Analysis and Correlation of Data on Pressure Fluctuations in Separated Flow

DENNIS G. MABEY*
Royal Aircraft Establishment, Bedford, England

The surface pressure fluctuations caused by bubbles at subsonic speeds are described and related with the mean pressure within the bubble and the development of the mixing layer. The pressure fluctuations caused by bubbles increase gradually from the separation line, reach a maximum near the reattachment line and then decrease gradually downstream of the reattachment line. Spectra of the pressure fluctuations near the reattachment line are similar for bubbles caused by leading-edge separation on wings, by forward facing steps, by rearward facing steps, by sudden enlargements in pipes and by cavities, if all the spectra are expressed in terms of a frequency parameter based on the bubble length. These observations should give a fairly good preliminary design method for evaluating fluctuating pressures.

Nomenclature

C = chord of wing
D_0,D_1 = diameters of pipe upstream and downstream of a sudden expansion
f = frequency (Hz)
$F(n)$ = contribution to $\langle p^2\rangle/q^2$ in frequency band Δf
h = height of projection
H = depth/length ratio of cavity
L = bubble length
M = Mach number
$n=fL/V$ = frequency parameter
$\langle p^2\rangle, \langle p\rangle$ = mean square and rms pressure fluctuation
$q=\frac{1}{2}\rho V^2$ = kinetic pressure
U_1,U_2 = downstream and upstream velocities on either side of a shear layer
V = freestream velocity
X = position of transducer downstream of separation
ε = analyser bandwidth ratio $\Delta f/f$
ρ = freestream density

Introduction

THIS paper summarizes some measurements of the low-frequency pressure fluctuations caused by bubbles at subsonic speeds and attempts to relate these pressure fluctuations qualitatively with the mean flow within the bubble.

Many different types of bubble cause broadly similar pressure fluctuations, both with regard to the rms levels and the spectra. The first type is the leading-edge bubble discussed by Tani[1] and Crabtree[2] which is formed by a laminar separation and a turbulent reattachment. Bubbles of this type have been observed in flight on wings with very sharp leading edges.[3,4] The other types of bubble have boundary layers which are generally turbulent at separation and reattachment. These bubbles are formed upstream of steps or downstream of steps,[5,6] or downstream of spoilers,[5,7,8] or downstream of a sudden enlargement in a pipe,[9] or within cavities.[10]

Mean Flow Patterns and Pressure Fluctuations Caused by Bubbles

The model of Norbury and Crabtree[11] may used to describe the time-average features of the bubble flow and to infer the probable character of the unsteady pressure fluctuations at low frequencies (Fig. 1). In the constant-pressure region of

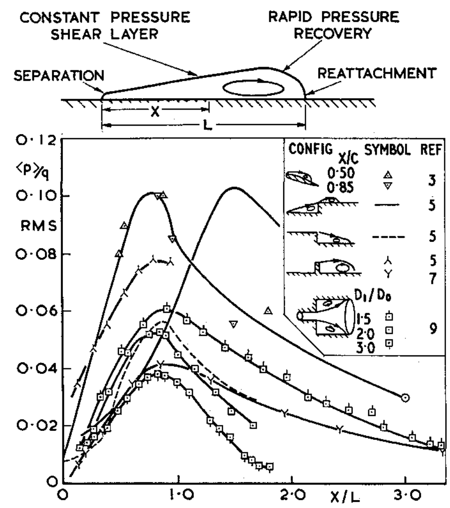

Fig. 1 Rms pressure fluctuations caused by bubbles.

the bubble, we would expect the pressure fluctuations caused by the fluctuations in the separation point to be relatively small, whereas in the reattachment region, where the rate of pressure recovery is high, the pressure fluctuations should be much higher. Thus the pressure fluctuations might be expected to reach a maximum in the middle of the reattachment region. These inferences from the mean static pressure distributions are broadly confirmed by the measurements, although the pressure fluctuations attenuate both upstream and downstream of the reattachment region owing to the influence of the shear layer.

The spectrum of surface pressure fluctuations for a boundary layer approaching separation in an adverse pressure gradient may be divided into high-frequency and low-frequency components.[12] The high-frequency pressure fluctuations are similar to those found under a boundary layer in zero pressure gradient[13] and are generated in the small scale inner region of the boundary layer associated with the law of the wall. The low-frequency pressure fluctuations are generated in the large-scale outer region associated with the law of the wake, and increase in intensity as the outer region of the boundary layer thickens. Between separation and reattachment, measurements suggest that the low-frequency pressure fluctuations continue to increase steadily as the separated boundary layer thickens, until a point is reached where the mixing layer turns towards the surface and the mean pressure starts

Received December, 1971; revision received May 1, 1972.
Index categories: Aircraft Vibration; Nonsteady Aerodynamics.
* Principal Scientific Officer.

to increase. Somewhere close to the reattachment point, the measurements show a maximum value of $\langle p \rangle / q$ between 0.10 and 0.04.

Recently, two authors[8,14] have attempted to predict the pressure fluctuations caused by separated flows. Greshilov[8] derives the simple formula $\langle p \rangle = 0.03\ (U_1 - U_2)^2$. Despite the rather implausible assumptions about the structure of the bubble, the formula predicts the correct order of magnitude of the large pressure fluctuations found in the reattachment region, if we assume $U_1 = V$ and $U_2 = 0$. Fricke[14] reviews other expressions for rms pressure fluctuations and finds them all unsatisfactory, so that the correlation of data presented here may be useful as a preliminary design tool.

Definition of the Pressure Fluctuations

The measured pressure fluctuations were made nondimensional in the form suggested by T. B. Owen,[15] i.e.,

$$[nF(n)]^{1/2} = p/q(\varepsilon)^{1/2}$$

where $n = fL/V$, L = bubble length, p = pressure fluctuation in a band Δf at frequency f, ε = analyser bandwidth ratio $\Delta f/f$, so that the total power of the pressure fluctuation is

$$\langle p^2 \rangle / q^2 = \int_{n=0}^{n=\infty} nF(n)\ d(\log n)$$

The bubble length L in the frequency parameter n correlates the measured pressure fluctuation spectra quite well, giving a peak pressure fluctuation when

$$n = fL/V = 0.5 \text{ to } 0.8 \qquad (1)$$

This probably implies a feed-back process between conditions at the reattachment and separation points. Equation (1) will be inappropriate when there is a strong, coherent disturbance in the wake (e.g. a von Kármán vortex street) or if there are acoustic resonances. The measured pressure fluctuations always cover a broad band of low frequencies, rather than a single discrete frequency as given by Eq. (1), probably because the velocity of the eddies in the shear layer varies with the eddy size.

Results

Leading-Edge Bubbles

Leading-edge bubbles were formed on the center section of the Bristol 188 aircraft[3] and on a Venom aircraft with a sharp leading-edge.[4] Figure 1 shows that the rms pressure fluctuations at two points on the Bristol 188 increase gradually from separation ($X/L = 0$), reach a maximum of $\langle p \rangle / q = 0.10$ just upstream of the reattachment point ($X/L = 1.0$), and then decrease. The frequency parameter n based on the bubble length has a maximum at about $n = 0.7$ and correlates the spectra quite well at $X/C = 0.85$ (Fig. 2), where most of the measurements are taken in the region of rapid pressure recovery ($X/L = 0.94$). The parameter n does not work so well at $X/C = 0.50$, where some of the measurements are taken in the constant-pressure region ($X/L = 0.56$). Measurements of pressure fluctuations on a Venom aircraft also conform to the general pattern shown in Figs. 1 and 2 and show no significant variation in the rms pressure fluctuations or the spectra over the Mach number range from $M = 0.3$ to 0.6. Only a small Reynolds number effect on the low-speed pressure fluctuations was measured between the aircraft and a model.[4] Some pressure fluctuation measurements on aerofoils with round leading-edges recently published[16] suggest similar rms levels and a peak frequency parameter of about 0.8 to 10.

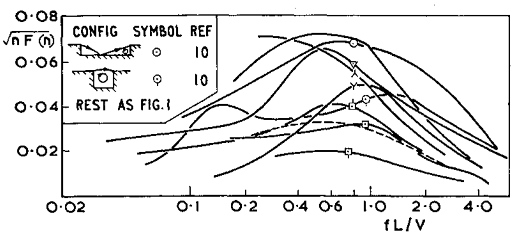

Fig. 2 Pressure fluctuation spectra near the reattachment point in bubbles.

Bubbles Upstream or Downstream of Steps

For a forward-facing step,[5] there are two separation bubbles: a long bubble upstream of the step with a length $= 3h$ and a short bubble downstream of the step with a length $= 1.5h$. The pressure fluctuations at the first reattachment point are only $\langle p \rangle / q = 0.06$, possibly because the rapid rise of pressure is restricted to the reattachment point region. (Lighthill[17] has provided a mathematical model which, in some cases, gives a steady flow for bubbles of this type.) The maximum pressure fluctuations just upstream of the second reattachment point are higher, viz $\langle p \rangle / q = 0.10$, and about the same level as in a leading-edge bubble, because here a rapid pressure rise is required to ensure reattachment. The pressure fluctuations have a broad spectrum (resembling that of the leading-edge bubble) with a weakly defined maximum value $[nF(n)]^{1/2} = 0.07$ at $n = 0.4$ to 0.8 (Fig. 2). For the aft-facing step, there is only one separation bubble. The maximum pressure fluctuation just upstream of reattachment is only $\langle p \rangle / q = 0.06$, and the spectrum has a weakly defined maximum value of $[nF(n)]^{1/2} = 0.03$ at $n = 0.6$.

Bubbles Downstream of Spoilers

The pressure fluctuations reach a maximum at the reattachment line on the flat surface of $\langle p \rangle / q = 0.08$ in the experiment of Mohsen[5] but only $\langle p \rangle / q = 0.04$ in the experiments of Fricke.[7] The difference in the rms pressure fluctuations between these two sets of measurements may be caused by the high level of the low-frequency pressure fluctuations in the experiments of Mohsen. The pressure fluctuations measured by Fricke were very similar to those measured behind a step by Mohsen and there seems little doubt that these two types of bubble flow should be closely related, unless the spoiler flow is sensitive to changes in the fence geometry. (The experiments of Mohsen were made in a wind tunnel with three sides closed and one side open, which might have generated additional low-frequency unsteadiness; the experiment of Fricke was made in a closed wind tunnel.) The peak frequency parameter for the spoiler is about 0.9 in the experiments of Fricke, rather than 0.7 for the leading-edge bubble.

The experiments of Fricke[7] (in air) and of Greshilov[8] (in water) give peak frequency parameters of about 0.9 and 0.8 although the bubble lengths are, respectively, $16h$ and $5.5h$. The coincidence of the frequency parameters based on bubble length suggests that this is a useful parameter for comparing the spectra of the pressure fluctuations generated by bubble flows.

Bubbles Downstream of Sudden Expansion in Pipes

The rms pressure fluctuations for three expansion ratios ($D_1/D_0 = 1.5$, 2.0 and 3.0) increase steadily from separation to reach a maximum just upstream of the reattachment point and then decrease (Fig. 1). The pressure fluctuation spectra for the points where the rms pressure fluctuations were a maximum, show weakly defined maxima for $n = 0.6$ and 0.8 based on the bubble length (Fig. 2). The pressure fluctuations are referred to the flow conditions in the approach pipe; the measurements[9] were made in water but care was taken to avoid cavitation.

Bubbles within Cavities

The flows found within cavities at subsonic speeds may be divided into two classes.[10] For shallow cavities ($H < 0.15$), the flow separates from the upstream face of the cavity, reattaches to the cavity floor and then separates again, upstream of the rear face of the cavity. Shallow cavities have high drag and large pressure fluctuations at the secondary reattachment line on the rear face. The pressure fluctuation spectrum here closely resembles the spectra at the reattachment line on the leading-edge bubble, or a bubble upstream of a forward facing step, and reaches a maximum of $[nF(n)]^{1/2} = 0.07$ at $n = 0.7$ (Fig. 2).

For deep cavities ($H > 0.15$), the flow separates from the upstream face of the cavity and then reattaches somewhere near the top of the rear face. Deep cavities have lower drag, and smaller pressure fluctuations on the rear face than for shallow cavities because the bubbles within them are formed by a shear layer at almost constant pressure. The pressure fluctuation spectrum for a deep cavity shows two weakly defined maxima of $[nF(n)]^{1/2} = 0.040$ and 0.055 at $n = 0.15$ and 1.5, respectively.

The pressure fluctuation measurements along the floor of the cavities upstream of reattachment do not correspond very well with the triangular distribution associated with leading-edge bubbles but the cavities were narrow and the flow within them was strongly three dimensional.

Base Pressure Fluctuations

The bubble formed behind a bluff body closes in the wake and has no reattachment point to a solid surface. Hence we might expect that the level of pressure fluctuations caused by wake bubbles would be higher than those produced by bubbles which reattach. Thus Roshko showed[18] that pressure fluctuations, vortex shedding and base drag can be increased by removing a splitter plate from the wake of bluff bodies, which probably interferes with the strong feedback loop between the two separations. Similarly, Mabey[19] showed that the pressure fluctuations in a diffuser with a bluff center body were higher than those in a diffuser of the same expansion ratio with steps on the sidewalls. The predominant frequency was $n = 0.6$, based on the length of the bubble shown by surface flow patterns on the floor of the diffuser. The spectra of the pressure fluctuations in this diffuser were almost unaltered by a change in Reynolds number by a factor of 9 from model to full scale.

The predominant frequency for the base pressure fluctuations on bodies of revolution appears to be somewhat lower[20] than for two dimensional bluff bodies. For a hemispherical nosed body with a conical flare upstream of the base, $n = 0.3$, based on the length of the bubble estimated from schlieren photographs. The spectra of the base pressure fluctuations were independent of Mach number from $M = 0.15$ to 0.85 and insensitive to wide changes in Reynolds number.

Trailing-Edge Bubbles

A bubble of this type forms on an aerofoil with a rear-loaded section when the boundary-layer separates upstream of the trailing-edge and does not reattach. As the separation extends forward from the trailing-edge and the trailing-edge pressure diverges, the mean circulation round the aerofoil alters rapidly. Hence we might expect large, well correlated pressure fluctuations over the complete chord of the aerofoil. This hypothesis was confirmed by some low-speed pressure fluctuation measurements on a flat plate with a flap,[21] but measurements at subsonic and transonic speeds are required for rear-loaded sections.

Implications for the Prediction of Buffeting

The pressure fluctuations caused by an attached turbulent boundary layer in a zero pressure gradient are of low level and high frequency and hence unlikely to excite structural modes significantly, although they might excite local panel vibrations. In contrast, the rise in the low-frequency pressure fluctuations before separation of the boundary layer under an adverse pressure gradient might sometimes be sufficient to excite the structural modes before a flow separation is shown by surface flow patterns. It is believed that this phenomenon has occurred occasionally during buffeting tests of wind-tunnel models.

If bubble flows occur on wings, the position and length of the bubble must be scaled correctly between the model and the aircraft to preserve the similarity of the pressure fluctuation spectra; this can possibly be achieved by ensuring the same ratio of turbulent boundary layer momentum thickness at the shock/wing-chord for the model and aircraft, despite the difference in Reynolds number.

Equation (1) helps us to discriminate between the excitation frequencies associated with long and short bubbles because of the large change in the bubble length between the two flows. A long bubble covers a significant area of the aerofoil chord and from Ref. 2, because $L/C = 0(1)$, the pressure fluctuations will be at comparatively low frequencies which can excite the structural modes; e.g. for a long bubble on a wing with a chord of 10 ft moving at 200 fps, the excitation frequency would be 0 (12 Hz). (Typical wing fundamental bending frequencies are 10 Hz for a small aeroplane and 2 Hz for a large aeroplane.) A short bubble only influences a small area of the wing but, in addition, because $L/C = 0(0.01)$, these pressure fluctuations will be at such high frequencies that they are unlikely to excite structural modes; e.g. for a short bubble on a wing with 10 ft chord moving at 200 fps, the excitation frequency would be 0 (1200 Hz).

Flight tests on the Venom with a sharp leading-edge,[4] and the canard control of the XB-70,[22] showed that buffet onset corresponded with the formation of a long bubble. The buffeting then increased steadily as the bubble extended downstream, until the reattachment point approached the trailing-edge and the trailing-edge pressure diverged. This point corresponded with heavy buffeting. Hence the local pressure fluctuations within a long bubble must be quite strongly correlated; to calculate the aircraft structural response correlations of the pressure fluctuations in space and time must be measured.[23] Typical pressure fluctuations associated with bubble flows at subsonic speeds are: at separation, $[nF(n)]^{1/2} = 0.005$ to 0.020; and at reattachment, $[nF(n)]^{1/2} = 0.060$ to 0.100. These pressure fluctuation levels are of the same order as the buffet category for wings, derived from measurements of unsteady wing-root strain, which is appropriate to heavy buffeting,[24] i.e. $[nF(n)]^{1/2} = 0.016$. Hence we might expect that bubble flows at subsonic speeds will generally cause heavy buffeting despite uncertainties about the degree of correlation of the pressure fluctuations and the value of aerodynamic damping appropriate to the wing motion.

The prediction of the onset and severity of buffeting is of crucial importance at transonic speeds. In this speed range, the mixed subsonic/supersonic flows and the different regimes of shock/boundary-layer interaction may modify the model for bubble flows suggested above, at least near the shock. However, downstream of the shock, an approximately constant average pressure is often observed in the separated flow region, followed by a rapid rise to reattachment.

Coe's investigation[25] of the buffet loads on launch vehicles includes some measurements at subsonic and transonic speeds of the mean and fluctuating static pressures caused by a separation bubble downstream of a step in a body of revolution. Both the mean and the fluctuating pressure distributions aft of the step correspond very well in general character

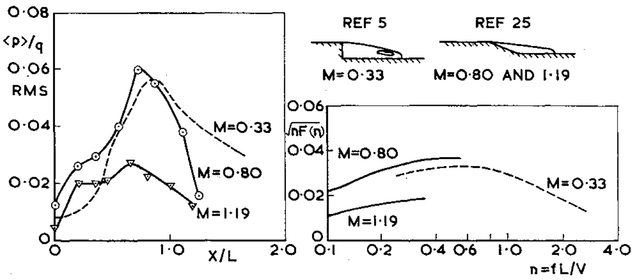

Fig. 3 Comparison of pressure fluctuations caused by the flow down a step at $M = 0.33$, 0.80 and 1.19.

with the low-speed pressure distributions over the complete speed range from $M = 0.60$ to 1.19, although the maximum fluctuating pressure falls steadily from $\langle p \rangle / q = 0.06$ at $M = 0.79$ to $\langle p \rangle / q = 0.03$ at $M = 1.19$. This fall in the pressure fluctuations is probably due to the improved stability of the mean bubble flow because of the reduction of upstream influence from the reattachment region as the region of supersonic flow expands. (The base-pressure fluctuations on a body of revolution also fall from subsonic to supersonic speeds and a similar explanation may be applicable.) The mean pressure distribution suggests that the length of the bubble does not change significantly from $M = 0.60$ to 1.19 so that, within this speed range, there is probably no major change in the internal structure of the bubble.

The apparent universality of the pressure fluctuations caused by bubble flows at subsonic speeds is well illustrated by Fig. 3 which compares the pressure fluctuations measured behind a two-dimensional step at $M = 0.33$ and those measured behind a step on a body of revolution at $M = 0.79$. (For zero and small pressure gradients, Willmarth and Yang[26] have demonstrated the relatively small influence of transverse surface curvature on wall-pressure fluctuations.) The similarity at subsonic speeds between both the rms pressure fluctuations and the spectra for the two different experimental configurations and Reynolds numbers is good.

Conclusions

An approximate correlation of the static pressure fluctuations generated by separated bubble flows at subsonic speeds is suggested. The origin of these pressure fluctuations may be attributed to variations in the mean static pressure distribution under the bubble and the development of the mixing layer.

The maximum value of the rms pressure fluctuations always occurs in the reattachment region, and seems to be relatively insensitive to fairly wide changes in Reynolds number for many bubble type separations.

The observations cover a wide range of separated bubble flows and should give a fairly good preliminary design method for evaluating fluctuating pressures at subsonic speeds.

References

[1] Tani, I., "Low-speed Flows Involving Bubble Separations," *Progress in Aeronautical Sciences*, Vol. 5, edited by D. Küchemann and L. H. G. Sterne, Pergamon Press, London, 1964, pp. 70–103.

[2] Crabtree, L. F., "The Formation of Regions of Separated Flow on Wing Surfaces, Pt. II Laminar Separation Bubbles and the Mechanism of The Leading-Edge Stall," Rept. Aero 2578, July 1957, Royal Aircraft Establishment, Great Britain; also ARC R & M 3122, Pt. 2, 1959, Aeronautical Research Council, Great Britain.

[3] Lawford, J. A. and Beauchamp, A. R., "Low Speed Wind Tunnel Measurements of Pressure Fluctuations on the Wing of a Twin Jet Aircraft (Bristol 188)," ARC R & M 3551, 1968, Aeronautical Research Council, Great Britain.

[4] Rose, R. and Nicholas, O. P., "Flight and Tunnel Measurements of Pressure Fluctuations on the Upper Surface of the Wing of a Venom Aircraft with a Sharp Leading-Edge," ARC CP 1032, Nov. 1967, Aeronautical Research Council, Great Britain.

[5] Mohsen, A. M., "Experimental Investigation of the Wall Pressure Fluctuations in Subsonic Separated Flows," Rept. D6-17094, AD 669214, Jan. 1967, Boeing Co. Commercial Airplane Div., Renton, Washington.

[6] Speaker, W. V. and Ailman, C. M., "Spectra and Space Time Correlations of the Fluctuating Pressures at a Wall beneath a Supersonic Turbulent Boundary Layer Perturbed by Steps and Shockwaves," CR 486, May 1966, NASA.

[7] Fricke, F. R. and Stevenson, D. C., "Pressure Fluctuations in a Separated Flow Region," *Journal of the Acoustical Society of America*, Vol. 44, No. 5, Nov. 1968, pp. 1189–1201.

[8] Greshilov, E. M., Evtushenko, A. V. and Lyamshev, L. M., "Spectral Characteristics of the Wall Pressure Fluctuations Associated with Boundary Layer Separation behind a Projection on a Smooth Wall," *Soviet Physics—Acoustics*, Vol. 15, No. 1, July–Sept. 1969, pp. 29–34.

[9] Rouse, H. and Jezdinsky, V., "Fluctuation of Pressure in Conduit Expansions," *Proceedings of the American Society of Civil Engineers, Journal of the Hydraulics Division*, Vol. 92, No. HY3, May 1966, Paper 4815, pp. 1–12.

[10] Fail, R., "Low Speed Wind Tunnel Tests on the Flow in Bomb Bays and Its Effect on Drag and Vibration," Rept. Aero 2511, May 1954, Royal Aircraft Establishment, Great Britain.

[11] Norbury, J. F. and Crabtree, L. F., "A Simplified Model of the Incompressible Flow Past Two-Dimensional Aerofoils with a Long Bubble Type of Separation," TN Aero 2352, June 1955, Royal Aircraft Establishment, Great Britain.

[12] Bradshaw, P., "'Inactive' Motion and Pressure Fluctuations in Turbulent Boundary Layers," NPL Aero Rept. 1172, Oct. 1965, National Physical Laboratory, Great Britain, ARC 27338, Aeronautical Research Council, Great Britain.

[13] Lilley, G. M., "On Wall Pressure Fluctuations in Turbulent Boundary Layers," ARC 24241, Nov. 1962, Aeronautical Research Council, Great Britain.

[14] Fricke, F. R., "Pressure Fluctuations in Separated Flows," *Journal of Sound and Vibration*, Vol. 17, No. 1, July 1972, pp. 113–123.

[15] Owen, T. B., "Techniques of Pressure Fluctuation Measurements Employed in the RAE Low Speed Wind Tunnels," AGARD Rept. 172, 1958, North Atlantic Treaty Organisation, Advisory Group for Aeronautical Research and Development, ARC 10780, Aeronautical Research Council, Great Britain.

[16] Heller, H. H., Bliss, D. B., and Widnall, S. E., "Incipient Stall Detection through Unsteady-Pressure Monitoring on Aircraft Wings," *Journal of Aircraft*, Vol. 9, No. 2, Feb. 1972, pp. 186–188.

[17] Lighthill, M. J., "On Boundary Layers and Upstream Influence. A Comparison between Subsonic and Supersonic Flows," *Proceedings of the Royal Society of London*, Ser. A, Vol. 217, No. 1130, May 1953.

[18] Roshko, A., "On the Wake and Drag of Bluff Bodies," *Journal of the Aeronautical Sciences*," Vol. 22, No. 2, Feb. 1955, pp. 124–132.

[19] Mabey, D. G., "Flow Unsteadiness and Model Vibration in Wind Tunnels at Subsonic and Transonic Speeds," ARC CP 1155, 1971, Aeronautical Research Council, Great Britain.

[20] Mabey, D. G., "Some Measurements of Base Pressure Fluctuations at Subsonic and Supersonic Speeds," TR 70148, Aug. 1970, Royal Aircraft Establishment, Great Britain, ARC CP 1204, 1972, Aeronautical Research Council, Great Britain.

[21] Fail, R. and Owen, T. B., "Some Measurements of the Pressure Fluctuations Associated with Various Types of Mean Flow Field," Unpublished Procurement Executive, Ministry of Defence, Great Britain.

[22] Jenkins, J. M., DeAngelis, V. M., Friend, E. L. and Monaghan, R. C., "Flight Measurements of Canard Loads, Canard Buffeting and Wing Tip Hinge Moments on the XB70 Aircraft Including Comparisons with Predictions," TND 5359, Aug. 1969, NASA.

[23] Mitchell, C. G. B., "Calculations of the Buffeting on a Slender Wing Aircraft at Low Speeds," *Proceedings of the Symposium on Structural Dynamics*, Loughborough Univ., England, March 1970.

[24] Mabey, D. G., "An Hypothesis for the Prediction of Flight Penetration of Wing Buffeting from Dynamic Tests on Wind Tunnel Models," ARC CP 1171, 1971, Aeronautical Research Council, Great Britain.

[25] Coe, C. F., "The Effects of Some Variations in Launch Vehicle Nose Shape on Steady and Fluctuating Pressures at Transonic Speeds," TM X 646, March, 1962, NASA.

[26] Willmarth, W. W. and Yang, C. S., "Wall-Pressure Fluctuations beneath Turbulent Boundary Layers on a Flat Plate and a Cylinder," *Journal of Fluid Mechanics*, Vol. 41, Pt. 1, March 1970, pp. 47–80.