JOURNAL OF AIRCRAFT
Vol. 38, No. 1, January–February 2001

Tail Buffet of F/A-18 at High Incidence with Sideslip and Roll (Part 2)

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In Part 1 the variations of the mean and rms normal force, bending and torsional moment coefficients on the vertical fin of an F/A-18 aircraft for different orientations and Mach numbers were examined by integrating the measured pressure differences across the fin's surfaces. This paper examines statistically the fin loading with particular attention paid to the relationships between the normal force coefficient and the local surface-pressure fluctuations. Space-time pressure correlation studies were conducted to estimate the average convection velocities and paths of the coherent turbulent structures over the two surfaces of the fin. Power spectra for the force and moments were also computed. Within ranges of small to moderate sideslip and roll angles, all spectra contained distinct peaks at the same nondimensional frequency for a fixed Mach number and angle of attack. Only results at an incidence of 30 deg are reported here, as representative of results at three angles of attack (25, 30, and 32.5 deg). At this angle the nondimensional frequency is shown to decrease as the Mach number increased from 0.25 to 0.80. At large positive roll angles (about 30 deg) distinct peaks were no longer identifiable. The correlations and spectra, as well as coherence functions between the buffet load and the measured pressure fluctuations, demonstrated that the unsteady loading on the fin is caused primarily by the passage of coherent turbulent eddies over the fin's surfaces. The general conclusion of the present work is that asymmetry in the aircraft's orientation has a significant effect on buffet loads.

Nomenclature

C_B = instantaneous bending moment coefficient about the fin root
C_N = instantaneous normal force coefficient
C_T = torsion moment coefficient about the quarter-chord line
c = wing mean aerodynamic chord (210 mm)
E_B = power spectrum of the bending moment coefficient about the fin root
E_N = power spectrum of the normal force coefficient
E_T = power spectrum of the torsional moment coefficient about the quarter-chord line
f = frequency
k = nondimensional frequency, fc/U_∞
M = freestream Mach number
U_∞ = freestream velocity
α = angle of attack
β = sideslip angle
φ = roll angle

Introduction

QUANTITATIVE pressure measurements[1–10] on the vertical fins of the F/A-18 have been carried out in a number of laboratories using various scale models. A wind-tunnel study at the Institute for Aerospace Research, using a rigid 6% F/A-18 model, was carried out to investigate the effect of sideslip and roll angles on tail buffet loads at large angles of attack and different Mach numbers. In Part 1 (Ref. 8) both mean (steady) and rms (unsteady) force and moment coefficients on the vertical fin have been reported and discussed in conjunction with flow-visualization results in a water tunnel. In that reference the paths and burst locations of the leading-edge extensions (LEX) vortices for wide ranges of angles of attack, sideslip, and roll were given. Part 2 complements the earlier reported load measurements by presenting typical spectra and correlations of the surface pressure with the normal force on the vertical fin.

Received 29 February 2000; revision received 19 June 2000; accepted for publication 20 June 2000.

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Experimental Facility and Measuring Procedures

The wind-tunnel model, instrumentation, and experimental procedures have been described in Part 1. Space-time cross correlations between different time series, the power spectral densities of the force and moment coefficients, and the coherence function between the instantaneous normal force and the local surface pressure were computed using the Institute of Electrical and Electronics Engineers algorithms.[11] The frequency resolution of spectra was 4.7 Hz. A Hamming window was used, and a 50% overlap was applied between consecutive data blocks. The computed coherence values were smoothed by averaging the coherence over a frequency window width of 23.4 Hz.

Results and Discussion

Correlation Studies

Space-time cross-correlation studies were carried out between individual pressure transducer signals as well as between individual pressure signals and the instantaneous normal force on the fin. An objective of the correlation studies was to detect signs of organized motions (coherent structures) of the turbulent flow over the fin's surfaces. At high angles of attack, vortices roll around the LEX and the forebody and break down further downstream to create turbulent eddies. If some of these eddies maintain a recognizable identity as they are convected past the fin and leave a distinct signature on the surface-pressure variation, then they can be characterized as coherent structures. The size, speed, and trajectory of such a structure over the fin's surface can be deduced from analysis of the surface-pressure cross correlations. If, for example, a structure produces a peak pressure at a point on the fin's surface at a given time, it will also produce a peak pressure at a neighboring point at a different time, as it convects downstream. The ratio of the distance between these points and the time delay for peak pressure occurrence would give an estimate of the convection speed of the structure. Considering that the timing, size, and paths of these structures can vary, one would need to use sophisticated phase-averaging and pattern recognition techniques in order to characterize their convection patterns and other statistical features. Instead, these patterns were described using a simpler approach. Figure 1 shows a typical set of isocontours of the time delays for peak correlations between the signals of each pressure transducer and that of transducer 13 (Part 1, Fig. 3), located in the central region of the fin (this location was close to the one used in earlier studies[10]). These contours correspond to the case with $M = 0.60$, $\alpha = 30$ deg and zero sideslip and roll. Transducer outputs for which there was no clear correlation peak were discarded. Although the details of the contour patterns on the two surfaces are different, both sets indicate that the dominant structures moved nearly diagonally from the fin leading edge at the root toward the trailing-edge tip. The average convection velocity was approximately $0.55U_\infty$ on the outboard surface and $0.75U_\infty$ on the inboard surface. Another observation that can be based on Fig. 1 is that the turbulent structures which contributed most to the two-point correlations remained identifiable over nearly the entire fin surface on both sides of the fin.

The next point of interest was to identify the regions on each surface of the fin that contribute most to its load. This was achieved by performing a correlation analysis between the instantaneous normal force C_N and the pressure signal from each transducer. For each transducer on both the inboard and outboard surfaces of the fin, the peak value (positive or negative) of the corresponding correlation coefficient was recorded and used to construct contours of peak correlation coefficient values for a given set of flow conditions. The peak correlation contours for $M = 0.60$ and $\alpha = 30$ deg are shown in Fig. 2 for zero sideslip and roll, in Fig. 3 for zero roll and varying sideslip, and in Fig. 4 for zero sideslip and varying roll.

The zero sideslip/roll correlation contours (Fig. 2) show a fairly strong negative correlation coefficient up to approximately -0.55, between the normal force and the surface pressure in the central region of the outboard surface. An even stronger positive correlation coefficient, exceeding 0.65, was found between C_N and the pressure near the root of the inboard surface. This indicates that the strongly positive (i.e., pointing outboard) loading of the fin observed for this case was, statistically, associated with large suction near the center of its outboard side and large pressure near the root of its inboard side. The correlation coefficient diminished away from the peaks but maintained appreciable magnitudes throughout the fin's

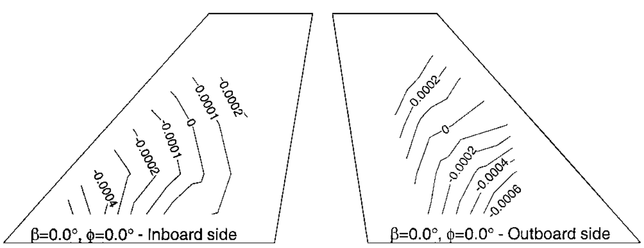

Fig. 1 Isocontours of peak correlation time delay (in ms), for M = 0.60, α = 30 deg, and zero sideslip and roll.

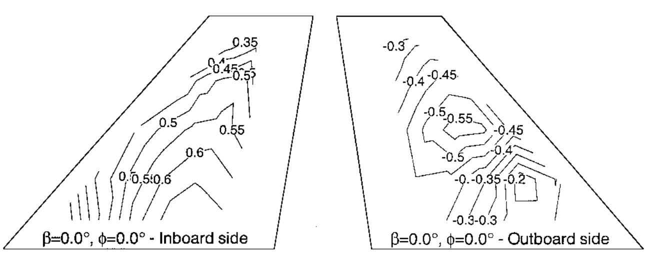

Fig. 2 Contours of peak correlation coefficient between the normal force and the surface pressure for M = 0.60, α = 30 deg, and zero sideslip and roll.

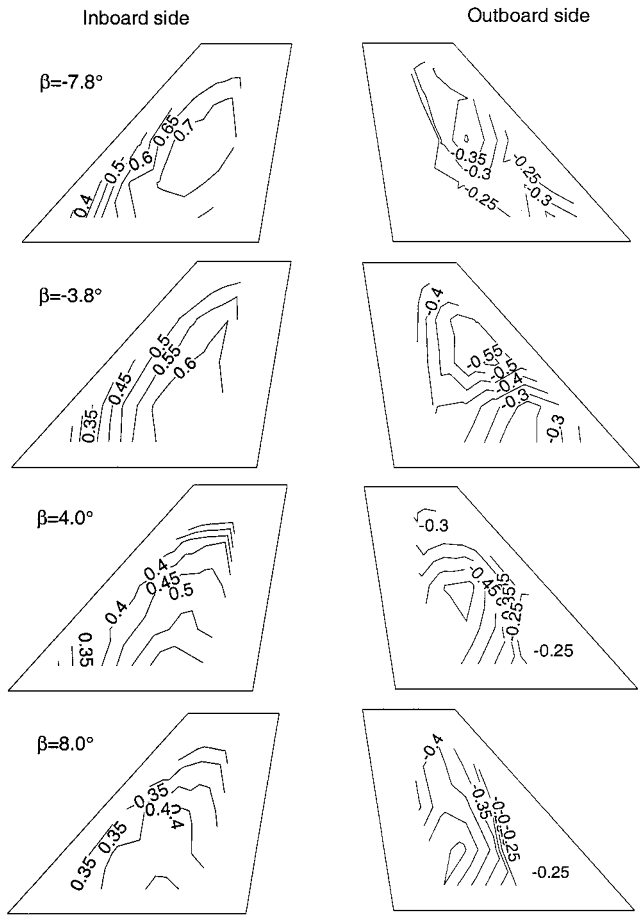

Fig. 3 Contours of peak correlation coefficient between the normal force and the surface pressure for M = 0.60, α = 30 deg, φ = 0 deg, and different sideslip angles.

surfaces without changing sign on a given surface. One may interpret the unsteady loading of the fin as the result of its interaction with relatively large coherent turbulent eddies, having typical length scales comparable to or possibly exceeding the fin's mean chord. These eddies can be traced back to the vortex that rolls up around the LEX leading edge and bursts aft the LEX fence for this angle of attack and Mach number. As a result, the vertical fin was entirely immersed in a turbulent flow possessing coherent structures.

Within the observed range from -7.8 to 8 deg, the effect of sideslip on the peak correlation coefficient was quite noticeable on both surfaces (Fig. 3). For a fixed angle of attack but with increasingly negative sideslip, flow-visualization[8] studies have shown that the starboard LEX vortex burst location moved further downstream toward the fin. The center of the vortical flow from the burst vortex was also displaced further away from the aircraft waterline and assumed a more outboard position. This is consistent with the presently observed movement of the high correlation regions toward the fin's tip. With increasing negative β, the port vortex burst location moved farther upstream toward the LEX apex, and some of the vortical flow passed through the gap between the vertical fins and impacted on the inboard surface of the starboard fin. Figure 3 shows that the peak correlation contours also moved closer to the fin tip, and the values increased with decreasing β. For positive β an increase in sideslip moved the center of the vortical flow region inboard, further away from the starboard fin outboard surface. The peak correlation contours on both surfaces decreased with β, and Fig. 3 shows that the highest correlation region moved toward the fin root.

The effect of roll (Fig. 4) on the surface correlation contours was also significant. The results presented include two cases with relatively large negative and positive φ. At $\varphi = -28.7$ deg the correlation coefficient reached the highest observed value 0.8 in the

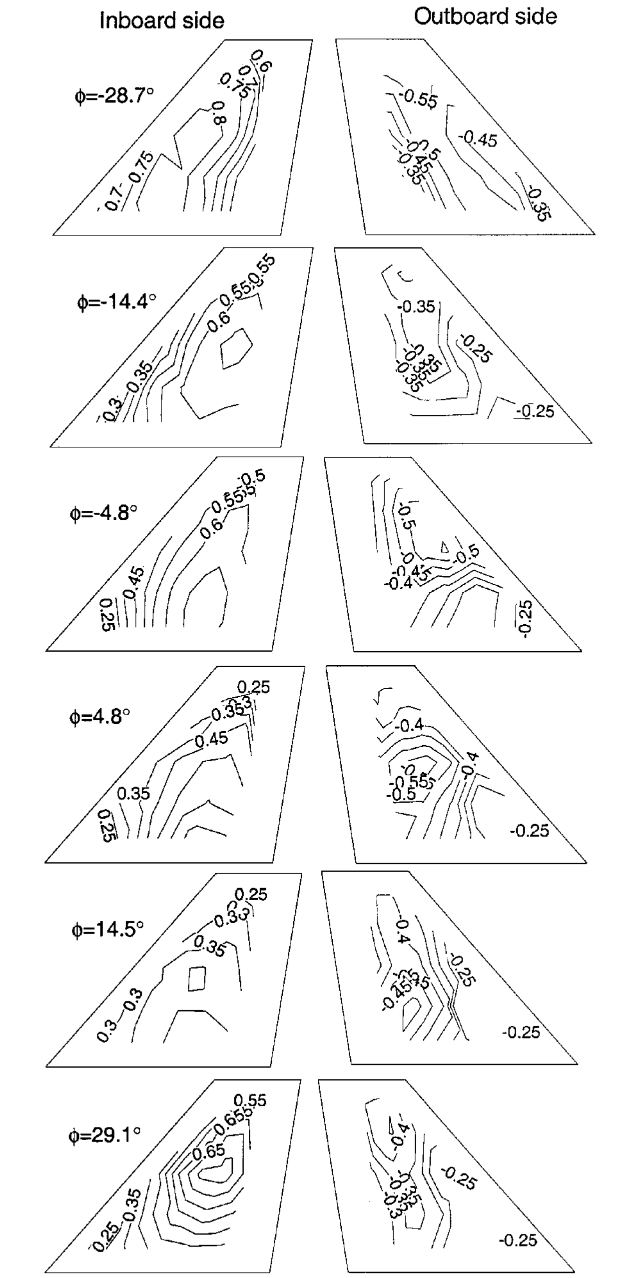

Fig. 4 Contours of peak correlation between the normal force and the surface pressure for M = 0.60, α = 30 deg, β = 0 deg, and different roll angles.

central region of the inboard surface. At $\varphi = 29.1$ deg a high peak of 0.65 was found in the central region of the inboard surface. This reverses the trend toward the fin root that the peak values followed at smaller positive φ. On the outboard side, the (negative) correlation peak occurred near the fin's tip at both extreme φ values.

Spectra

Power spectra of the normal force and the bending and torsional moment coefficients were computed for different sets of aircraft orientations and Mach numbers. The spectra were plotted vs the dimensionless frequency $k = fc/U_\infty$. On examining typical spectral curves such as those shown in Fig. 5 for a fixed model orientation and Mach number, the power spectra of the force and moment coefficients showed very comparable variations. This is to be expected because the peak pressure regions occurred neither very close to the fin root nor close to the quarter-chord line so that it was the same regions which contributed dominantly to the magnitudes and spectral characteristics of all three coefficients.

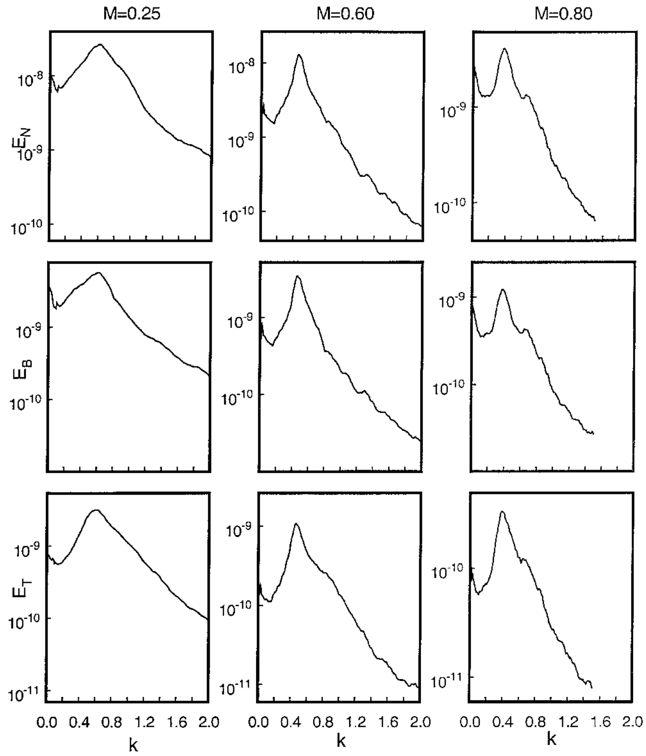

Fig. 5 Power spectra of the normal force and bending moment and torsion moment coefficients for α = 30 deg and zero sideslip and roll, at three different Mach numbers; the scales of the spectral axes are arbitrary but consistent.

As representative of the dependence of spectral contents on the aircraft orientation, we present power spectra of the normal force at $\alpha = 30$ deg, $M = 0.60$ and different roll angles in Fig. 6. At small roll angles we observe only minor differences in these spectra. It is clear that all spectra in the range -14.5 deg $\leq \varphi \leq 14.5$ deg contained distinct peaks at the same nondimensional frequency $k \approx 0.45$. At this point it is worth recalling that the instrumented fin was rigid, designed to have natural frequencies of vibration that were much larger than the frequencies of the observed spectral peaks. This excludes any significant aeroelastic contamination of the pressure signals and leads one to conclude that the frequency of the spectral peaks was equal to the characteristic frequency of production of the turbulent structures that contributed most to the unsteady loading of the fin. The fact that most of the spectral energy was concentrated near the peak implies that these structures dominated the turbulent activity in the vortex and that their rate of production was quite regular. All of these observations point to the plausible hypothesis that these structures are coherent and essentially periodic. At relatively large negative values of the roll angle (-28.7 deg $\leq \varphi \leq -19.2$ deg), the peak region centered at $k \approx 0.45$ broadened substantially. At large positive roll angles (19.4 deg $\leq \varphi \leq 29.1$ deg) the peak disappeared altogether, and the spectrum decreased monotonically. Similar observations were made for the $M = 0.80$ results, which are not shown here. Flow visualization[8] has demonstrated large changes in the paths and bursting locations of the LEX vortices at large roll angles. For example, at $\varphi = -30$ deg the windward LEX vortex was highly turbulent and burst far upstream of the fins, whereas the leeward LEX vortex burst in the vicinity of the starboard fin, well past the trailing edge of the main wing. In consequence, the port fin was fully immersed in the wake of the port vortex, and the inboard surface of the starboard fin was impacted upon by vortical fluid from the port LEX vortex. These results are compatible with the spectral shapes and the wind-tunnel measurements of unsteady forces.[8] At large positive roll the unsteady loading of the starboard fin was caused by a random turbulent flow and did not show a preferred frequency. At large negative roll the fin was affected to a much greater degree by the LEX vortex bursting process,

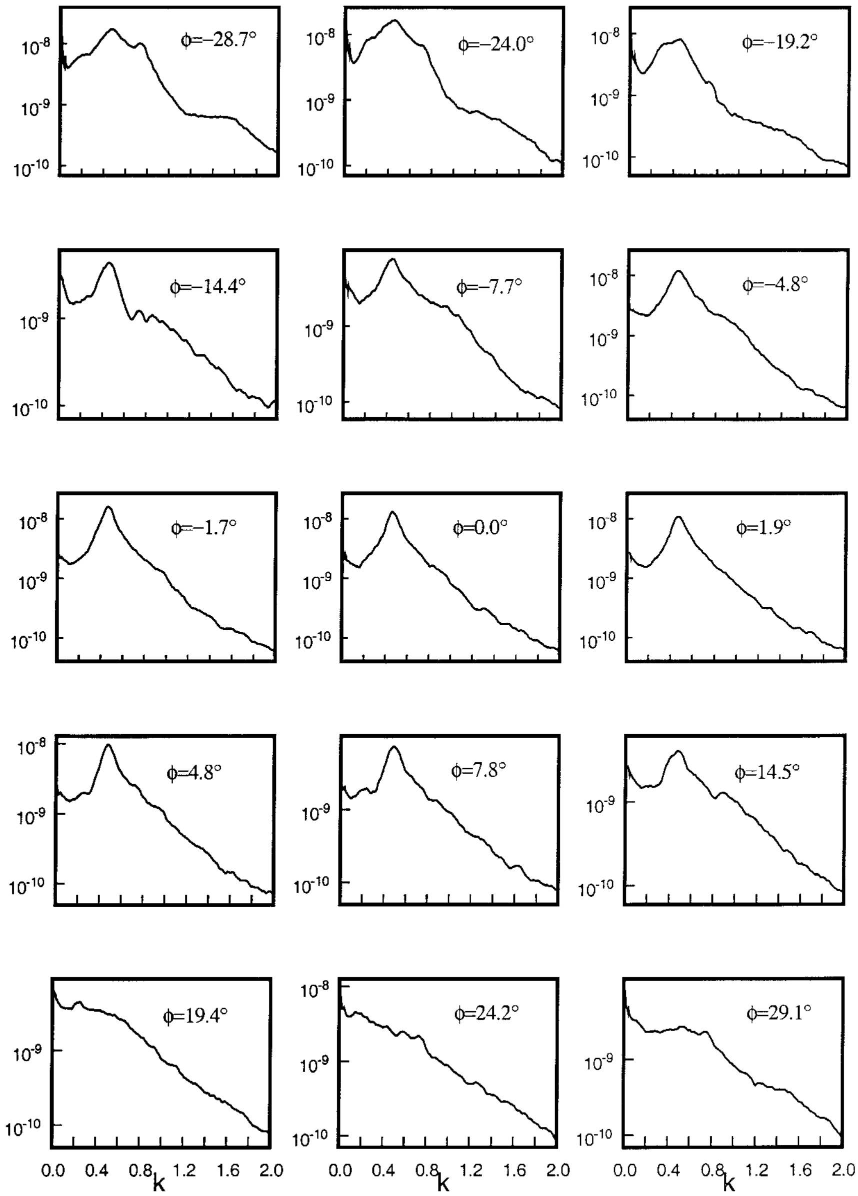

Fig. 6 Effect of roll on the power spectrum of the normal force; M = 0.60, α = 30 deg, β = 0 deg; the scales of the spectral axes are arbitrary but consistent.

which occurred mainly on its outboard side, as shown in the flow-visualization studies.[8] In the latter case the vortical flow did not have a distinct characteristic frequency as it did in the cases at smaller roll angles. The rms normal force was found to increase substantially at large negative roll angles,[8] possibly indicating an increasing importance of noncoherent turbulence in the flow approaching the vertical fin.

Coherence Studies

Coherence studies between individual pressure transducer signals and the normal force coefficient on the fin were carried out for $\alpha = 30$ deg, $M = 0.6$, and various values of β. The coherence function of two random processes, defined as the ratio of their cross spectrum and the square root of the product of the two power spectra, is, generally, a complex function. Its magnitude indicates the degree by which the two random processes are affected by the same excitation mechanism at a particular frequency. The results have been plotted in the form of contours of constant coherence magnitude on each side of the fin at a fixed value of the nondimensional frequency k. Plots at $k = 0.25$, 0.50, 0.75, and 1.00 were examined, but of particular interest are the contours at $k = 0.50$, because, as shown in Figs. 5 and 6, peaks at $k \approx 0.45$ represented the spectral range that contributed the most to the loading of the fin. Sample coherence contours are presented in Fig. 7, which correspond to measurements at zero roll and three sideslip angles $\beta = -3.8$, 0.0, and 4.0 deg. The coherence reached relatively large values, especially on the inboard side, where it was as high as 0.8 (note that the value of 1 corresponds to perfect coherence). The coherence contours resemble in shape to the correlation contours presented in Fig. 3 and support the earlier results that the major contribution to the unsteady fin loading was a result of the excitation by the coherent structures of the vortical flow. At the three sideslip values considered, the coherence peak was found in a region in the vicinity of the midchord, approximately 30% span, for the inboard surface of the fin. For the outboard surface the maximum coherence magnitude was located close to the midspan in the vicinity of the fin leading edge. The coherence magnitude at different values of k (not shown here) was substantially lower than that at $k = 0.50$, reinforcing the earlier hypothesis that the coherent eddies of the burst LEX vortical flow are largely responsible for the peak buffet load having a characteristic frequency of approximately 0.45.

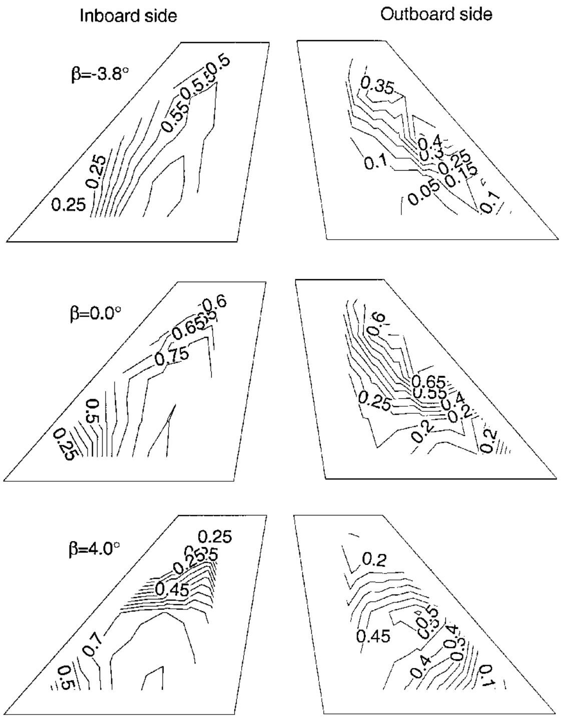

Fig. 7 Isocontours of the pressure-normal force coherence function magnitude for $M = 0.60$, $\alpha = 30$ deg, $\varphi = 0$ deg and three different sideslip angles.

Conclusions

The effects of sideslip and roll on the buffet loads experienced by the vertical fins of the F/A-18 at high angles of attack were investigated. The buffet loads were computed for three Mach numbers (0.25, 0.60, and 0.80), three angles of attack (25, 30, and 32.5 deg), and moderate ranges of sideslip and roll angles. Statistical information on the pressure field, forces, and moments on the starboard vertical fin have been presented. Surface-pressure correlation studies indicate that the flow over both surfaces of the vertical fins contained coherent structures, whose spatial extent was identifiable over nearly the entire fin surface. At $\alpha = 30$ deg, $M = 0.6$, and zero sideslip, these structures moved faster over the inboard side than over the outboard side. Correlation studies between the local surface pressure and the instantaneous normal force on the fin identified the regions on the two sides of the fin that experienced the most intense loading. These regions shifted toward the fin tip with sideslip or roll. Representative power spectra for the normal force, bending and torsional moments show a dominant peak at a particular frequency, which varied with the Mach number and angle of attack. The spectral peak is attributable to the interaction of the vertical tail with a burst LEX vortical flow containing coherent structures. Asymmetric orientations caused significant changes in the spectral shapes, and for large positive roll angles produced monotonically decreasing spectra, which is evidence of a broadband excitation. The coherence function between the buffet load and the surface-pressure fluctuations was used to identify the fin surface regions that were subjected to the most intense loading.

Acknowledgments

Financial support for this project has been provided by the Department of National Defence and by the National Research Council of Canada, Institute for Aerospace Research.

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