz

Shock Strength and Severity of Separation in Unsteady Flow

In attempting to provide an understanding of the instability, we shall first mention the following. The strength of the shock wave in steady flow is dependent on its position at the surface of an airfoil. In unsteady flow, however, it is dependent on the velocity of movement of the shock wave over the surface as well as on its position. The severity of the separation of the boundary layer in unsteady flow, therefore, is dependent on both of the position and velocity of movement of the shock wave, since the severity of the separation itself should be determined by the strength of the shock wave. Lambourne was the first who noticed the relation just mentioned.[1] On considering this relation, we can state that for sufficiently fast oscillatory movements of the shock, the shock strength, and hence, the severity of the separation due to the shock will become primarily determined by its velocity of movement rather than by its position at the surface of the airfoil. A tentative explanation for result 2 in the foregoing Summary of Experimental Results is thus given. Comparison of the static and dynamic effects of movement of the shock on its strength is given in a little more detail in Ref. 7.

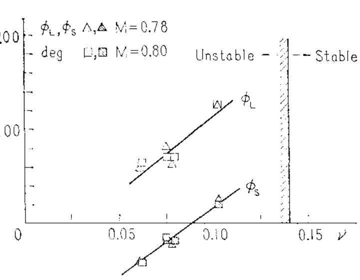


Fig. 8 Variations with frequency parameter of the phase lags of position of shock wave and height of shear layer with respect to flap.

Incremental Hinge Moment due to Flow Separation

The purpose of this section is to find possible correlations among items 1, 5, and 6 in the Summary of Experimental Results, namely, to understand the variations of the unsteady hinge moment derivative vector with frequency parameter in connection with the changes in the flow pattern around the airfoil. As mentioned before, the changes in unsteady hinge moment derivative vector with frequency parameter are comparatively small in the range of the subcritical Mach numbers where buzz does not occur. On the other hand, it is well known that in steady flow an incremental restoring hinge moment is produced at the onset of the trailing-edge pressure divergence. This corresponds to a large reduction in pressure recovery downstream of the shock with the rapid extension of the separation bubble towards the trailing edge.[9] The incremental hinge moment increases with the severity of the separation.

The consideration of these experimental evidences leads us to the assumption that there also must be the production of an incremental hinge moment due to the flow separation in unsteady flow. The flowfield where buzz occurs is then assumed to be composed of the hypothetical flow in which the boundary layer would not be separated at the same Mach number and of the perturbed flow that would be produced by the shock-induced separation of the boundary layer. Correspondingly, the total hinge moment derivative vector $\mathbf{H}$ is assumed to be the vector summation of the hinge moment derivative vector $\mathbf{H}_o$ for the hypothetical nonseparated flow and an incremental hinge moment derivative vector $\Delta\mathbf{H}$ due to the flow separation.

$$\mathbf{H} = \mathbf{H}_o + \Delta\mathbf{H} \tag{1}$$

If such an assumption is accepted, the hypothetical hinge moment derivative vector $\mathbf{H}_o$ may be obtained by extrapolating the measured values at the subcritical Mach numbers, retaining the values of the frequency parameter.

Figure 9 shows the variations with frequency parameter of the phase lags ϕ_H and the magnitudes $|\Delta\mathbf{H}|$ of the vectors $\Delta\mathbf{H}$ thus obtained for M = 0.78 and 0.80 at the atmospheric pressure; the phase lag ϕ_H is defined for convenience as a phase angle relative to the steady restoring moment. Here, the vectors $\mathbf{H}_o$ for the hypothetical nonseparated flow for M = 0.78 and 0.80 are represented by the hinge moment derivative vector for M = 0.75; the change in $\mathbf{H}_o$ with the Mach number is assumed to be small and is neglected. It is quite interesting to point out that the phase angles ϕ_H for both of the Mach numbers are the same and nearly equal to that of the height of the shear layer; the numerical values of $|\Delta\mathbf{H}|$ increase with the Mach number and decrease slightly with the frequency parameter.

On the basis of the foregoing analysis of the experimental results, the changes in the unsteady hinge moment with frequency parameter can be understood as follows. In unsteady flow, with the onset of effects of shock-induced separation of the boundary layer, an incremental hinge moment is created, the value being dependent on the severity of the

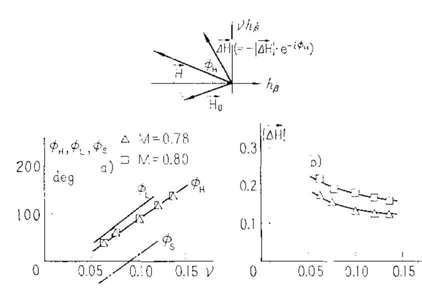


Fig. 9 Variations with frequency parameter of the magnitudes and phase lags of incremental hinge moment due to flow separation with respect to flap.

separation downstream of the shock, and hence, on the strength of the shock. Thus, the total hinge moment is the vector sum of the hinge moment corresponding to the hypothetical nonseparated flow and the incremental one due to the flow separation. In the case where the strength of the shock is primarily determined by the velocity of its forward movement, the incremental hinge moment varies almost in phase with that velocity. On the other hand, according to the present experimental results, the phase angle of the shock movement with respect to the flap is small for the range of the frequency parameter where buzz occurs. Therefore, the incremental hinge moment varies almost in phase with the velocity of deflection of the flap. The negative aerodynamic damping moment which can amplify the motion of the flap is thus produced. As the movement of the shock lags considerably behind the motion of the flap with increase of the frequency parameter, the phase angle of the incremental hinge moment becomes correspondingly large. As a result, the damping moment of the total hinge moment changes from negative to positive, and then buzz ceases to occur. The numerical value of the magnitude of the incremental hinge moment is of the same order as that of the hinge moment for the hypothetical nonseparated flow. Large rotation of the incremental hinge moment derivative vector with frequency parameter thus gives rise to large change in magnitude of the total hinge moment derivative vector with frequency parameter.

It should be pointed out that in this approach, neither the phase lag of the shock movement with respect to the flap nor the hysteresis effects of the separated flow behind the shock would be necessary to deduce the negative damping of the hinge moment. As mentioned in the Introduction, these were the main frames of the past theories. In fact, Erickson and Stephenson considered that the aerodynamic restoring hinge moment lagged behind the motion of the flap with the observed phase lag in the motion of the shock wave.[4] Phillips and Adams concluded from their low-speed experiment that the hysteresis effects of the separated flow behind the shock would be essential to the onset of the buzz instability.[5] In Smilg's approach, the unsteady aerodynamic hinge moment applying under potential-flow conditions was retained in magnitude but suffered a phase lag identified with time lag in the flow; the time lag was considered to be the sum of the two factors just mentioned.[6] In the light of the present experimental results none of these is difficult to justify. In particular, a logical conclusion from item 3 in the Summary of Experimental Results is that the pressure signal created by the motion of the flap should travel in the flow up to the shock quickly enough, and in consequence, the adjustments in the over-all flow should take place.

It appears that Lambourne was the first to put forward the concept of an incremental hinge moment due to flow separation in explaining the mechanism of the onset of buzz.[2] The development of the concept by the present author in the manner described in this section seems to justify his early hypothesis.

Unsteady Hypothetical Nonseparated Flow—Extension of Sinnott's Theory to Unsteady Flow

In discussing the onset of buzz in the preceding section the movement of the shock with respect to the flap was specified in advance; the flow separation and its effects on the hinge moment as a result of the shock movement were discussed in order to deduce the negative aerodynamic damping moment. However, it is obvious that the onset and growth of the separation bubble must bring about appreciable changes in the characteristics of the viscous flow near and downstream of the trailing edge and the repercussion of this must induce changes in the position of the shock itself.[9] Thus, the effects of unsteady shock-boundary layer interaction not only on the local but also on the over-all flow around an

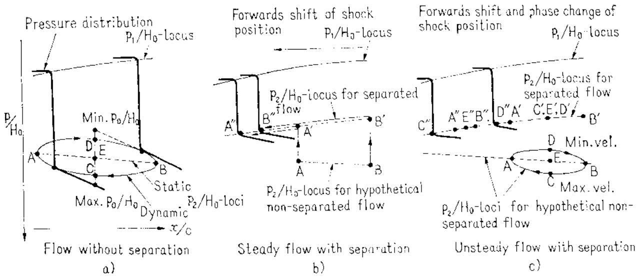


Fig. 10 A sketch (not in scale) showing changes in surface pressure distribution for a given stroke of flap deflection for various conditions of flow.

airfoil should be investigated in order to understand the precise mechanism of the onset of buzz. For this purpose we shall proceed with our discussion by considering the unsteady hypothetical nonseparated flow.

Sinnott and Osborne proposed a semi-empirical method for determining the surface pressure distribution in steady, nonseparated, high subsonic flow including shock waves.[10] It consists of the following three steps: 1) On the basis of the experimental evidence that the pressure distribution over the surface of an airfoil upstream of the shock is almost the same as that for sonic flow, they have succeeded in empirically deriving the former with the aid of the latter for any given airfoil and flow conditions; the locus of the surface pressure p_1/H_o immediately upstream of the shock is then obtained. 2) They have given an empirical relation between the shock pressure ratio or the shock strength p_2/p_1 and the shock upstream pressure p_1/H_o which is valid for wide ranges of parameters, such as the airfoil profile, the incidence, and the Mach number.† 3) It was found empirically that the surface pressure distribution of the flow between the shock and the trailing edge is obtained by applying some compressibility transformation, for example, the Prandtl-Glauert transformation, to the experimental incompressible pressure distribution of the same airfoil. The position of the shock is then determined as an intersection point of the p_2/H_o locus with the downstream "shock-free" distribution. The pressure distribution over the whole surface of an airfoil is determined in this way.

We now attempt to extend Sinnott's theory to unsteady nonseparated flow. First of all, the pressure distribution upstream of the shock in unsteady flow is assumed to remain the same as that for steady flow. Secondly, the independent variable in Sinnott's empirical formula giving the shock strength is transformed from the pressure p_1/H_o to the local Mach number M_1. The value for the strength of the moving shock wave is then obtained by putting into the same formula the value of $M_1 + u_s/a_1$, an equivalent Mach number. Here, u_s is the velocity of forward moving shock over the surface of the airfoil and a_1 is the local velocity of sound. Third, the unsteady pressure distribution downstream of the shock is assumed to be given by the flow calculated by the unsteady subsonic potential flow theory for flat plate as superposed on the basic steady flow for zero deflection of the flap. The improvement of this first-order approach may be obtained by W. P. Jones's "equivalent profile method" within the scope of the linear theory.[11] The steps just described provide a possible method for constructing the unsteady pressure distribution over the surface of an airfoil in nonseparated, high subsonic flow including shock waves for given oscillatory deflection of the flap.

Figure 10a is a sketch showing the surface pressure distribution in the vicinity of the shock, which illustrates the present approach. Here, the dotted curve AEB is the p_2/H_o

† The thickness of the shock is neglected for this theory so that the pressure p_2/H_o now under consideration is somewhat different from that observed in the actual flow. See Ref. 10 for details.

locus for steady flow corresponding to a given stroke of the flap deflection; the mean position of the shock and the pressure of the shock-free distribution there are represented by E and p_o/H_o, respectively. It is to be mentioned, on the other hand, that with an oscillatory stroke of the flap deflection, the variation of p_2/H_o forms a closed loop such as ADBC in Fig. 10a. Consider, for example, the shock at the mean position. The forward moving shock indicated as C has larger strength than that for the stationary shock indicated as E, and vice versa with the rearward moving shock indicated as D. It is also worth noting that with increase of the frequency of oscillation, the strength of the shock will become dependent more and more and finally completely on its velocity of movement over the surface of the airfoil. Another important point to be mentioned is that in the present approach, unless the flow separation occurs as a result of the increase in shock strength, the unsteady hinge moment of the flap is determined by the shock-free distribution. It is with the onset of effects of shock-induced separation of the boundary layer that the movement of the shock will influence directly the downstream flow, and hence, affect the hinge moment of the flap. The difference in the role played by the movement of the shock between nonseparated and separated flows is thus very important in order to understand the mechanism of the onset of buzz. It will hardly be necessary to add that the hypothetical hinge moment derivative vector $\mathbf{H}_o$ defined in the Eq. (1) corresponds to the shock-free flow, and the damping of the hinge moment for the shock-free flow is shown theoretically to be positive except for very small values of the frequency parameter.

Onset of Flow Separation in Steady and Unsteady Flows

We now consider the flow separation occurring downstream of the shock wave. According to Pearcey,[9] the strength of the shock p_2/p_1 in steady flow, which is increased monotonically with the local Mach number M_1, is suppressed at the onset of effects of the flow separation and it remains almost constant with further increase in the value of M_1. Correspondingly, the shock becomes oblique. The severity of the separation is thus associated with the value of the local Mach number M_1 rather than with the observed value of the shock strength p_2/p_1; the severity of the separation may be represented by the height of the shear layer behind the shock wave. There is another important aspect of the interaction which is related to the change in the over-all flow, namely, the slow-down in the rate of rearward movement of the shock wave at the onset of effects of the flow separation. The physical interpretation for this is given by Pearcey.[9] The rapid extension of the separation bubble towards the trailing edge means a characteristic change in the viscous flow near and downstream of the trailing edge, thus giving rise to a remarkable decrease in the downstream pressure recovery. This large change in the characteristics of the viscous flow near the trailing edge could not be directly compatible with the wake flow far downstream, the static pressure of which must recover to the value of the freestream. Although the precise mechanism of the pressure recovery in the wake flow is not yet known, the forward shift of the separation point and the associated flow changes must therefore occur in order to reduce the severity of the separation near the trailing edge. In transonic flow, this simply means the forward shift of the shock wave, since the separation point is fixed at the shock foot and the flow upstream of the shock is "frozen."

Figure 10b illustrates the change in strength and forward shift of position of the shock wave due to the flow separation in steady flow. Here, the p_2/H_o locus AB in the hypothetical nonseparated flow corresponding to a given stroke of the flap deflection is transformed to A′B′ on a new p_2/H_o locus in the hypothetical separated flow; the new locus is given, assuming p_2/p_1 to be constant. The position of the shock wave A″B″ in the actual separated flow is then obtained by shifting A′B′ forward on the new locus, as shown by the arrow, in order to satisfy the downstream compatibility condition. In considering unsteady separated flow the following assumptions are made: 1) The severity of the separation behind the shock is determined by the shock strength given in Sinnott's formula by putting in it the equivalent Mach number, $M_1 + u_s/a_1$, for the moving shock. 2) The pressure ratio p_2/p_1 through the moving shock after the onset of effects of the flow separation remains constant and equal to that for steady flow.

Phase Change in the Movement of Shock Wave as Induced by Unsteady Shock-Boundary Layer Interaction

The purpose of this section is to find a possible interpretation for items 3 and 4 in the Summary of Experimental Results given earlier. Let us first confine our attention to the oscillation of the flap with small frequency parameter for which the compatibility condition with the far downstream wake flow in unsteady flow is assumed to be the same as that in steady flow. In Fig. 10c, the steady and unsteady p_2/H_o loci in the hypothetical nonseparated flow corresponding to a given stroke of the flap deflection are expressed as AEB and ADBC, respectively. The shock at an arbitrary position represented by the points, E, C, and D is considered. As mentioned in the previous section, the point E moves, under the condition of the flow separation, to E′ and then to E″ in steady flow. On the other hand, as the strength of the forward moving shock at C is larger than that at E, the corresponding position C″ of the moving shock in the actual separated flow should be more forward than that for steady flow E″; the over-all severity of the separation for the forward moving shock would thus be less severe at C″ than at E″. Similarly, the point D″ should lie backward of the point E″. This means that the movement of the shock wave in the actual separated flow should lead that in the hypothetical nonseparated flow.

In summary, the observed phase lag ϕ_S of the movement of the shock wave in the separated flow with respect to the flap is expressed as

$$\phi_S = \phi_1 + \phi_2 + \phi_3 \tag{2}$$

where ϕ_1 is the phase lag with respect to the flap of the local pressure p_o/H_o of the shock-free distribution at the mean shock position, ϕ_2 is the phase lag with respect to p_o/H_o of the movement of the shock wave for the hypothetical nonseparated flow, and ϕ_3 is the phase lag of the movement of the shock wave in the actual separated flow with respect to that for the hypothetical nonseparated flow. The values for ϕ_1 and ϕ_2 may be obtained theoretically. Although the calculation has not yet been made at the present stage, the trend in the incompressible solution indicates that ϕ_1 and ϕ_2 will be positive over the surface sufficiently upstream of the hinge for the ranges of the Mach number and the frequency parameter now under discussion. The experiment by Bergh[12] shows that ϕ_1 is positive over the surface sufficiently upstream of the hinge for $\nu = 0.10$ at $M = 0.70$, which seems to support the present speculation. For this reason, it is to be expected that the unsteady shock-boundary layer interaction is the only factor producing the negative values of the observed phase lag ϕ_S for small frequency parameters.

According to Fig. 9, however, the phase lag ϕ_S increases with frequency parameter, changing sign from negative to positive at $\nu = 0.09$, approximately. The foregoing argument based on the downstream compatibility condition applying to the steady flow fails to explain this experimental result. To look for a suitable compatibility condition applying to the fully unsteady separated flow would seem to be one of the most important future problems.

The problem remaining is to understand the manner in which the slow-down in the rate of rearward movement of the shock in steady flow disappears in unsteady flow. It is to be noticed that the amplitude of the variation in shock strength for a given stroke of the flap deflection in the hypothetical nonseparated flow, and hence, the amplitude of the variation in the severity of the separation for similarly situated moving shock increase with frequency parameter. It follows that when the downstream compatibility condition is introduced, the corresponding amplitude of the variation of forward shift of the shock position increases with frequency parameter. If the shock at C in Fig. 10c has maximum strength, the corresponding position C″ in the actual separated flow can be more forward than A″, and similarly, the point D″ can be more rearward than B″; A″ and B″ denote the extreme shock positions for steady flow. In its extreme case where the rearward moving shock at D is so weak as not to induce the separation of the boundary layer, the point D″ will coincide with the point D. A possible interpretation for result 4 in the Summary of Experimental Results is thus given.

Finally, mention is given to the role played by the air jet in suppressing buzz. The air jet clearly influences the separated flow, and it seems likely that it is this influence that upsets the mutual interaction between shock wave and flap. It is relevant to note that the air jet is no longer effective when the shock, and hence, the separation point have passed downstream of the jet. That is, the air jet is only effective when injected downstream of separation, which is in agreement with the well-known fact that the whole nature of the separation is very sensitive to injection on this region.

Effects of Reynolds Number on Buzz Characteristics

The results of the present experiment show that the limit-cycle amplitude of the flap angle and the magnitude of the unsteady hinge moment increase with the Reynolds number. It appears, therefore, that the severity of the separation would decrease with decrease of the Reynolds number. If we remember that the boundary layer upstream of the shock was turbulent, the trend seems to be paradoxical. Haines et al.,[13] however, observed that in steady flow, a considerable improvement in the rate of pressure recovery downstream of the shock occurred with models with artificially fixed transition at low Reynolds numbers, say, 1.0×10^6, approximately. They concluded that at low Reynolds numbers the separated shear layer is thick relative to the depth of the dead air region and can then support a larger pressure recovery. This might explain also the trend in unsteady flow just mentioned. However, further investigations are necessary in order to understand precisely the effects of Reynolds number on the buzz characteristics and extrapolate the wind-tunnel results to those for the range of higher Reynolds numbers.

Conclusions

An analysis based on the new experimental results has been put forward on the mechanism of the onset of buzz at high subsonic speeds where the shock waves form upstream of the flap. With the onset of effects of the shock-induced separation of the boundary layer, an incremental hinge moment is created, the value being dependent on the severity of the separation, and hence, on the strength of the shock wave. The strength of the shock under consideration is determined by the equivalent Mach number of the flow immediately upstream of the moving shock. The total hinge moment is the vector sum of the hinge moment for the hypothetical nonseparated flow and the incremental one due to the flow separation. The hypothetical nonseparated flow is obtained by an extension of Sinnott's semi-empirical theory. In case where the strength of the shock is primarily determined by the velocity of its movement, the incremental hinge moment varies almost in phase with that velocity. On the other hand, the unsteady shock-boundary layer interaction is found to cause the forward shift and phase lead of movement of the shock wave. The phase angle of movement of the shock with respect to the flap is then small for the range of the frequency parameter where buzz occurs. As a result, the incremental hinge moment varies almost in phase with the velocity of deflection of the flap. The negative damping moment that can amplify the motion of the flap is thus produced. As the movement of the shock lags considerably behind the motion of the flap with increase of the frequency parameter, the phase angle of the incremental hinge moment becomes correspondingly large. Therefore, the damping of the total hinge moment changes sign from negative to positive, and then buzz ceases to occur.

A method depending on the use of an air jet issuing from the upper surface of the airfoil was devised to prevent the onset of buzz. The effects of Reynolds number on the buzz characteristics with a turbulent boundary layer were discussed.

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