



An introduction to aircraft buffet and buffeting

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AN INTRODUCTION TO AIRCRAFT BUFFET AND BUFFETING

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AN INTRODUCTION TO AIRCRAFT BUFFET AND BUFFETING

SUMMARY

Buffet is defined as the aerodynamic excitation due to separated flows and buffeting as the corresponding uncoupled structural response. Buffeting is essentially a dynamic phenomenon and hence both buffet onset and the severity of buffeting are best established by dynamic methods.

Types of flow separation occurring on aerofoils and wings are discussed with reference to pressure distributions, steady force data and unsteady measurements. These are used to indicate effects of incidence and Mach number on the growth of separated flow and buffet. Some techniques for the detection of buffet onset are considered and some general advice is given on their use.

A section of the Item relates to the preparation of a wind-tunnel model for dynamic buffeting tests and the extrapolation of wind-tunnel measurements to flight. Some wind-tunnel buffeting measurements on a systematic series of wings are reviewed, to illustrate the experimental problems, to show the effects of design variations and to provide a datum for prediction methods for the onset of buffeting.

Brief notes are given also on buffeting due to other components and the methods available to alleviate buffeting.

Predictions of buffet are dealt with for two types of separated two-dimensional flows – bubbles at subsonic speeds and periodic pressure fluctuations due to shock oscillations at transonic speeds.

1. NOTATION AND UNITS

		<i>SI</i>	<i>British</i>
A	aspect ratio (gross wing)		
b	wing span	m	ft
C_A	axial force coefficient		
C_B	rms wing-root strain signal/kinetic pressure (see Section 5.2)	$V \text{ m}^2/\text{N}$	$V \text{ ft}^2/\text{lbf}$
C'_B	buffeting coefficient (see Equation (5.6))		
C''_B	corrected buffeting coefficient (see Equation (5.7))		
C_D	drag coefficient		
C_L	lift coefficient		
C_{Lb}	lift coefficient at buffet onset		
C_l	rolling moment coefficient		

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C_m	two-dimensional pitching moment about quarter chord/ qc^2		
C_N	normal force coefficient		
C_{NL}	local normal force coefficient		
C_p	pressure coefficient		
C_{pT}	trailing-edge pressure coefficient		
c	chord	m	ft
$\bar{c}$	standard (geometric) mean chord	m	ft
c_t	wing tip chord	m	ft
c_0	centre-line chord	m	ft
f	frequency	Hz	Hz
f_1	wing fundamental bending frequency	Hz	Hz
Δf	analyser bandwidth	Hz	Hz
$\sqrt{nF(n)}$	level of pressure fluctuations (see Equation (5.3))		
$\sqrt{nG(n)}$	buffet excitation parameter (see Equation (5.1))		
K	factor in Equation (5.5)	V m ² /N	V ft ² /lbf
L	reference length for frequency parameter ($L = c, \bar{c}, l$ or w)	m	ft
l	bubble length	m	ft
M	Mach number		
m	generalised mass in Equation (5.1) (see Reference 24)	kg	slug
n	frequency parameter, fL/U		
p	pressure	N/m ²	lbf/ft ²
$\bar{p}$	rms pressure fluctuations	N/m ²	lbf/ft ²
Δp	pressure fluctuation in frequency band Δf at frequency f	N/m ²	lbf/ft ²
q	kinetic pressure	N/m ²	lbf/ft ²
R	Reynolds number based on reference chord $\bar{c}$		
R_i	instantaneous resistance of strain gauge i	Ω	Ω

S	area of planform (gross wing)	m^2	ft^2
S_n	area of planform (net wing)	m^2	ft^2
t	thickness	m	ft
U	free-stream velocity	m/s	ft/s
V	voltage applied to Wheatstone bridge circuit	V	V
ΔV	output signal from Wheatstone bridge circuit	V	V
w	wind-tunnel width	m	ft
x	streamwise distance from bubble separation point	m	ft
x_s	chordwise location of shock wave	m	ft
x_0	axial distance of leading edge of c_0 from nose tip (see Figure 11)	m	ft
z	wing tip deflection	m	ft
$\ddot{z}$	rms wing tip acceleration (see Equation (5.1))	m/s^2	ft/s^2
α	incidence	degree	degree
α_f	foreplane effective incidence	degree	degree
α_w	effective angle of incidence of wing	degree	degree
α_{wb}	effective angle of incidence of wing at buffet onset	degree	degree
ε	analyser band width ratio, $\Delta f/f$		
ζ	ratio of total damping to the critical (see Equation (5.1))		
η	spanwise distance from centre line as fraction of semi-span		
η_f	foreplane setting	degree	degree
Λ_0	sweep of leading edge	degree	degree
$\Lambda_{1/4}$	sweep of quarter-chord line	degree	degree

Subscript

rms root mean square

2. INTRODUCTION

The occurrence of separated flow over limited surface areas of an aircraft can provide a source of energy to sustain vibrations of the airframe. These may take the form of undesirable rigid body motions that adversely affect performance or handling characteristics, but do not constitute buffeting. The present Item concerns the situation in which either the angle of attack or the Mach number is large enough to induce flow separation (see Section 3) which gives rise to vibrations in the flexible modes of the structure. Buffeting spectra contain pronounced peaks at structural frequencies low enough to influence the ride qualities of the aircraft. Although the onset of buffeting does not impose a strict limit to the flight envelope, the pilot would then become aware that serious problems of control or excessive steady or fatigue loads could result from further increase in angle of attack or Mach number. At low air speeds onset of buffet can be used as a stall warning.

Buffeting on bodies and structures in non-aeronautical applications is discussed in Item No. 77032 (Reference 24).

2.1 Scope of the Item

The purpose of this Item is to provide a general introduction to the subject of aircraft buffet and buffeting. The Item, which is largely illustrative, aims to give an insight into some aspects of this most complex and potentially hazardous phenomenon. The flow separations on aerofoils and wings are discussed in Section 3 to indicate the possible effects of Mach number and incidence on the occurrence and growth of buffet. Currently available methods for the assessment of buffet onset (Section 4) and the severity of buffeting on wings (Section 5) are discussed and advice is given on the optimum usage of nominally rigid wind-tunnel models for buffeting tests. In particular, the use of dynamic measurement and analysis techniques is encouraged. Some general effects of wing design variations on the onset and severity of buffeting are illustrated in Section 6 by means of a review of results from tests on a systematic series of wings. Although the Item is largely concerned with wing buffeting due to separations on the wing, it also acknowledges that due to flow interference and flow separation on other components such as control surfaces, high-lift devices and externally-mounted stores (Section 7). Some devices for the alleviation of buffeting are briefly considered in Section 8, and the two special cases of buffet for which the excitation may be predicted are discussed in Section 9.

2.2 General Considerations

It is essential to accept and use consistent definitions.

Buffet is defined as the excitation given to a structure by separated flows. The buffet excitation is characterised by a total broadband rms pressure level, $\bar{p}$, (generally represented in terms of $\bar{p}/q$) and a spectrum function (generally represented as $\sqrt{nF(n)}$).

The excitation at a point may be generated by a local separation, by an upstream separation (e.g. when a tailplane is immersed in a separated wake from a wing) or a downstream separation (e.g. when a rear fuselage is excited by separations on the afterbody). The buffet excitation normally covers a wide range of frequencies²⁰, and is random in character. However, in certain separated flows the excitation may be confined to a single frequency and be periodic rather than random, e.g. the vortex wake shed from circular cylinders at sub-critical Reynolds numbers³⁵ or the shock/wake oscillation on rigid biconvex aerofoils at transonic speeds^{28, 29}.

Buffeting is defined as the response of the structure to the buffet excitation. The structure acts as a selective filter and may respond both in its main structural modes (often in the first bending and torsional modes) or in local panel modes, which are of higher frequencies. The response of a structure leaves the buffet excitation essentially unaltered. Buffeting thus represents an uncoupled response in contrast to the coupled response observed in single degree of freedom flutter or buzz (Reference 11).

With regard to aircraft performance, the requirements of transport and combat aircraft are different and typical examples are shown in Figure 1. Transport aircraft are designed to cruise below the buffet onset boundary. It is generally accepted, but not required, that for transport aircraft during cruising flight a manoeuvre load factor of at least 1.3g must be available without the occurrence of buffeting. Buffet onset is determined in turning flight manoeuvres and is sometimes defined as being a vibration of more than 0.2g peak-to-peak measured at the pilot's seat. A severe gust (which occurs infrequently) may take a transport aircraft above the buffet boundary for a short period. This rare event must not create any structural or control problems and is generally more serious for the steady loads than for the fatigue loads. In contrast, combat aircraft cruise much further below the buffet onset boundary but will manoeuvre frequently well above it. Hence for combat aircraft the buffeting loads may be significant with respect to the fatigue life of the structure.

3. FLOW SEPARATIONS

Some familiar types of flow separation¹⁴ encountered in or around engineered structures are shown in Figure 2, taken from Reference 20. These are quasi two-dimensional bubble separations which can be modelled and the associated pressure fluctuations predicted, Section 9.1. Surface discontinuities causing such separations should be avoided by careful design. However, aircraft performance is also influenced by the increase of drag and buffeting arising from the separation of a boundary layer from an essentially smoothly-contoured lifting surface. Because of the wide variation of Mach number and angle of attack, flow separation on combat aircraft wings can be expected in certain regions of the flight envelope. In manoeuvring flight a combat wing could exhibit a complex, changing pattern of attached, separated and vortex flows across its span. The management of separated flows and minimisation of buffet require significant design effort⁶.

Even for aerofoil sections the nature of flow separation is complex. Figure 3 illustrates several different characteristics encountered in the flow over the upper surface of aerofoils as incidence is increased for a range of subsonic speeds^{12, 17}. In producing high maximum lift at low speed a strong adverse pressure gradient is generated well forward on the section which can separate the boundary layer (possibly still laminar) as a bubble close to the leading edge. The bubble itself is a source of buffet and circumstances can cause a sudden expansion of the bubble, creating a wide unsteady wake, and rapid increase of buffet (Cases 1 and 2 of Figure 3). In practice excessively high suction on the leading edge could be relieved by introducing camber (perhaps in the form of nose droop) or providing a leading-edge device. In that case, the initial buffet would arise from the growth of separation spreading forward from the aerofoil trailing edge (Case 3).

In general at higher speed (Cases 4 to 7) a region of supersonic flow will develop on the upper surface of the aerofoil, terminated by a shock wave. With increasing incidence and/or Mach number the shock wave moves rearwards until the pressure rise through the shock is sufficient to cause the boundary layer to separate at the foot of the shock. Initially, this shock-induced separation will form as a closed bubble with a re-attachment a short distance downstream from the shock wave. At this stage there may be no trailing-edge separation (Case 4); or a trailing-edge separation could form as a result of the shock-induced separation (Case 5); or a trailing-edge separation may be present prior to the shock-induced separation onset (Cases 6 and 7). All these cases of breakdown of attached flow involve flow unsteadiness and pressure fluctuations. A method of prediction for such cases based on correlations involving features of shock-induced separations is presented in Reference 32.

In many respects the appearance of flow separation on a three-dimensional wing is analogous to the two-dimensional situation, provided that the sweep is modest and the wing is of moderate to high aspect ratio. The wind-tunnel results presented in Figures 4a and 4b show the typical development and breakdown of pressure distributions measured at mid-semi-span on the upper surface of a wing with 25° sweepback. The changes in character of the wing stall are clearly revealed for a range of four Mach numbers. Also shown are the variations of the local trailing-edge pressure with incidence, integrated normal force coefficient, overall lift coefficient (a balance measurement), and wing buffet parameter (derived from the rms response of a strain-gauge bridge recording unsteady wing-root bending moment).

As M increases through the design Mach number, M_3 , in Figure 4b the pressure distributions indicate that:

- At M_1
(typically
 $M_3 - 0.25$)
 - Separation appears first at the trailing edge and grows steadily with incidence. Local and overall lift-curve slopes show a steady decrease from the linear. Buffet output rises steeply only above $\alpha = 12^\circ$ when the leading-edge suction peak starts to fall (analogous to Case 3 of Figure 3).
- At M_2
(typically
 $M_3 - 0.10$)
 - Here the shock has moved back from the leading edge and induces a separation above $\alpha = 9^\circ$. The separation region is quite pronounced by $\alpha = 11^\circ$ when trailing-edge pressure divergence is just imminent. The breakdown is then severe causing a significant loss of local lift, reflected in the overall lift curve (Figure 4a), and a rapid growth of buffet (analogous to Case 5).
- At M_3
(around
design Mach
number)
 - A significant extent of supercritical flow is now apparent with a rearward shock movement up to $\alpha = 7^\circ$. Under the action of the shock-induced bubble then created, the supercritical region starts to collapse forward, and does so more rapidly, producing increased buffet when the bubble has spread to merge with the trailing-edge separation above $\alpha = 8^\circ$. Note that leading-edge suction continue to rise for a margin of incidence beyond the first separation growth (analogous to Case 5).
- At M_4
(typically
 $M_3 + 0.05$)
 - Increased Mach number produces a further aft shock wave but causes separation at a lower incidence, above $\alpha = 4^\circ$. Overall lift curve (Figure 4a) does not monitor so clearly the local separation conditions at higher Mach number (analogous to Case 4).

In the case shown here the measured parameters present a reasonably coherent representation of the flow situations. Without the pressure information, preferably supplemented by surface flow visualisations, a proper understanding of the flow is very difficult. A full array of static pressure tubes is not always installed in wind-tunnel models. However, in analysing results to determine the origins of separation on a wing and hence buffet, great help is provided by pressures derived from a few static tubes in the leading-edge and particularly trailing-edge regions of the wing, preferably spaced along the whole semi-span.

For any particular configuration the characteristics of the wing buffet variation with increasing incidence, at a given Mach number, will depend upon:

- (i) the region of wing first causing separation,
 - (ii) the type of local separation produced initially,
 - (iii) the stage and rate at which a trailing-edge separation growth occurs,
 - (iv) the manner in which the separation spreads across the wing,
 - (v) the stage at which suction peaks are lost locally at the leading edge,
 - (vi) the tendency for the separated regions to form part-span vortex sheets,
- and
- (vii) any tendency to vortex breakdown.

At a given Mach number, with increasing incidence, the exact moment that the boundary layer separates somewhere on a lifting surface is clearly difficult to predict. The dominant factors will be the character of the adverse gradient in the pressure distribution, the local state of the boundary layer (*i.e.* laminar or turbulent) and its momentum thickness. In particular situations Reynolds number can have an important influence on the onset and subsequent growth of the separated flow, and therefore the buffet excitation. Whenever possible, wind-tunnel tests should be conducted over a range of Reynolds number, and the effects of transition-fixing techniques should be carefully investigated. The confident extrapolation of experimentally derived aerodynamic parameters to full-scale flight conditions presents a continuing problem^{12, 23, 40}.

The determination of the growth of buffet is complicated by the difficulty in predicting the type and progression of the flow separation. With low aspect ratio wings at high subsonic Mach numbers three-dimensional effects are strong, and the classic three-shock wave pattern dominates⁵. Separation and buffet onset are usually initiated by the strength of the outboard shock wave near the wing tip.

4. BUFFET ONSET

The prediction of buffet and the consequent buffeting is essentially a problem in unsteady flow. Hence, ideally, methods of prediction (theoretical, empirical and experimental) should be essentially dynamic in character. This remark holds with particular force for buffet onset. The condition for initial flow separation (which can sometimes be predicted from steady aerodynamics) may not always correspond with buffet onset (although it often does). A very small separation will give excitation only at very high frequencies without significant structural response, whereas a larger area of flow separation is required to give significant excitation in, say, the wing first bending mode.

Unfortunately no theoretical method is yet available to predict the random excitation normally characteristic of buffet onset. Hence for wings the ideal procedure is to infer buffet onset from wind-tunnel measurements of unsteady wing-root strain, as described in Section 5. Measurements of unsteady wing-root strain should be regarded as an essential complement to the measurement of steady force coefficients, even on nominally rigid wind-tunnel models. However, such dynamic measurements are frequently omitted. Instead, attempts are made to infer buffet onset from steady measurements, the measurement of trailing-edge pressures (Reference 7) for example. The point at which separation is first felt in the boundary-layer flow at the trailing edge is usually indicated by a marked divergence as the mean static pressure varies with incidence or Mach number (Figure 5b). However, this may be misleading in some cases. For example, on thin wings with sharp leading edges and low sweep, leading-edge flow separation gives buffet onset and is followed initially by reattachment (say at 5 per cent chord). Further increases in the angle of incidence extend the bubble progressively towards the trailing edge as the severity of buffeting increases. The buffet severity reaches a maximum as the reattachment point reaches the trailing edge, and the trailing-edge pressure diverges. This has been observed in both wind-tunnel and flight experiments¹⁰. On the basis of Reference 22 the large variety of observations that are used to infer buffet onset both from wind-tunnel tests and flight are shown in Figure 5. Most of the techniques for buffet onset in Figure 5 are based on steady measurements. However, it should be pointed out these are approximate methods which will not always give satisfactory results for all configurations. Therefore, it is advisable that as many as possible of these techniques be employed and buffet onset assessed as a matter of cautious judgement. It should also be noted that where pilot opinion is used to identify buffet onset in flight tests, the results will be affected by the location of the pilot relative to the nodal points in the mode of vibration of the airframe.

5. WING BUFFETING

The measurement of unsteady wing-root strain or wing-tip acceleration is recommended as the standard method for the prediction of wing buffeting from wind-tunnel tests.

The notes that follow outline the preparation of the model, the test procedure, the method of analysis and the possible extrapolation of the wind-tunnel measurements to full-scale flight. Similar techniques may be applied to measure the buffeting on other aerodynamic surfaces such as foreplanes, tailplanes and fins.

5.1 Experimental Techniques

Buffeting measurements may be made on nominally rigid wind-tunnel models (made of steel or aluminium alloy) or on flutter models. It is an advantage to use aluminium alloy or flutter models because there may be significant aerodynamic damping in the total damping coefficient and thus such models more correctly simulate conditions in full-scale flight. Structural damping should be kept to a minimum and remain constant with wing amplitude, for example, by the use of a model of one-piece construction.

Ideally a complete model should be selected for buffeting tests, so that both symmetric and antisymmetric responses can be measured. If a half model is used, only symmetric responses can be measured.

Four strain gauges² should be applied on each of the wings and wired in two Wheatstone bridge circuits (Figure 6a) according to Figures 6b and 6c so that one measures the sum and the other the difference of the port and starboard bending moments. The bridge signal giving the sum of the bending moments gives the symmetric response (Figure 6b), whereas the bridge signal giving the difference between the bending moments gives the antisymmetric response (Figure 6c).

The common practice of providing four gauges on one wing of a complete model is not recommended because the signals are additive from both symmetric and antisymmetric modes (Figure 6d). For each model and every mode of interest a dynamic calibration must be established between the rms bridge output signal (represented by $(\Delta V)_{\text{rms}}/V$ and the rms wing-tip acceleration, $\ddot{z}$. These calibrations are essential because of variations in mode shape, gauge factors and gauge alignment.

Wind-off ground resonance tests prior to the wind-on tests are highly desirable, if not essential, and two important modes should be identified in such tests:

- (i) the rigid-body roll mode (which gives a response signal predominantly antisymmetric),
- and (ii) the wing first bending mode (which gives a response signal predominantly symmetric).

For both modes the generalised mass, m , must be determined either by calculation or by noting the change of frequency produced by the addition of small masses. In addition it is helpful to determine the wind-off structural damping in both modes and to establish whether these quantities have any significant variation with the response amplitude. Variations in structural damping due to response amplitude or wing lift are undesirable, because it will then be difficult to extract the contribution of the aerodynamic damping from the total damping measured with the wind on (see Section 5.3).

Buffeting is measured as output from the strain gauge bridges in volts. With reference length taken as $L = \bar{c}$, the buffet excitation parameter in any mode is given by the relation¹⁸

$$\sqrt{nG(n)} = \frac{2}{\sqrt{\pi}} \frac{m\ddot{z}}{qS_n} \zeta^{1/2}, \quad (5.1)$$

where $\ddot{z}$ = rms wing-tip acceleration in mode,

q = kinetic pressure,

S_n = wing area (net),

ζ = ratio of total damping to the critical*,

and m = generalised mass in the mode shape relative to the tip (see Reference 24 for definition).

* For a discussion of critical damping see Section 8 of Item No. 77032 (Reference 24).

Ideally the response signals will be measured in a pressurised conventional wind-tunnel at constant Mach number (M) at two or more kinetic pressures (q), and therefore two or more Reynolds numbers (R). The tests should be made with suitably fixed transition, and they should cover an adequate range of aerodynamic parameters likely to influence wing buffeting.

5.2 Analysis of Measurements

The rms responses in both modes will be plotted as functions of the angle of incidence at each kinetic pressure. The point at which the signal level increases above the level due to ambient tunnel unsteadiness marks the point of buffet onset (Figure 6e). Generally buffet onset will occur somewhat earlier in the higher frequency, wing first bending mode than for the lower frequency, rigid body mode. This is because the initial, small-scale, separations create high frequency buffet excitation rather than low frequency excitation. While making the measurements of z , in order to calculate m , $\ddot{z}$ and ζ , it is essential to use a sufficiently wide bandwidth (ε) for the measurements, while excluding other modes. For a wind-tunnel model ζ is typically between 0.01 and 0.03 so that $\varepsilon = 0.1$ is adequate (*i.e.* 10 per cent bandwidth). For an aircraft ζ is typically between 0.05 and 0.10 so that $\varepsilon = 0.2$ is adequate (*i.e.* 20 per cent bandwidth).

A few selected signals should be recorded on magnetic tape, so that accurate values of the total wind-on damping ratio, ζ , can be determined by standard techniques (such as the measurement of the half-power point or the 'random-dec' method described in References 3 and 27). Thus knowing m , $\ddot{z}$, q , S_n and ζ the buffet excitation parameter may be calculated according to Equation (5.1).

Experience on a wide range of configurations³¹ covering combat aircraft and slender wings (both in wind-tunnel and flight tests) suggests the following criteria for buffeting in the wing first bending mode, based on reference length $L = \bar{c}$.

Buffeting Criteria of Reference 31

Level of $\sqrt{nG(n)}$	Buffeting Criterion
0.00075	Light
0.00150	Moderate
0.00300	Heavy

Occasionally levels of $\sqrt{nG(n)}$ higher than 0.0030 will be encountered. Such high levels are indicative of:

- (i) a bi-stable flow separation,
 - (ii) transonic flow attachment at the leading edge,
- and (iii) some kind of aerodynamic resonance.

Manifestly, any of these conditions is undesirable and would deserve further investigation.

The buffeting criteria given earlier are absolute coefficients, but their derivation requires careful measurements of m , $\ddot{z}$ and ζ . This may not be possible, in which case for comparative wind-tunnel tests (say, when differing wing designs are being evaluated) the level of flow unsteadiness at the frequency of interest may provide a scale of the severity of buffeting, to be related with the measured model response. This method is based on Equation (5.1) and a number of carefully specified assumptions described in Reference 16.

The basic hypothesis is that the low-level response of the model wing to the unsteadiness in the air stream before the onset of significant flow separations on the model can be linearly related to the small-scale tunnel unsteadiness and that the tunnel unsteadiness does not interfere with the development of the flow separations.

At any angle of incidence above buffet onset the wing responds to both the base-level tunnel unsteadiness and the buffet pressure fluctuations. If it is assumed that the same linear relationship between the wing response and the tunnel unsteadiness applies as between the wing response and the buffet pressures, model response is then a direct measure of the buffet pressures and may be calibrated from its response to the known tunnel unsteadiness. If this hypothesis holds, then curves of unsteady wing-root strain (model response) against angle of incidence can be transformed into curves showing the variation of equivalent excitation or buffeting coefficients on the model. The corresponding excitation below buffet onset is the tunnel unsteadiness function, $\sqrt{nF(n)}$, at the wing fundamental bending frequency, f_1 .

The tunnel unsteadiness $\sqrt{nF(n)}$ is defined (Reference 4) so that the total mean-square pressure fluctuation coefficient is given by

$$\bar{p}^2/q^2 = \int_{-\infty}^{\infty} nF(n)d(\log_e n), \quad (5.2)$$

where $n = f_1 w/U$,

$w =$ tunnel width,

$U =$ free-stream velocity,

and $F(n) =$ contribution to $\bar{p}^2/q^2$ in a frequency band Δf .

The tunnel unsteadiness at the wing fundamental frequency, f_1 , required for this analysis is

$$\sqrt{nF(n)} = \Delta p/(q\varepsilon^{1/2}), \quad (5.3)$$

where $\Delta p =$ pressure fluctuation in a frequency band Δf ,

$q = \frac{1}{2}\rho U^2$,

and $\varepsilon =$ analyser bandwidth ratio, $\Delta f/f_1$.

Figure 7a shows a typical curve of unsteady wing-root strain at the wing fundamental frequency, f_1 , plotted against angle of incidence (taken from Reference 8). The flow is assumed to be insensitive to changes in Reynolds number, and the total damping of the wing fundamental mode is regarded as constant. Then

$$(\text{wing-root strain signal})/q = C_B(M, \alpha), \quad (5.4)$$

where $C_B(M, \alpha)$ is a dimensional function which is independent of q when M and α are given. Before the onset of flow separations on the model, most of the curves in Reference 8 and results from other tests¹⁵ show that C_B is also independent of α . This is the portion of the model response caused by the tunnel unsteadiness, $\sqrt{nF(n)}$, at the appropriate Mach number and the same frequency, f_1 , and so it is possible to write

$$C_B(M, 0) = K\sqrt{nF(n)}, \quad (5.5)$$

and then

$$C_B'(M, 0) = \frac{1}{K} C_B(M, 0) = \sqrt{nF(n)}, \quad (5.6)$$

where $C_B'(M, 0)$ is dimensionless and $1/K$ is a scaling factor.

This scaling factor is different for every model and will depend on the mass and stiffness distribution of the model, the sensitivity of the strain gauges and also the total damping in the fundamental mode. It is not necessary to assume the same scaling factor $1/K$ for all Mach numbers, but if so, the dimensionless model-response $C_B'(M, 0)$ can be directly compared to the tunnel unsteadiness $\sqrt{nF(n)}$. There may be some variation of $1/K$ with M in the wind tunnel, but it is often convenient to use a fixed value to be applied to C_B for all Mach numbers. If the same scaling factor $1/K$ is also applied to the coefficients $C_B(M, \alpha)$ above buffet onset, curves of C_B' against α are obtained for a fixed M , and a typical example is shown in Figure 7b. The level of C_B' at $\alpha = 0$ represents the tunnel unsteadiness and the model response to that unsteadiness. The subsequent increase in C_B' as the angle of incidence increases gives a measure of the integrated pressure fluctuations arising from the wing buffet and of the model response to this excitation. Having used the tunnel unsteadiness, $\sqrt{nF(n)}$, to establish a datum buffeting scale, this signal must now be subtracted to estimate the buffeting level in the absence of tunnel unsteadiness. Thus a corrected buffeting coefficient can now be calculated by the formula

$$C_B''(M, \alpha) = \sqrt{C_B'(M, \alpha)^2 - C_B'(M, 0)^2}. \quad (5.7)$$

The angle of incidence at which $C_B''(M, \alpha)$ first differs from zero is buffet onset. Buffeting coefficients are then readily obtained as functions of Mach number and angle of incidence or lift coefficient. Comparisons of the contours of the corrected buffeting coefficient, C_B'' , of nine aircraft models with full-scale flight-test data¹⁶ suggest the following semi-empirical criteria for the severity of wing buffeting.

Buffeting Criteria of Reference 16

Level of C_B''	Buffeting Criterion
0.004	Light
0.008	Moderate
0.016	Heavy

In practical reporting of experience in flight these three descriptive levels of buffeting are insufficient. To achieve a satisfactory consistency between pilots the following buffeting rating system has been used for combat aircraft.