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Experimental Investigation of Twin-Fin Buffeting and Suppression

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An investigation has been undertaken to study the characteristics of vertical fin buffeting for various twin-fin configurations at high angles of attack. Tests were performed in the 2.1 × 1.5 m low-speed wind tunnel at the University of Bath, using three 60-deg cropped generic delta wings of 0.5-m span. To sense unsteady pressures at the fin surface, a rigid fin instrumented with miniature pressure transducers was fabricated, whereas a flexible fin of similar planform and size was used to measure the buffeting response. It was found that the fin configurations were typified by two maximum buffeting conditions. The first peak response was effectively a vortex/fin interaction in isolation, whereas the second peak response was the result of a vortex shear-layer oscillation between the fins. A novel flow concept (tangential leading-edge blowing) was then used to decrease the levels of buffeting response for all fin configurations. By reducing the effective angle of attack of the vortical flow, peak buffeting responses were shifted to higher angles of attack.

Nomenclature

C_μ = blowing momentum coefficient, jet momentum/qS
$\bar{\bar{c}}$ = wing mean aerodynamic chord, 0.36 m
f = frequency
n = reduced frequency, $f\bar{\bar{c}}/U$
n_m = modified frequency parameter, $n \sin \alpha$
m = generalized mass
$\sqrt{nG(n)}$ = buffet excitation parameter
$\bar{p}$ = broadband rms pressure fluctuation
q = dynamic pressure
S = wing reference area
S_f = fin reference area
U = freestream velocity
$\ddot{z}$ = fin tip acceleration, rms
α = angle of attack
β = sideslip angle
θ = model pitch angle
ξ = total damping, fraction of critical
ϕ = model roll angle

Introduction

THE application of vortical flows to provide enhanced high-α performance for present generation combat aircraft has received much attention.[1,2] It is anticipated that future combat aircraft will be required to operate at high-α for longer periods.

Severe fin buffeting has been encountered on this type of aircraft (both single and twin finned) during operation at high angles of attack. From wind-tunnel and flight tests performed on such aircraft,[3,4] the buffeting has been attributed to the unsteady pressure field associated with the vortical flow enveloping the fin(s). The pressure field excites the natural frequencies of the structure, decreasing the life of the airframe, and may also limit the maneuver envelope of the aircraft. Clearly, this is an undesirable situation that must be addressed early in future combat aircraft designs.

At present a common form of fin buffet attenuation is the structural reinforcement. This reduces the fin vibration, but increases the overall weight of the aircraft, impairing the aircraft's performance. This method is only remedial, since it does not solve the problem at source. Fin buffeting has also been reduced by modifying the impinging flow, e.g., leading-edge extension (LEX) fence for the F/A-18 (Ref. 5).

A research program has been undertaken at the University of Bath to determine the characteristics of vortical flows over delta wings, with a view to obtaining a relationship between the buffet excitation and response for different fin configurations. It has been shown that the mechanism for single-fin buffeting is different than that of twin-fin buffeting,[6] yet both mechanisms revealed a strong correlation between buffet excitation and response.

A recent study has demonstrated the ability of tangential leading-edge blowing (TLEB) to suppress single-fin buffeting at any angle of attack for similar wing planforms.[7] Symmetric TLEB reduced the effective angle of attack of the vortical flow, so that the single-fin response was shifted to higher angles of attack. It was stated that through the use of an optimum blowing profile, the buffeting could be suppressed at angle of attack without impairing the wing lift characteristics.

The present study includes measurements of buffeting response levels on a flexible fin, and unsteady pressure measurements on a rigid fin of similar planform, for both blown and unblown 60-deg delta wings with twin-fin configurations.

TLEB

Previous research has demonstrated the ability of TLEB to modify vortical flowfields and to provide lateral control at both prestall and poststall angles of attack.[8,9] TLEB is an application of the phenomenon of Coanda jet attachment to convex surfaces.

If the leading edge of a delta wing is sharp, the leading-edge separation point is fixed, and the vortex equilibrium condition is influenced only by the vortex strength and position for a given angle of attack. However, if the leading edge is rounded, the separation point is able to move around the leading edge, providing an additional degree of freedom on the flowfield. Therefore, there exists a unique vortex strength and

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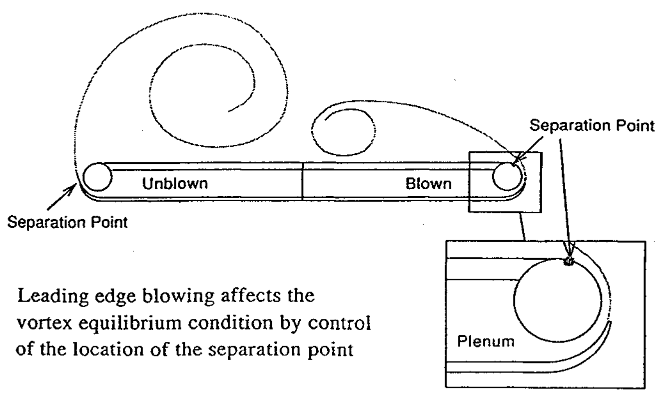

Fig. 1 TLEB.

location for each leading-edge separation point at a constant angle of attack. By injecting a thin tangential jet into the crossflow boundary layer near the leading edge (see Fig. 1), further control of the boundary-layer separation is provided by the momentum of the jet, so that the jet enables control of the vortex equilibrium condition at a given angle of attack.

At low angles of attack, the effect of TLEB is to reduce the leading-edge vortex strength and relocate the vortex inboard with negligible reduction in wing normal force. At poststall angles of attack, blowing moves the vortex burst points aft, and augments the wing normal force. TLEB can be considered as reducing the effective angle of attack of the vortex, i.e., at fixed incidence, increasing blowing momentum modifies the vortical flow to represent that at a lower angle of attack.

Experimental Apparatus

Model Support System

A model support system has been designed to be used in the 2.1 × 1.5 m tunnel at the University of Bath, specifically for research into high angle-of-attack aerodynamics. The rig is a pantograph mechanism mounted on its side with pitch control provided by an electric linear actuator, which provides a pitch range from 0 to 90 deg. With an integral roll shaft (capable of ±180 deg), the system offers a ±90-deg capability in both model angle of attack and sideslip using the following relationships[10]: $\alpha = \tan^{-1}(\cos\phi \cdot \tan\theta)$ and $\beta = \sin^{-1}(\sin\phi \cdot \sin\theta)$.

The model is sting mounted on an A-frame layout to give maximum lateral stiffness, and model forces and moments are measured by a three-component strain gauge sting balance.

Glass panels in the tunnel walls provide laser access, and the instrumentation wires and blowing air supply were passed inside the A-frames.

Wind-Tunnel Models

Three models of similar planform and size have been built to determine the effects of TLEB on buffeting response. All models are 60-deg delta wings of 0.5-m span, with a trailing-edge extension for fin attachment. The wing incorporating TLEB is 3% thick and has two separate plenum chambers providing the blowing supply for the slots, which extend over the majority of the leading edges. The plenum pressures are monitored separately by miniature pressure transducers, and manually controlled. The leading-edge slot height is adjustable from 0.0 to 1.0 mm, and may vary along the slot length. Previous experience has shown that TLEB is most efficient when a linear tapered slot is used[8] (tapering towards the wing apex). This slot configuration gives results that are easiest to interpret, as the vortical flow responds quasiconically. The unblown models are of similar planform, one with a rounded leading edge, 4% thickness, 90 upper surface pressure tappings situated at x/c = 0.30, 0.45, 0.59, and 0.73. The other wing has a sharp leading edge.

Two types of unsteady data were measured. The fin used to detect the excitation pressures was rigid, manufactured from aluminium, and of similar planform and section to the flexible fin. A miniature differential pressure transducer was mounted on each face of the fin at 75% span and 40% chord, to monitor the pressure fluctuations in the flow. Although a single transducer does not give an accurate representation of the buffet excitation over the entire fin surface, data could be acquired to establish surface unsteadiness and periodicity.

The buffeting response was measured using a flexible fin, whose natural frequencies were designed using the following reduced frequencies (based on wing mean aerodynamic chord and the maximum tunnel velocity): bending (1st mode), n = 0.3–0.4 and torsion (1st mode), n = 1.0–1.5.

These reduced frequencies are typical of a modern combat aircraft. The frequency term in this expression is the frequency of the natural mode (and therefore unrelated to the excitation

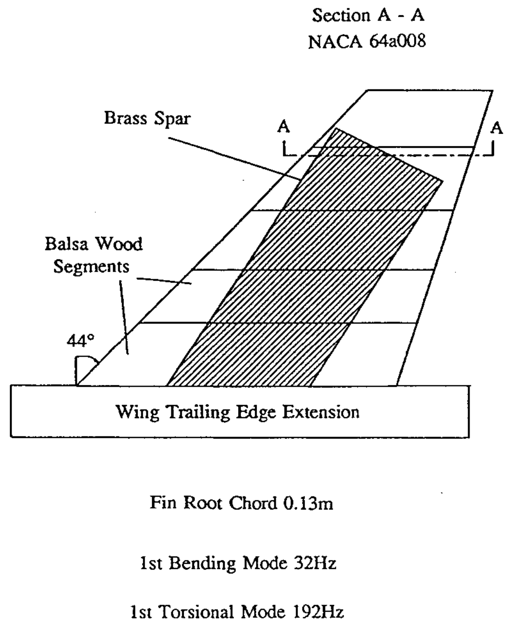

Fig. 2 Flexible fin schematic.

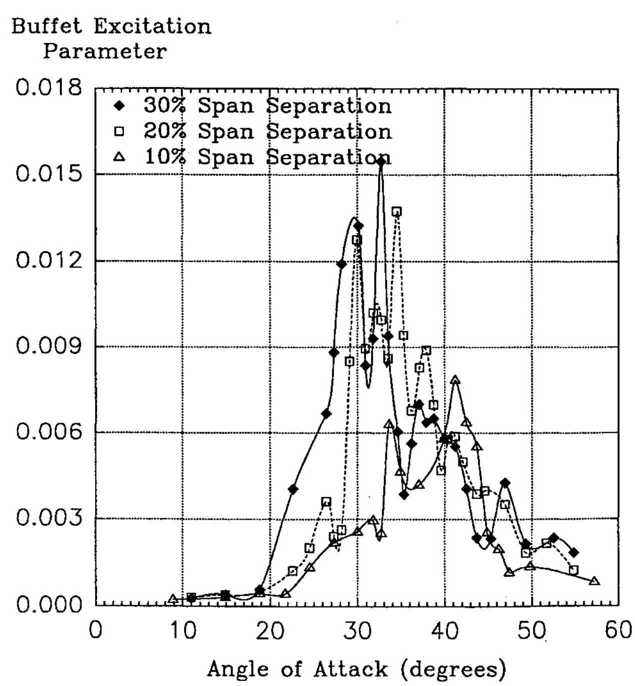

Fig. 3 Effect of lateral fin separation on buffeting response profiles, port fin, fundamental bending mode 32 Hz.

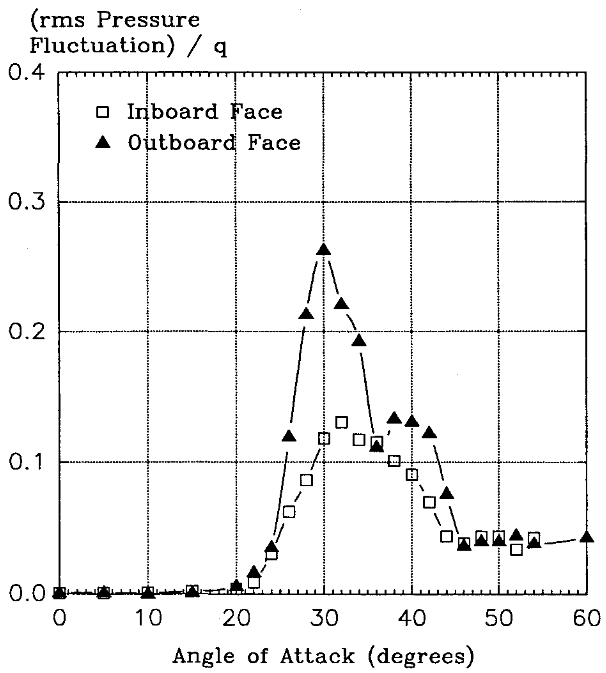

Fig. 4 Variation of nondimensional pressure fluctuation, 20% span separation configuration.

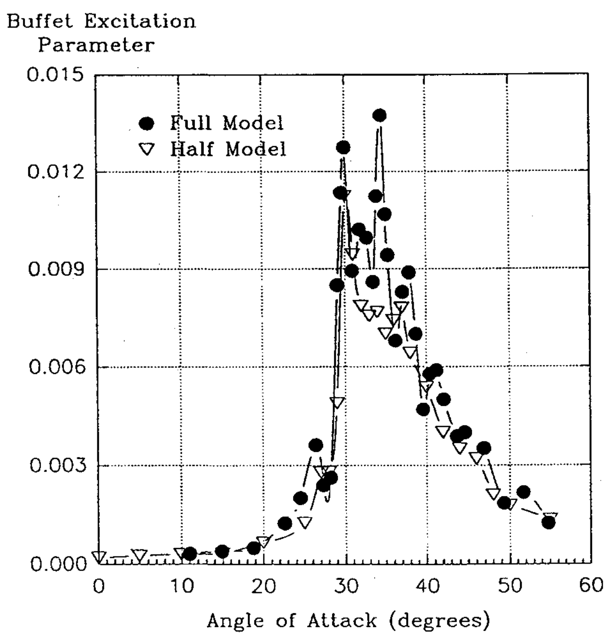

Fig. 5 Comparison between buffeting response profiles for half- and full-models, 20% span separation, port fin, fundamental bending mode 32 Hz.

frequency). The flexible fin is shown in Fig. 2. It consists of a thin brass spar, surrounded by a balsa wood shroud to provide an aerodynamic fairing and the correct fin area. Fin vibration levels were sensed by root strain gauges, instrumented in half-bridge circuits.

Both fins were rigidly fixed to the trailing-edge extensions of the models. Typical test Reynolds numbers were 0.8×10^6 based on wing root chord.

Data Acquisition and Reduction

The fin excitation and response data were nondimensionalized for comparison between different test configurations. The

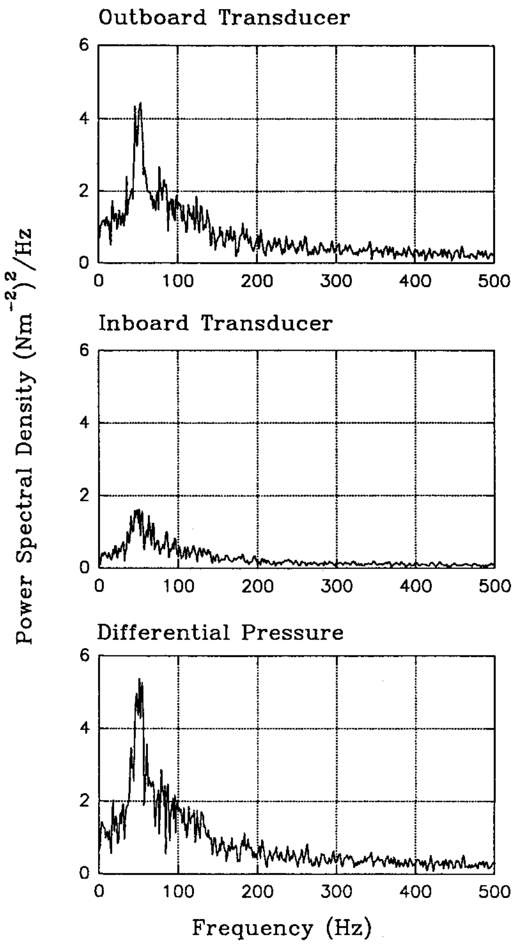

Fig. 6 PSD functions, 20% span separation, α = 30 deg.

response (strain gauge) data were reduced into the nondimensional buffet parameter[11]:

$$\sqrt{nG(n)} = (2m\ddot{z}/\sqrt{\pi q S_f})\sqrt{\zeta} \tag{1}$$

where ζ is the total damping (measured as the fraction of critical) for each natural mode.

The generalized mass was determined using modal analysis. A known impulse was applied to the fin structure using an instrumented hammer, and a light accelerometer sensed the natural modes present. The mass term for each natural mode was then derived from the spectra of both signals.

Buffeting spectra were obtained using a fast Fourier transform (FFT) size corresponding to 6–7 s of raw data. The total damping values (typically 2–3%) were derived using the half-power method, and were found to be independent of free-stream speed, indicating that the damping was predominantly structural (and therefore lower than flight test damping values).

The excitation (unsteady pressure) data was nondimensionalized into the form $\bar{p}/q$. This parameter represents the oscillatory nature of the flow at the fin surface, which is primarily because of the vortical flow.

Presentation of Results

All published results correspond to tests performed at a reduced frequency of 0.6 (based on the first bending frequency and wing mean aerodynamic chord), except where stated.

Unblown Results

The buffeting response profiles for several twin-fin configurations in the fundamental bending mode for the sharp leading-edge wing are shown in Fig. 3. Buffet onset occurs at

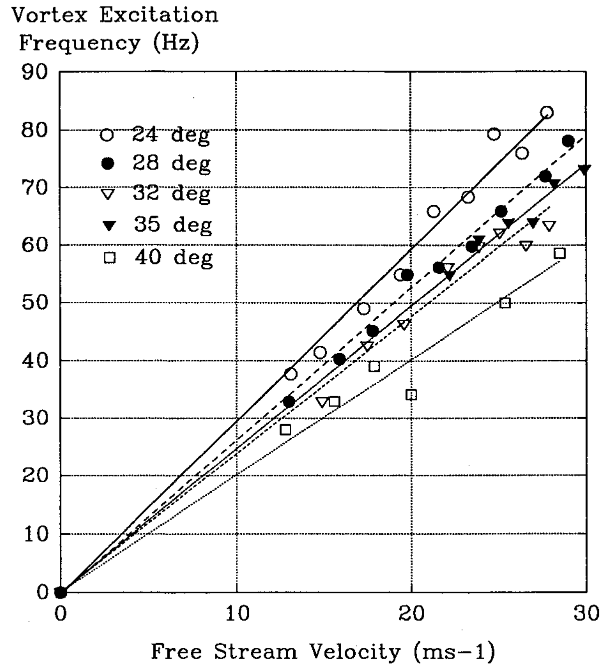

Fig. 7 Vortex excitation frequencies for 20% span separation configuration.

Table 1 Variation of n and n_m with angle of attack (no TLEB)

$(f_{VORTEX}\bar{\bar{c}}/U)\sin\alpha$ = const, n_m

α, deg	$(f_{VORTEX}\bar{\bar{c}}/U)$	$(f_{VORTEX}\bar{\bar{c}}/U)\sin\alpha$
24	1.08	0.44
28	0.94	0.44
32	0.87	0.46
35	0.91	0.52
40	0.73	0.47

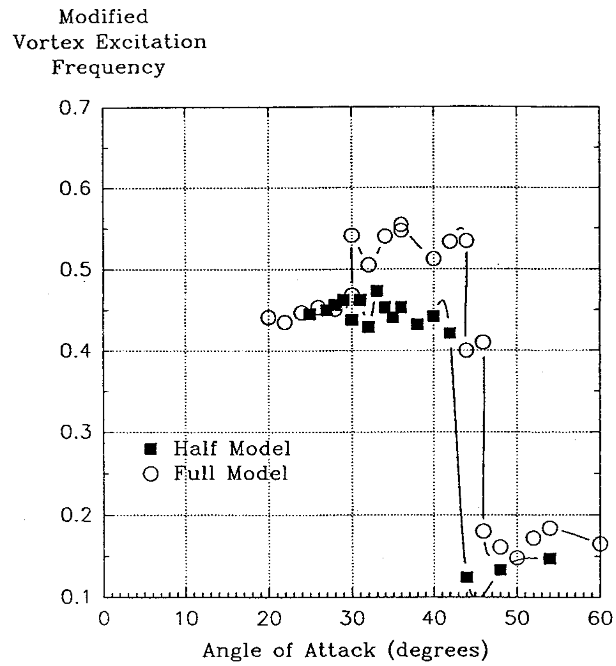

Fig. 8 Variation of modified frequency parameter for half- and full-models.

approximately 20 deg. As the fin separation increases, the buffeting levels rise more quickly after buffet onset to peak at a lower angle of attack. This is because of the increase in vortex diameter with increasing angle of attack, exciting the wider spaced fins at lower angles of attack. Virtually no buffeting in the fundamental torsional mode was detected at this test reduced frequency.

From the buffeting response profiles, it is clear that the maximum values of the buffet excitation parameter are large compared to the heavy buffet criterion suggested by Mabey,[11] which was devised for buffeting wings. The peak value of the parameter measured here was approximately 0.020 (around 6–7 times the level described as heavy), whereas Mabey[12] reports fin response levels of around 0.037. The wing buffeting criterion based on pilot opinion was used in the absence of an alternative reference level.

Figure 4 shows the variation of rms excitation pressure levels for the 20% span separation configuration (sharp leading-edge wing). At low angles of attack, both traces contain little unsteadiness, since the vortices are located away from the fins. Then, at around $\alpha = 22$ deg, both traces increase, the outboard trace rising more quickly (because of the vortex tracking inboard as the angle of attack increases). The outboard face experiences peak unsteadiness at $\alpha = 30$ deg, and then falls before reaching a value corresponding to a fully stalled wing. In contrast, the rms levels rise to peak at $\alpha = 34$ deg before falling to the fully stalled value. When the rms pressure levels are compared to the response profile (Fig. 3) it can be seen that the first response peak occurs at a similar angle of attack to the peak outboard rms pressures. Each leading-edge vortex has overlapped the fin to reattach around the fin leading edge and tip, and so the majority of the buffet excitation is experienced on the outboard face. Hence, the first buffeting peak is primarily caused by peak rms outboard pressures, together with some inboard excitation.

The inboard rms pressure peak coincides with the second buffeting response peak. Here, the vortex shear layers have merged in the region between the fins themselves, resulting in a lateral shear-layer oscillation, providing additional inboard excitation. The second response peak is a result of a twin vortex/fin interaction, induced by high outboard rms pressures, and augmented by maximum inboard excitation.

To confirm that the second response peak was caused by an interaction between both leading-edge vortices, it was necessary to repeat some tests ensuring that only one leading-edge vortex was present. By removing one of the vortices, a buffeting reduction would confirm the hypothesis. Therefore, it was decided to perform tests using a sharp leading-edged, half-delta wing model of similar planform, the details of which are presented in Ref. 13. Figure 5 compares the buffeting response profiles for the half-model and full model for the 20% span separation configuration. It can be seen that the curves are similar around buffet onset, with both curves exhibiting a first peak at similar angles of attack. As the angle of attack increases further, the full-model profile peaks a second time, whereas the half-model curve does not exhibit a second peak. This suggests that the interaction between the two vortices is responsible for the second response peak.

The nature of the fin excitation pressures can be further analyzed by subtracting the pressure time trace corresponding to one face of the fin from the other. This subtraction emphasizes the out-of-phase components of the pressure traces (and, hence, the differential pressure across the fin), and suppresses the effect of any in-phase components. When the pressures are out of phase, one face of the fin experiences an instantaneous suction, and the other face experiences an instantaneous pressure (and vice versa). A side force is therefore produced, resulting in possible fin deflection. Figure 6 shows the power spectral density (PSD) function for the point $\alpha = 30$ deg (full model, first peak), for the outboard and inboard faces, and the instantaneous differential pressure across the fin. It can be seen that the majority of the buffet excitation is experienced on the

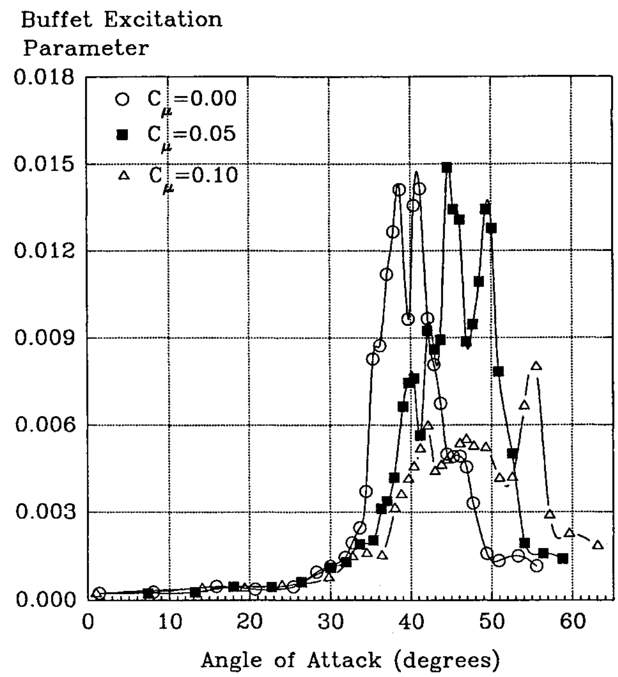

Fig. 9 Effect of TLEB on buffeting response profiles, blown wing, 20% span separation, port fin, fundamental bending mode 32 Hz.

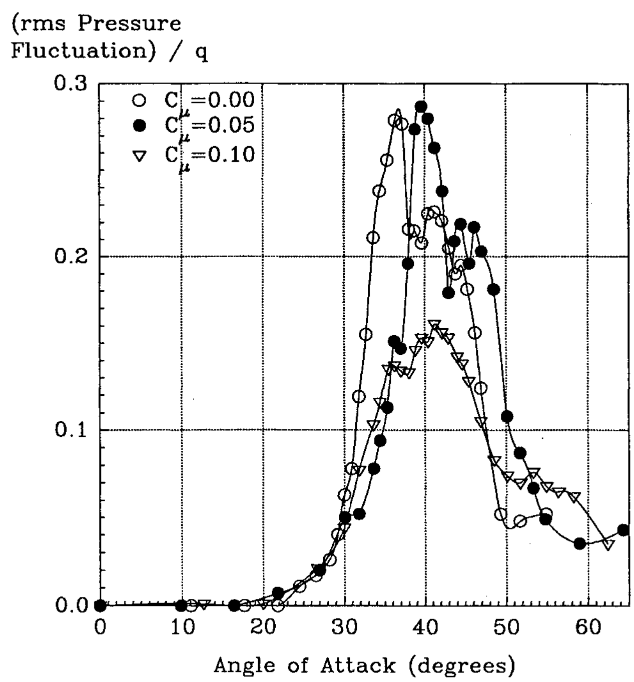

Fig. 10 Effect of TLEB on rms pressures, outboard fin face.

outboard face of the fin. Also, the subtraction process has resulted in larger excitation levels and a peak can be found at approximately 53 Hz. The corresponding PSDs for $\alpha = 34$ deg (second peak) show similar trends, but the inboard face experiences more excitation compared to the first peak. The majority of the excitation is still experienced on the outboard face.

Thus, it can be seen that the vortical flowfield is concentrated at a distinct frequency. Furthermore, it was found that the peak excitation frequency varied linearly with freestream velocity,[14] as expected. Figure 7 shows the variation of vortex excitation frequency with freestream velocity for the same twin-fin configuration. The curves are linear for all cases. Using a reduced frequency parameter incorporating the vortex excitation frequency f_{VORTEX}, and a nominal wake width

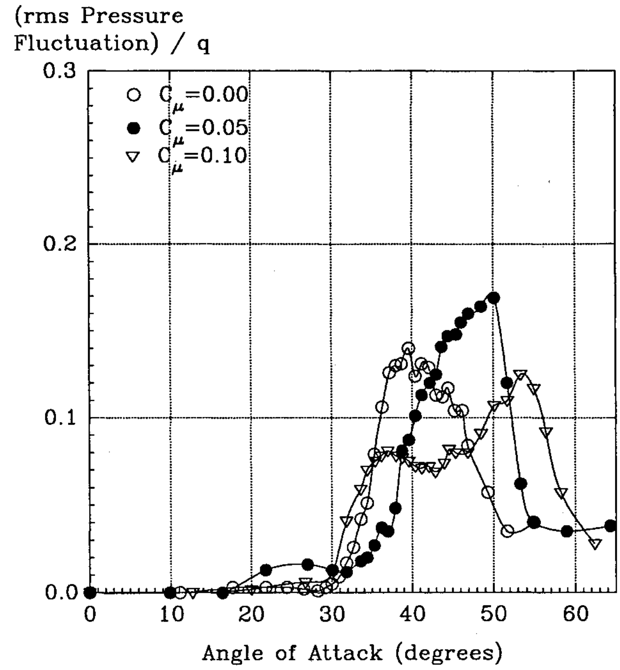

Fig. 11 Effect of TLEB on rms pressures, inboard fin face.

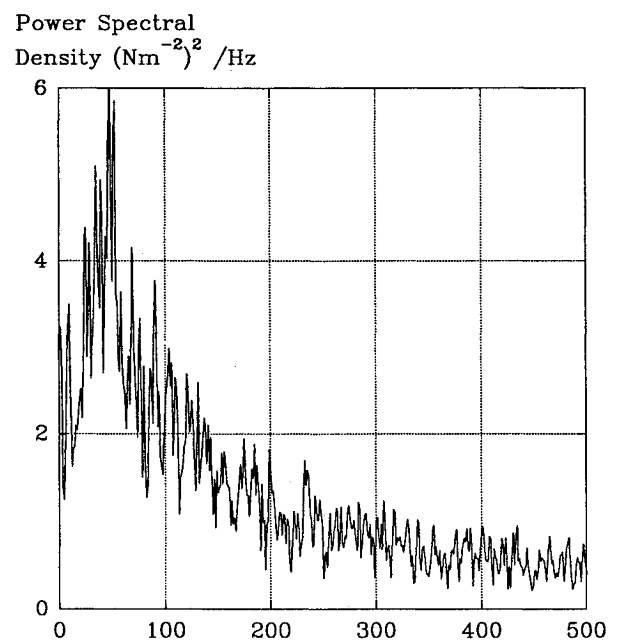

Fig. 12 PSD of fin differential pressure, blown wing, 20% span separation, α = 38 deg, C_μ = 0.00.

$\bar{\bar{c}} \sin \alpha$, it can be seen that the peak excitation frequency can be expressed in the form shown in Table 1.

The variation of n_m (obtained from the fin differential pressures) with angle of attack is shown in Fig. 8 for the 20% span separation case (half- and full-models). For $\alpha < 20$ deg, little periodicity is present in the flow around the fins. The parameter then takes a value of approximately 0.44 up to the first response peak, where a step change to $n_m \approx 0.54$ occurs for the full model. Previous research has indicated that $n_m = 0.55$ is the value associated with a vortex shear-layer oscillation typical of single-fin configurations,[7] and so this oscillation is thought to be a primary factor in the second peak buffeting mechanism. The half-model curve does not exhibit such a step change, as no shear-layer oscillation is present. Both curves then fall to a value corresponding to bluff body flow. The

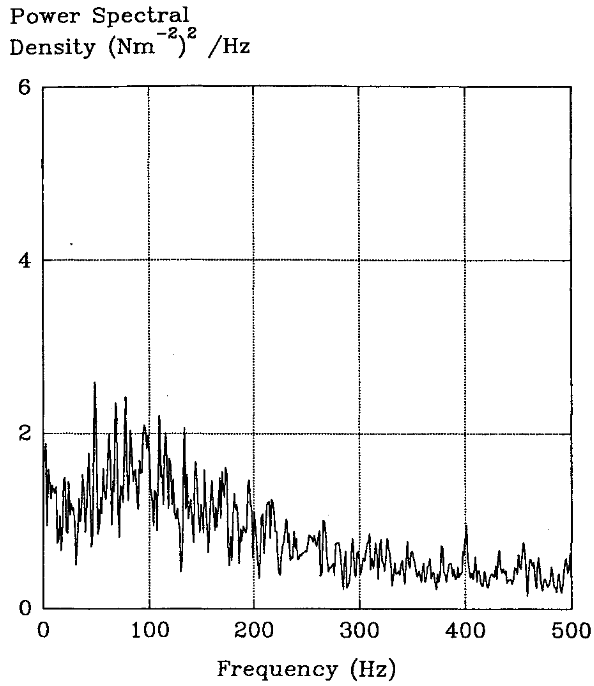

Fig. 13 PSD of fin differential pressure, blown wing, 20% span separation, α = 38 deg, C_μ = 0.10.

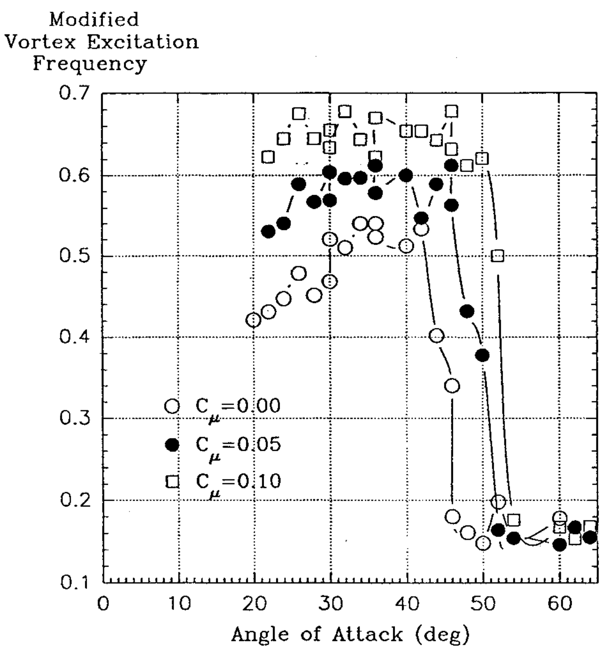

Fig. 14 Effect of TLEB on modified vortex frequency parameter, blown wing, 20% span separation configuration.

previous curves were relatively insensitive to changes in lateral fin separation.

Comparisons between different buffeting studies suggest that ($\bar{c}$ sin α) is not an appropriate scaling parameter since different values of the modified frequency parameter are found for different flows [0.55 (Ref. 7), 0.22 (Ref. 3), 0.29 (Refs. 14 and 15), using unsteady pressures, and 0.71 (Ref. 16) using the response].

Effect of TLEB

Figure 9 shows the effect of symmetric TLEB on the first bending response for the 20% span twin-fin configuration. It can be seen that buffet onset occurs at around 27 deg for all cases. The effect of TLEB is to decrease the rate of buffet increase, so that the curves peak at higher angles of attack. A steady blowing rate of C_μ = 0.05 induces a simple shift in the twin-fin buffeting mechanism of around 6–7 deg, which is comparable to the angle-of-attack shift induced for a single-fin configuration.[7] However, the larger blowing rate gives an overall reduction in response levels, yet two peaks are discernable. Similar results were found for the 30% span separation configuration.

The effect of C_μ on the outboard and inboard rms pressures is presented in Figs. 10 and 11, respectively. For both cases, it can be seen that a blowing momentum coefficient of C_μ = 0.05 has induced a simple shift in the rms excitation levels, and that the larger blowing rate has caused lower overall levels of rms excitation. Both of these observations are consistent with the TLEB effects on the buffeting response.

Figures 12 and 13 show the PSD function of the fin differential pressures corresponding to C_μ = 0.00 and C_μ = 0.10, respectively, at α = 38 deg. It is clear that excitation levels are greatly reduced using TLEB, and hence, large reductions in twin-fin buffeting are achieved.

The effect of TLEB on the vortex modified frequency parameter is shown in Fig. 14. It can be seen that the parameter has been shifted to higher values (n_m = 0.60, C_μ = 0.00 and n_m = 0.65, C_μ = 0.10), which is equivalent to a reduction in effective angle of attack for a given wing sweep.

Conclusions

A system to alleviate twin-fin buffeting has been designed, built, and tested.

Two basic mechanisms for twin-fin buffeting were found for these wings. The first was when the leading-edge vortex shear layers overlapped the fins to reattach near the inboard face (near the tip), and was therefore a vortex/fin interaction in isolation. The second was characterized by the shear layers meeting between the fins themselves, providing additional inboard excitation. The buffeting mechanisms were typified by two different values of the modified frequency parameter, with the value for the second peak similar to that for single-fin configurations. Tests performed without the opposite vortex present confirmed that the second peak was a twin vortex phenomenon.

It was found that symmetric TLEB (at a rate of C_μ = 0.05) induced a linear shift in the buffeting excitation and response. Larger blowing rates reduced overall buffet excitation levels, and hence, substantially reduced buffeting response levels.

Acknowledgments

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