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A Survey of Buffeting Loads

by

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SUMMARY

In this paper a summary has been made of the information available on the buffeting phenomena of aircraft based on flight and wind tunnel tests and theoretical work. Methods of predicting buffet loads are discussed. It is found that maximum buffet loads may be high in relation to existing design criteria and that in general, tail buffeting loads are more severe than wing buffeting loads and that tail buffeting loads on straight-wing aircraft tend to be much higher than on swept-wing aircraft.

Comparisons of wind tunnel with flight test results suggest that it may be feasible to predict buffet loads from wind tunnel tests although further research in this field is needed.

The influence of various parameters on buffeting is discussed.

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1 INTRODUCTION

It has been known for a long time that buffeting can cause serious structural troubles and has in fact caused some structural incidents and failures but no method has yet been produced for forecasting accurately either the onset of buffeting or the magnitude of the buffet loads. A number of reports have been published giving the results of flight and wind-tunnel tests on specific aeroplanes and the attempts that have been made to generalise the findings. The information is reviewed in this report and, in particular, attention is drawn to:-

(a) the large tailplane buffeting loads which have been measured in flight tests,

(b) the parameters which affect the occurrence and size of buffeting loads,

(c) the possible methods of predicting these loads.

2 MAXIMUM BUFFETING LOADS

2.1 Straight wing aircraft

In general wing buffeting loads are much smaller in relation to the design loads than tail buffet loads. Although some wing and tail buffeting loads have been measured at transonic and low supersonic speeds (i.e. up to $M = 1.4$), most of the measurements have been made at lower speeds.

A number of structural failures and incidents have occurred which are attributed to the combination of large buffeting, manoeuvring and balancing tail loads. (Further details of the aircraft and incidents are given in Appendix 1).

The buffet loads are often presented in terms of design loads and, whilst strictly speaking this is illogical as buffeting is not a function of the design load, it is useful as a means of showing the relative severity of the buffet loads. Thus, on a straight wing jet fighter, the measured tailplane buffet load exceeded 45% of the (unfactored) design load and, on a straight wing jet bomber, the maximum tailplane buffeting load measured was about 24% of the design load and the elevator buffeting load was 75% of the design load.

In several cases it has been necessary to impose a speed limitation or even to strengthen the tailplane structure because of buffeting at subsonic speeds.

2.2 Swept-wing aircraft

The tail buffeting loads are again much more significant than the wing loads at all speeds. On one aircraft however large buffeting loads were measured on the aileron rods at high subsonic Mach numbers and in one instance the buffeting load alone exceeded the design load.

At high subsonic Mach numbers, the severity of the buffeting loads tends to decrease with increase in sweepback; measured tailplane buffeting loads for an aircraft with 35° sweep being only about 30% of those on a straight wing aircraft of similar size and performance. Maximum tail buffeting loads have been measured varying from 20% of the unfactored design load on a fighter with 35° sweep to 5% on an aircraft with 60° sweep.

Tail buffeting loads have in some cases necessitated extensive modifications such as fitting vortex generators to the wing to alleviate the buffeting, or strengthening the tailplane structure. In other cases buffeting has been the limiting factor on performance and manoeuvrability at high subsonic Mach numbers.

The importance of buffet loads in design has been recognised in two instances, additional design factors being imposed to provide for this condition.

3 PARAMETERS IMPORTANT IN BUFFETING

3.1 Buffeting frequencies

On most straight wing aircraft the measured predominant buffet frequencies correspond to the wing and tail structural primary bending frequencies or, when the tail loads are antisymmetric, to the fuselage torsional frequency. For swept-wing aircraft the frequencies are more likely to correspond to the fundamental bending and torsion modes. (See Appendix 2). In power spectral studies the part of the structure responding to the buffeting is often regarded as having only one structural degree of freedom, with frequency corresponding to the fundamental mode, as it is assumed that this will give a good first-order approximation.

It has been found possible to reduce the response at the relevant frequencies by means of mechanical dampers.

3.2 Reduced frequency

When comparisons between a model and an aircraft or two aircraft or different sizes are to be made, ω, the frequency, is a less pertinent parameter than the reduced frequency, $\omega \bar{c}/V$ ($\bar{c}$ - average chord, V - velocity), which makes allowances for differences in size and speed. The reduced frequency is particularly useful when comparing power spectra from different configurations.

3.3 Flow separation

Two types of flow separation give rise to buffeting, firstly, the actual flow separation over the wing itself and, secondly, premature flow breakaway, which may occur at the wing-fuselage or tailplane-fin junction, for instance. Although it is unlikely that flow separation can be completely eliminated it may be postponed and alleviated by good design. A few of the methods of treating this problem are discussed in the following paragraphs.

Decreases in thickness-chord ratio and aspect ratio and increase in sweepback all tend to alleviate buffeting at high Mach numbers and moderate C_L where compressibility triggers off the vibratory flow. In this region sweepback can reduce the buffet amplitudes by as much as 50% to 70% as compared with a similar straight wing aircraft and it may also delay the onset of buffeting to a higher Mach number.

It is known that a low thickness-chord ratio is definitely beneficial in reducing buffeting fluctuations in the shock region, although in the stall region a thicker section is more favourable. It may be possible to improve the low speed characteristics of a thin aerofoil with only a slight sacrifice in its superior qualities at higher speeds by moving the position of maximum thickness forward and by using a larger leading edge radius.

Vortex generators are useful both because they delay the onset of buffeting and reduce the magnitude of the actual buffet loads. Fences have also been shown to be a very effective means of reducing buffeting on a sweptback wing with high aspect ratio. To a much lesser degree a Kuchemann fuselage indentation also reduces buffeting, but a wing leading edge extension is ineffective as a means of alleviating buffeting and under some test conditions can even worsen the case. (See Appendix 3).

In a number of instances buffeting at high speeds has been due to the intersection of thin aerodynamic surfaces, the maximum thickness of the wing root lying very close to the maximum body diameter, and to the bad positioning of wing stores relative to the fuselage. This type of buffeting could probably be avoided if more attention were paid to aerodynamic design.

Local buffeting arising from a separation of flow at the tailplane-fin or wing-fuselage junction can be severe, but tufting tests in the wind-tunnel will probably give an indication of this premature breakaway and also show whether any aerodynamic reshaping is necessary.

3.4 Position of tail in wake

One obvious method of reducing the induced buffeting fluctuations on the tailplane is to remove the tailplane from the wing wake by mounting it either high on the fin or low down.

3.5 Dynamic pressure

The primary variables affecting the magnitude of loads are speed and altitude. Data show that $\sqrt{q}$ is probably a better measure of load than the dynamic pressure q for both straight and swept wings both in the stall and shock conditions. This indicates that at a given altitude the loads would be directly proportional to the Mach number or the true airspeed, whereas at a given Mach number (or airspeed) the loads would vary directly as the square root of the density. (See Appendix 2).

3.6 Penetration beyond buffet boundary

In the shock region there is evidence that the buffet intensity varies linearly with penetration beyond the buffet boundary (definition in Appendix 4) for straight and swept-wing aircraft both in the subsonic and transonic regions.

3.7 Other factors affecting the magnitude of buffeting loads

There are indications that the maximum load encountered during buffeting increases with the total duration of time spent in buffeting up to an asymptotic value. In one case from periods of less than one second to periods of four to five seconds, the increase is of the order of 90% but does not appear to be linear.

Also, the method of entry into the stall appears to affect the magnitude of the buffet loads. In one case it is claimed that, compared with abrupt pull-ups, a load alleviation of about 50% is obtained by gradual entry into the stall.

4 POSSIBLE METHODS OF ESTIMATING BUFFET LOADS

4.1 Statistical methods

4.1.1 Semi-statistical method

One approach to the problem of estimating buffeting loads is to collect all the flight test results where excessive buffet loads have been measured, and to see whether these give any indication of the parameters (aerodynamic shape, operating conditions, frequency, etc.) which most affect the buffeting loads. It may then be possible to evolve empirical formulae for estimating buffeting loads based on these parameters.

Since the buffeting phenomenon is very complicated and involves many different parameters this semi-statistical approach is unlikely to give general formulae which can be used for different planforms.

The data obtained on one aircraft may however be of some help to designers when considering buffeting problems on aircraft of similar planform and manoeuvre range. (See Appendix 4).

4.1.2 Power spectral methods

Power spectral methods have been widely used during the past few years in the solution of a variety of problems. The method has been extended to the prediction of buffeting loads on the assumption that buffeting is a phenomenon which is largely random in character. Whether this approach is legitimate needs to be investigated more thoroughly and further work done to check whether the results are reasonable. (See Appendix 5, Section 2). Several formulae for predicting loads have been evolved using the method, (See Appendix 5, Section 3).

4.2 Theoretical methods

Wind tunnel tests have shown that buffeting is dependent fundamentally upon fluctuations of a random nature and is therefore not amenable to a purely theoretical treatment.

4.3 Aerodynamic measurements

Since buffeting is wholly aerodynamic in origin wind tunnel tests may be expected to provide a direct method of estimating buffeting loads. However, in practice, buffeting loads are difficult to measure in a wind tunnel and even more difficult to relate to full scale aircraft. Viscosity and compressibility of the fluid are fundamental parameters for the occurrence of buffeting. Thus the Reynolds number becomes important when comparing wind tunnel and flight tests.

The presence of wind tunnel turbulence often makes it difficult to obtain buffet loads and in some tunnels the turbulence level is so high that it is impossible to obtain even approximate measurements of the loads. No reliable method of correcting the total load for turbulence effects has yet been devised.

The problem of damping has also to be considered in connection with the scaling of wind tunnel model results to the actual aircraft. Flight tests have shown that the damping is primarily aerodynamic and so the damping of the model should be likewise.

With regard to the use of models, flexible models have been mainly used in the past. When they are used the shape of the vibration mode and reduced resonance frequency (see para. 3.2) should be the same for both aircraft and model. This is fairly easy to realise for solid-metal wing models but more difficult when modes such as fuselage torsion have to be considered.

More work is necessary to investigate the fluctuations in the wake of a rigid wing to gain better insight into the wake structure and to see what excitation is in fact applied to a tailplane lying in the wake of a wing and also to measure the pressure fluctuations in the wake over a rigid tailplane. This work may also enable buffeting loads to be calculated for rigid and flexible aircraft although it may be found in practice that the amount of work involved is prohibitive. These results can be checked later by applying the previously measured excitation to the tailplane itself and then measuring the actual loads. This method of finding the relationship between two measurable parameters and then applying analytical methods is likely to be more accurate and successful than merely measuring buffet loads on flexible models.

To develop this approach to the buffeting problem it is essential that the extension of wind tunnel results to the full scale aircraft should be thoroughly checked by flight tests. (See Appendix 3).

5 MEASURING TECHNIQUES

A brief description of the various types of measuring techniques used to obtain the measured flight and wind tunnel results quoted in this paper is given in Appendix 6.

6 CONCLUSIONS

(1) The results show that tail buffeting loads tend to be much more severe than wing buffeting loads for both straight wing and swept-wing aircraft.

(2) On a straight-wing aircraft the maximum tail buffeting loads achieved in the stall, when combined with the balancing and manoeuvring loads may be critical enough to cause a structural failure. Wing buffeting loads have been measured at transonic and supersonic speeds and found to be low but few results are available for tail loads at these speeds.

(3) The buffeting loads on most swept-wing aircraft are appreciably smaller than those on a straight-wing aircraft of comparable size and performance and over the same Mach number range. There is less likelihood of high intensity buffeting at high speeds although even small buffeting loads may result in restrictions being placed on manoeuvres.

(4) The possible occurrence of large buffeting loads needs to be considered in the early design stages of an aircraft. By the time the aircraft is flying it may be too late or too expensive to make the necessary aerodynamic and structural modifications. Evidence seems to indicate that wind tunnel testing would be the most successful way of predicting buffet loads.

(5) In view of the complexity of the buffeting problem, efforts should be made to establish empirical criteria for use in design, and also reliable methods for checking the adequacy of these empirical methods.

(6) Further work is needed to test the validity of the power spectral approach to buffeting problems.

(7) More extensive buffeting flight tests are necessary to confirm theoretical concepts and any methods for predicting buffet loads.

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APPENDIX 1

BUFFETING LOADS MEASURED IN FLIGHT

1 AMERICAN AIRCRAFT

1.1 Straight-wing aircraft

A considerable number of flight test results are available on a straight-wing fighter and a multi-engine jet bomber.

On the fighter the flight tests cover the Mach number range up to $M = 0.8$. The results show that the maximum value of the measured buffeting wing root shear fluctuations is small[1] but the maximum resultant tail-plane load increment is about 45% of the (unfactored) tailplane design load[2], and it is possible, for critical combinations of manoeuvring and buffeting loads to exceed the design load and approach the ultimate load.

The results of flight tests on the multi-engine jet bomber[3,4,5] show that the wing bending moments and shear increments due to buffeting are again small. The maximum total tailplane buffeting load measured was about 24% of the design load, but a buffeting load of 75% of the design load was measured on the elevator.

A report issued by an American aircraft corporation gives details of a number of accidents and incidents to aircraft which are believed to have been caused by excessive buffeting tail loads. In some cases the loads were measured experimentally but in others calculated by a method given in the report, which appears to predict loads, which either correlate fairly well with measured loads or are conservative. Where structural tailplane failures occurred on the F6F-3, P.47B,[7] XP-60D, XF8F-1, subsequent calculations, and in some cases experimental results, showed that under the accident conditions the buffeting loads were high and, in combination with the manoeuvring and balancing loads, could certainly cause a failure.

Few measurements of buffét loads on wing or tailplane have been made at transonic or supersonic speeds. On the scaled X-1 wing, buffet was experienced at $M < 1.0$, but there was no evidence of any buffeting at Mach numbers > 1.0 [8] on this aircraft or on a rocket-propelled straight wing model[9].

1.2 Swept-wing aircraft

In general the buffeting tailplane loads tend to be more severe than those on the wing and buffeting loads on both the wing and tail of a straight-wing aircraft are more severe than those on a swept-wing aircraft. Flight tests on an aircraft[10], with 35° sweepback, in the Mach number range from $M = 0.6$ to $M = 1.03$ showed the buffeting tailplane loads to be only about 30% of those for a comparable straight wing fighter over a similar Mach number and manoeuvre range.

An elevator failure on the F-86 in the high speed buffet region was thought to be due to buffeting as the buffeting load on the elevator was a large percentage of the design strength.

Moderate buffeting was obtained on a 60° delta aircraft, XF-92[11], flying at transonic speeds, peak wing buffeting loads were about 10% of the estimated design load. On the D.558[12,13,14] at supersonic speeds flight test results showed that there was an absence of high intensity buffeting during manoeuvres to high C_L.

On one high speed fighter, flight tests showed that the buffeting loads might be expected to be severe and to allow for this eventuality the tailplane was designed to carry an arbitrarily decided additional load, which was equal to one half of the weight of the aircraft and applied in equal halves on each side, symmetrically in one case and asymmetrically in the other.

2 BRITISH AIRCRAFT

Flight tests on the Tudor 4b showed that the maximum tailplane buffet load in the stall was likely to be about 15% of the tailplane design failing load[15].

Low frequency tail buffeting occurred on a Lancastrian aircraft fitted with Sapphire engines in the outboard nacelles. The intensity of the buffeting appeared to increase with forward speed and was severe enough to warrant the imposition of a speed limitation until the tail vibration could be reduced to an acceptable level. As a result of a special investigation the tail buffeting was considerably reduced, although not completely eliminated, by fitting modified rudders.

Symmetrical tailplane buffeting loads on the Hunter were measured by the R.A.E. Results obtained during pitch-up at 35,000 feet, in the Mach number range from 0•8 to 0•95, showed that the loads were fairly large, some being as much as 20% of the design load.

At transonic speeds, tail buffeting was experienced on the Hunter trainer. Flight measurements led to a substantial increase being made in the size of the fairing behind the cockpit, which did cure the buffeting.

The disengagement of the elevator auto-pilot at high altitude caused a jet aircraft to build up speed rapidly and to reach the never-exceed Mach number and a very high acceleration. During this time very severe buffeting conditions were experienced and as a result, the starboard elevator tip massbalance arm was lost and the tailplane tips cracked.

Severe symmetric tail buffeting was encountered on the first production Vickers Valiant at speeds above about 320 knots E.A.S. Although no actual measurements of the buffeting loads were made, the pilot thought the buffeting might possibly be severe enough at the maximum design speeds, to cause a structural failure and consequently the aircraft was limited in speed until a way was found of alleviating the buffeting. This was eventually done by improving the sealing of the movable tailplane.

Lateral tail buffeting at M = 0•8 and the maximum E.A.S. in the flight envelope i.e. at 25,000 feet , occurred on the same aircraft, but this was reduced to safe limits by fitting vortex generators to the fin-tailplane junction.

Also on the Valiant at high Mach number, high E.A.S. and under excess 'g' conditions aileron-wing buffeting was experienced. On one occasion a failure of the aileron rods occurred which was attributed to wing-aileron flutter under reduced aileron aerodynamic damping. This failure could equally well have been explained by fatigue due to buffeting, and flight measurements showed that the buffeting produced stresses which implied a distinct possibility of fatigue failure. The rods have since been strengthened and vortex generators fitted to the wing.

Large aileron rod loads have been measured on a number of aircraft at high Mach numbers and failures have occurred.

APPENDIX 2

PARAMETERS IMPORTANT IN BUFFETING

1 BUFFETING FREQUENCIES

The predominant buffet frequencies on most straight-wing aircraft correspond to the wing and tail structural primary bending frequencies [2,4,5,16,17,18,19,20] or, when the tail loads are asymmetric, to the fuselage torsional frequency. In some cases however the maximum response of the structure may occur in a higher order mode[21].

On swept-wing aircraft, although in a few instances the buffeting is mainly associated with one fundamental mode[10,17,22], in general one would expect to find a certain amount of coupling between bending and torsion and consequently to find buffeting response in both the fundamental bending and torsion modes[11,12,13,23].

2 SWEEPBACK, THICKNESS-CHORD RATIO AND ASPECT RATIO

A number of reports have shown that decreases in aspect ratio and thickness-chord ratio and increases in sweepback[24,25,26] all tend to alleviate high speed buffeting. It is however difficult to separate the effects of sweepback and thickness-chord ratio as insufficient data are available. However, tests have shown that in the shock region, sweepback can reduce the buffet amplitudes by as much as 30%[10] or 50%[27] as compared with a similar straight-wing aircraft, and it may also delay the onset of buffeting to a higher Mach number[16].

Although results indicate that the maximum thickness-chord ratio is not suitable as a sole criterion of buffeting it does have a powerful effect at high subsonic Mach numbers. A considerable amount of work has been done on straight-wing aircraft in connection with this problem and full-scale aircraft, rocket and wind tunnel models have been used[28]. Buffeting at low lift coefficients may occur on wings with thickness-chord ratio greater than 7%[29] but in general is not expected to occur on thinner wings; although it was encountered on a straight 6% thickness-chord wing mounted symmetrically on a clean body[27], this was thought to be due to the intersection of relatively thin aerodynamic surfaces.

Wind tunnel tests on models, with thickness-chord ratios varying from 2% to 12% show that, at Mach numbers less than 0·6, amplitudes due to buffeting are lowest on the 12% or 8% aerofoils. At Mach numbers greater than 0.75, they are lowest on the 4% aerofoil. There appears to be a limit to the beneficial effect of thickness-chord ratio on buffeting since the buffeting forces are more severe on a 2% than on a 4% aerofoil[22,30]. The 4% aerofoil appears to be fairly successful in improving the buffeting position at high speeds and an improvement might be made in the low speed characteristics with only a slight sacrifice in its superior character at higher speeds by moving the position of maximum thickness forward and by using a larger leading edge radius.

3 PROFILE

It seems possible, on sharp-edged straight wings, that the onset of violent buffeting might be as important a criterion in fixing the maximum usable C_L as the force and moment characteristics. At comparatively low angles of incidence the sharp leading edge can give rise to a large flow separation and to a growth in the amplitude of low frequency pressure oscillations on the wing and in the wake. Tests on a wind tunnel model of a supersonic fighter have shown that it is possible to delay the onset of separation and consequently of the pressure oscillations by means of either leading edge flaps or fairings.

4 POSITION OF TAILPLANE IN THE WAKE

It is desirable from the buffeting point of view to mount the tailplane in such a position that it lies outside the wing wake. The tailplane of the Blackburn naval strike aircraft is mounted high up on the fin to avoid, among other things, buffeting troubles originating from local flow separation on the upper fuselage. On the Republic F.105, it is placed low in relation to the wing to avoid the wing wake.

5 EFFECT OF EXTERNAL BODIES

Unfavourable store locations may cause buffeting where normally it would not be expected to occur. This is illustrated by a series of tests on a rocket-powered fuselage carrying an external store in the Mach number range from 0·7 to 1·4[31]. On the fuselage were four unswept, tail surfaces of 4% thickness-chord ratio.

No buffeting was expected on the basic fuselage and tailplane configuration over the range covered, and none was experienced with the semi-submerged stores. However buffeting was encountered at or near trim conditions on all the models with completely external stores. The transonic buffeting recorded on the tangent-mounted store was about three times as severe as on the store mounted on the 10% thick pylon and about six times as severe as on the store mounted on the 4% pylon. The data indicated that the buffeting at supersonic speeds was induced primarily by mutual interference between body, store and pylon and was aggravated by store-body proximity and pylon thickness. It was thought that the maximum fuselage thickness might have contributed to buffeting but no other store positions were tested to investigate this problem. In another case[32], on a rocket-propelled model where buffeting was encountered at high Mach numbers on a swept tail with thickness-chord ratio of 7%, it was thought to be due to the maximum thickness of the wing root lying very close to the maximum body diameter.

6 DYNAMIC PRESSURE

In the stall region, data have shown that the magnitude of the buffeting loads is affected by speed and altitude and that the square root of the dynamic pressure is probably a better measure of the load than the actual dynamic pressure[1,3,4,33,34]. Results have also shown agreement with the root of the dynamic pressure relationship for swept-back wings at transonic speeds[17].

7 OTHER FACTORS AFFECTING THE SIZE OF BUFFET LOADS

Data obtained from a straight wing fighter aircraft[1] suggested that the maximum load encountered during buffeting increased with the total duration of time spent in buffeting. It is expected that the loads will approach an asymptotic value after a certain period of time.

In this same report, there is an indication that a load alleviation of about 50% might be obtained by a gradual entry into the stall. The physical basis for this alleviation is not yet understood but it may be associated with a less completely developed stall in the slower manoeuvres resulting from a less abrupt flow breakdown. This case should be examined more thoroughly as it may be an important factor in buffeting.

8 EFFECT OF MACH NUMBER AND ANGLE OF INCIDENCE

8.1 Stall buffeting

In the stall region there is some correlation between tail buffet intensity and the angle of incidence[18,35,36].

8.2 Shock buffeting

There are indications that the buffeting intensity varies with lift and Mach number[12,13,22,24,37].

APPENDIX 3

THE USE OF WIND-TUNNEL TESTS IN THE SOLUTION OF BUFFETING PROBLEMS

1 CHARACTERISTICS OF TURBULENCE IN THE WING WAKE

Roshko[38] classifies the periodic wake phenomena behind bluff cylinders into two distinct Reynolds number ranges connected by a transition region. Below $Re \approx 1 \cdot 5 \times 10^2$, classical stable Karman vortex streets are formed, above this value and up to about $Re = 1 \times 10^5$, the periodic shedding is accompanied by irregular or turbulence velocity fluctuations and at higher Reynolds numbers the regular character of the wake disappears and so also do the periodic wake disturbances and the fluctuations in the wake became completely turbulent. Similarly for two dimensional wings it appears that the Karman vortex street may be taken as a first order approximation to the wake at low Reynolds numbers, whereas at high Reynolds numbers the fluctuations are completely random in character.

The non-dimensional reduced frequency $\omega\bar{c}/V$ has been found to be a more useful parameter than the frequency when measuring fluctuations in the wing wake. In the case of a stalled wing where there may be one or more frequencies at which the power spectrum is concentrated, past results show that at angles of incidence less than 17° the reduced frequency will remain nearly a constant[39,40,41].

Considerable difficulty may be experienced in simulating full-scale conditions in wind-tunnels for both low speed and shock-induced flow separation. In the latter case separation tends to be more severe and to occur earlier for turbulent boundary layers and high Reynolds numbers than for laminar boundary layers and moderate Reynolds numbers[42] so that wind tunnel tests with the transition of the boundary layer occurring at moderate Reynolds numbers could give misleadingly optimistic results and it might be necessary to fix the transition artificially.

2 USE OF WIND TUNNELS FOR BUFFET PREDICTION

Wind tunnel work on buffeting problems can be grouped into four main sections, each dealing with a different aspect of the phenomena as follows:-

(1) The determination of buffet boundaries[20,42,43,44].

(2) Measurements of fluctuations in the wing wake. The power spectral representation of the results has been used in America[41].

(3) Measurements of buffet loads on aircraft models and methods of relating them to the full scale aircraft[17,22,33]. Much of this work has been done by Huston and Skopinski and this is discussed in Appendix 5.

(4) The effect of aircraft modifications on buffet loads[45,46].

APPENDIX 4

EMPIRICAL FORMULAE DERIVED FROM STATISTICAL INFORMATION

1 BUFFET BOUNDARIES

One of the most important factors in the study of the buffeting phenomenon is the establishment of the buffet boundary. This is difficult to predict in the early design stages and many attempts have been made to find a relationship between flow changes and the Mach number and lift coefficient at the onset of buffet.

Pearcy[42], Purser[20], Gadeburg and Ziff[43] all agree that trailing edge pressures or related measurements, and, in particular the lift divergence Mach number, can be used for predicting buffet onset on a straight wing aircraft and even on swept-wing aircraft. The lift divergence Mach number, defined by the inflexion point on the curve of the lift coefficient against Mach number for a constant angle of incidence, gives a conservative estimate. From experimental results[43] it appears that an empirical buffet relationship obtained by a method suggested by Outman and Lambert[47] gives the closest approximation to the buffet boundary.

2 CRITERIA FOR ESTIMATING BUFFET LOADS

2.1 An American aircraft corporation has produced an empirical method for predicting buffeting tailplane loads, which is based on an effective incremental tailplane buffet angle of incidence related to the wing angle of incidence. In this theory it is assumed that the buffeting loads caused by fluctuations in the wing wake are much greater than those caused by buffeting originating on the tailplane and therefore the self-induced buffet loads on the tail can be neglected.

This method was used to calculate the buffeting loads on a number of aircraft and it was found that the loads either correlated fairly well with experimental data or were conservative. In the latter case the large loads were thought to be mainly due to the fact that in the calculation, the maximum load factor was used although, in practice, buffeting may occur at a smaller load factor.

2.2 Huston and Skopinski[1] have evolved formulae for the wing and tail loads in the stall condition for a specific aircraft by using regression techniques to analyse flight results. These formulae may have some limited applications. They take into account, the maximum rate of change of the angle of incidence per chord travelled, the square root of the dynamic pressure, the wing fundamental frequency and the duration of time spent in an abrupt stall.

2.3 In the same report[1] formulae are also obtained for the wing and tail buffeting loads in the shock region. These are based on the assumption that penetration beyond the buffet boundary is the primary variable affecting the magnitude of the load. CN_{MAX} is used in the definition of the penetration but this is a difficult value to obtain in the case of most aircraft.

The formula given for the buffeting tail load is as follows:-

$$L_T = QP\sqrt{q}$$

where Q is a constant

P is the penetration beyond the buffet boundary

$$= \frac{CN - CN_{BB}}{CN_{MAX} - CN_{BB}}$$

$CN = \frac{nW}{qS}$

CN_{BB} is CN at the buffet boundary

CN_{MAX} is the maximum value of C_N

A similar expression is applicable for the wing buffeting increment.

APPENDIX 5

POWER SPECTRAL ANALYSIS

1 USE OF POWER SPECTRAL METHODS IN BUFFET ANALYSIS

Reports on the application of power spectral techniques to buffeting problems have been written by Liepmann[34,48,49,50,51,52], and Press who base this theory on the assumption that buffeting is the linear response of an aerodynamically damped elastic system to an aerodynamic excitation, which can be considreed to be a stationary random process. (A stationary function has statistical properties which are independent of time). This aerodynamic excitation, which may be caused by the turbulence in the wake of a wing, can be described by a continuous power spectrum and, as the energy of the fluctuations in the turbulent flow is distributed over a wide frequency range, resonance with the tail or fuselage is unavoidable.

In the first instance, the problem was considered as a one-dimensional stochastic process (i.e. the input was taken to be a random function of time alone) and the response of the system was described by a simple transfer function. The theory has now been extended to cover functions which vary in space and time, i.e. are not uniform along the wing span. Based on these assumptions the characteristic of output, input and the system may be expressed in terms of three related frequency functions as:-

$$\phi_o\ (\omega) = A^2\ (\omega)\ \phi_i\ (\omega)$$

where $\phi_i\ (\omega)$ = frequency content of the input force.

$\phi_o\ (\omega)$ = frequency content of the output

(This may be structural load, displacement velocity, acceleration, etc.)

$A^2\ (\omega)$ = the square of the absolute value of the admittance of the system to a sinusoidal force.

The admittance can be very complex and involve many degrees of freedom. In the case of an unswept wing and tail the spectrum reflects predominantly the response of a single degree of freedom. However, for a swept wing aircraft, where flexure-torsion coupling occurs, it may be necessary to include at least two degrees of freedom, although one degree of freedom may be sufficient to obtain first order effects. An expression for the aerodynamic admittance has been obtained by a generalisation of Sear's results[53] for a wing of finite span.

The exact shape of the turbulent power spectrum has been found in some cases to have a relatively small effect on the root mean square lift of a tail surface located in the wake of the wing. Formulae for predicting the lift assuming isotropic turbulence may give satisfactory results if the turbulence scale is correctly estimated[41].

The power spectral method has been used in a number of instances as follows:-

(1) It was used to correlate flight and wind-tunnel buffeting loads[17] on three aircraft, a straight-wing, a swept-wing and a delta-wing aircraft. The results appear promising and indicate the possibility of making simple

strain-gauge measurements on a wind-tunnel model to predict wing buffet loads on the actual aircraft. They also show that, under certain conditions of lift and Mach number, the wing buffet loads are normally distributed.

(2) On the F.51-D[1,18] buffeting loads were found by power spectral methods and the consistency between these results and flight tests is good enough to suggest an examination of other data on the same basis. The flight results show that whilst, for a representative stall manoeuvre, wing buffeting appears to be a Gaussian random process, the tail loads do not follow the same pattern and, in the shock region under manoeuvring conditions, the loads are neither stationary or Gaussian.

(3) Power spectral methods[22] were used in the analysis of flight tests on two swept-wing fighters, F.86A and D.558-II and wind tunnel tests on straight wing models. A semi-empirical approach for estimating wing buffet loads at transonic speeds was derived which appears to correlate the data between wings of different structural properties and to give a measure of agreement between flight and wind tunnel results.

(4) A further analysis of flight results on the F.86A was made in another report[23], using frequency analysis techniques to determine the nature of the buffeting.

(5) On the F-80A[21], power spectral methods were used in the examination of flight results to determine the effect of dampers on the response of an aircraft structure during buffeting. The damper was fitted to the wing tip and consisted of a weight mounted on a rigid arm attached to the shaft of a rotary-vane-type damping cylinder and supported by a folded cantilever spring.

2 DISCUSSION ON THE POWER SPECTRAL APPROACH

In the power spectral methods it is assumed that buffeting is a phenomenon which is largely random in character and the time histories for the variables can therefore be disregarded. Power spectral analysis therefore is unlikely to furnish very reliable estimates of maximum buffeting loads in flight, although it may be useful for estimating overall buffeting intensity and its relationship with various aerodynamic and structural parameters.

If the buffeting loads have a known distribution then it may be possible to predict the magnitude of the maximum load, but extrapolation over a long time interval can lead to a very large error if the assumed distribution is not correct. The assumption that buffeting loads are normally distributed has been made in a number of reports, but the results from a straight-wing fighter[18] show this is not always true.

Very little information is available on the character and structure of the turbulent flow in the wake of a wing after stall or shock-induced separation has occurred. Although the turbulence has been measured in wind tunnel tests and, in some cases, the power spectra have been calculated, most of the tests were carried out at low Reynolds numbers and it is known that these results may not necessarily apply at higher Reynolds numbers[38].

In addition to measuring the power spectrum of the turbulence, it is necessary to know the response of the aircraft, represented by an "admittance function", in order to estimate the power spectrum of the buffet load. The admittance may be very complex in form and it may be difficult to apply the results obtained from one aircraft to another with widely different characteristics such as configuration and stability. Experimental verification of the theoretical determination of aircraft responses over different ranges will be needed to determine usable frequency response functions. This is especially important in view of the difficulty of instrumenting and obtaining accurate wind tunnel results under turbulent conditions.

3 BUFFET CRITERIA BASED ON POWER SPECTRAL METHODS

3.1 Power spectral methods were used on a simplified wing buffeting model[1], with one degree of freedom - fundamental wing bending - to obtain an expression for the wing buffeting load increment obtained in a stall. The formula relates the maximum wing buffeting load in a stall of given duration to the geometric, structural and aerodynamic characteristics of the model.

The experimental flight results for the full-scale aircraft in the stall condition are sufficiently consistent with the results of this semi-analytical method to suggest that the buffeting of other aircraft should be examined on the same basis.

3.2 Huston[17] has extended the use of power spectral methods to the correlation of flight and wind tunnel buffeting loads on a wing and has evolved a semi-empirical formula relating the root mean square bending moment of the wing buffeting loads to a number of parameters. These parameters can be grouped into several sections. The first section includes the principal physical characteristics of the wing such as mass, natural frequency, average chord and span. In the second section is a factor which expresses the ratio of the effective masses, areas and moment arms pertinent to the fundamental bending mode to the actual values. The operating conditions involving speed and altitude are represented by the square root of the dynamic pressure. The final section represents both the magnitude of the input spectrum at the given value of reduced frequency and also the effective slope of the lift curve for bending oscillations at the same value of the reduced frequency.

The results obtained using this formula indicate that there is a possibility that simple strain-gauge measurements made on a wind tunnel model may be used quantitatively to predict the wind buffet loads on the aircraft.

3.3 The analytical expression in the previous sub-section has been used as a basis for finding a similar expression for the buffeting loads at transonic speeds[22], assuming that buffet loads at transonic speeds have been shown to vary linearly with penetration above the buffet boundary and the effect of the wing thickness.

APPENDIX 6

INSTRUMENTATION

This appendix gives a list of the various types of measurements made during buffeting flight and wing tunnel tests.

1 FLIGHT TESTS

1.1 Strain gauges

Buffeting shears and bending moments are mainly obtained from strain gauge measurements[1,2,16,20,22,43]. The gauges are wired in 4-active-arm bridges and attached near the roots of the principal structural members. In one case the error in the readings was claimed to be of the order of ±5%.

1.2 Pressure measurements

The differential pressures between the upper and lower surfaces of the wing or tail surfaces can be measured by orifices installed opposite each other[35].

One report describes two methods of obtaining the power spectra of the buffeting load intensities from pressure measurements used when measuring buffeting loads on external tanks[23].

2 WIND TUNNEL TESTS

2.1 Strain gauge measurements

Power spectra of the bending moments can be obtained by recording the strain-gauge input on magnetic tape and later analysing the tape recorder[33,44], or they can be obtained, at the time of the test, by means of a thermocouple meter, which is sensitive to the mean square of a random electrical current. An instrument has been developed which measures the peak buffet loads in successive ten second intervals over a period of several minutes. This is basically a condenser charged through a diode that conducts the current only during a peak which is higher than any previous peak, thus the change on the condenser is a measure of the highest peak.

2.2 Pressure measurements

Pressure pulsations[28] on a wind tunnel model are obtained by miniature electrical induction pressure cells which are mounted on the end plate along the model chord line and are connected to the pressure orifice in the models. Although the calibration factor differs for each cell because small differences exist in the sensitivity of the cells, the pressure response may still be accurate to within ±4% of a constant value over a given range of frequencies.

Pressure fluctuations have been measured in the wake of a two-dimensional wing with a wake-survey instrument attached to a horizontal sting supported by a vertical strut placed some distance behind the trailing edge[54].

Fluctuating total pressures in the wake of a wing can also be measured with rakes. The error in the results may be of the order of ±5%.

2.3 Displacement measurements

On very small models it is not always feasible to measure forces by means of pressure pick-ups and it may be easier to obtain them from displacement measurements. In one case[55], where the power spectra of the lift and turbulent fluctuations were required, the displacement pick-up was a small differential transformer. An excitor current supplied to the transformer by a crystal oscillator, was modulated by an iron core, which moved with the aerofoil.

2.4 Hot wire measurements

Hot wire techniques are often used for measuring velocity fluctuations in turbulent flow[41]. The difference between the true and indicated root mean square is claimed to be less than 10%.

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Comparisons of wind tunnel with flight test results suggest that it may be feasible to predict buffet loads from wind tunnel tests although further research in this field is needed.

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