Buffeting of Fins: An Assessment of Surface Pressure Loading

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Introduction

BUFFETING of aircraft fins by streamwise vortices has emerged as a problem of central importance. Typically, vortex breakdown occurs prior to impingement of the vortex(ices) on the leading edge of the fin. Such breakdown induces surface pressure fluctuations, which may lead to vibration of the fin. In recent years, there have been a wide variety of investigations of both simplified fin–delta wing configurations and fins on actual model aircraft. Bean and Wood,[1] Washburn et al.,[2] Wolfe and Rockwell,[3] and Canbazoglu et al.[4] have determined the pressure spectra at various locations on fins mounted on or immediately downstream of delta wings having sweep angles in the range of 60 deg $\leq \lambda \leq$ 76 deg. Triplett[5] has characterized the fluctuations on the fin of a model F-15 and Wentz,[6] Ferman et al.[7] Shah,[8] Lee and Tang,[9] Martin and Thompson,[10] and Lee et al.[11] have determined the surface pressure spectra on fins of model F/A-18 aircraft. A summary of recent investigations is given in Table 1. Reynolds numbers Re are based on root chord for delta wing configurations and on mean aerodynamic chord for scale models of F-series aircraft. These investigations span a wide range of Reynolds number, $0.4 \times 10^4 \leq Re \leq 3.38 \times 10^6$ and freestream Mach number, $0 \leq M \leq 0.6$. The issue arises as to whether the shapes of the surface pressure spectra and the predominant frequencies of these spectra exhibit common features and obey simple scaling laws.

The onset of vortex breakdown is presumed to play a major role in dictating the spectral content of the pressure fluctuations on the fin. Assessments of criteria for the onset of vortex breakdown are given by Leibovich[12] and Brown and Lopez.[13] The spectral content of the fluctuating velocity field following the onset of vortex breakdown is addressed by Garg and Leibovich.[14] Such breakdown will, of course, give rise to unsteady loading of the surface of the wing in absence of a fin. Roos and Kegelman[15] have characterized the fluctuating normal-force coefficient for delta wings, and Gursul[16] has determined the predominant frequencies of surface pressure fluctuation on surfaces of families of wings. Gursul establishes a scaling criterion $fx/U_0 = f(\Gamma/U_0)$ in which x is the distance from the apex of the wing, U_0 is the freestream velocity, and Γ is the circulation of the leading-edge vortex. This dimensionless frequency is nearly constant for fixed angle of attack and sweep angle. Moreover, Gursul found that the pressure fluctuations on the surface of the wing are due to helical waves arising from instability of the swirling wake flow in the region of vortex breakdown. Indeed, characterization of the instantaneous structure of vortex breakdown on a delta wing shows a helical-mode instability involving well-defined concentrations of azimuthal vorticity, as described by Towfighi and Rockwell[17] and Lin and Rockwell.[18]

Of course, a rigorous approach to scaling the unsteadiness of vortex breakdown that buffets the surface of a wing or fin requires knowledge of the characteristic axial and swirl velocities and the local diameter of the vortex. Such detailed information is typically not available from practically oriented aerodynamic studies. In fact, in many investigations, the location of the onset of vortex breakdown is unknown. The intent of this Note is to provide a summary of existing data on fin buffeting and its approximate scaling based on global length and velocity scales. Only those investigations involving a rigid fin were considered; exceptions involve cases where the surface pressure spectra were sufficiently decoupled from the structural response spectra.

Spectra of Surface Pressure Fluctuations

Figure 1 shows comparison of dimensionless spectra of surface pressure on the outboard and inboard sides of the fin. The amplitude ratio A/A_0 represents the ratio of the power spectral density of the surface pressure fluctuation to its maximum value occurring at the peak frequency f_0, i.e., $\overline{p^2}(f)/\overline{p^2}(f_0)$. The symbols of Fig. 1 correspond to the investigations given in Table 1. These symbols are for identification purposes only; actual spectra in all investigations are presented as continuous curves. Moreover, it should be emphasized that the geometry of the fins in each of these cited investigations was different. In Fig. 1, the overall features of each fin are defined in terms of the parameters given in the schematic. The locations x and y of the surface pressure transducers are normalized by the root chord C_F of the fin and its span S_F. Spectra on the outboard side of the fin, taken at approximately midspan, i.e., $0.58 \leq y/S_F \leq 0.60$, are shown in the plot at the upper left of Fig. 1. Correspondingly, spectra taken on the outboard side near

Table 1 Definition of configurations and parameters for investigations of surface pressure fluctuations on fins

	Authors	Model	Sweep angle, deg	Re	M
○	Canbazoglu et al.[4]	Delta wing	75	5.01×10^4	0
-●-	Triplett[5]	13% F-15	——	$\sim 8 \times 10^5$	~0.09
●	Lee/Brown[19]	6% F/A-18	——	3.38×10^6	0.6
▽	Shah[8]	6% F/A-18	——	1.08×10^6	0.08
-▼-	Wentz[6]	2.1% F/A-18	——	$0.4\text{-}1.3 \times 10^4$	0
▼	Ferman et al.[7]	12% F/A-18	——	6.5×10^5	0.07
□	Wolfe/Rockwell[3]	Delta wing	75	5.01×10^4	0
■	Lee/Tang[9]	6% F/A-18	——	3.38×10^6	0.6
△	Lee et al.[11]	6% F/A-18	——	3.38×10^6	0.6
▲	Washburn et al.[2]	Delta wing	76	$0.5\text{-}1.0 \times 10^6$	0.04–0.14
◇	Bean and wood[1]	Delta wing	60	$\sim 0.8 \times 10^6$	~0.08
◆	Martin and Thompson[10]	11% F/A-18	——	$0.5\text{-}1.6 \times 10^6$	0.06–0.18
▭	Gursul[16]	Delta wings	60–75	$0.3\text{-}1.0 \times 10^5$	0.01–0.05

Received Aug. 31, 1994; revision received Jan. 13, 1995; accepted for publication Jan. 25, 1995.

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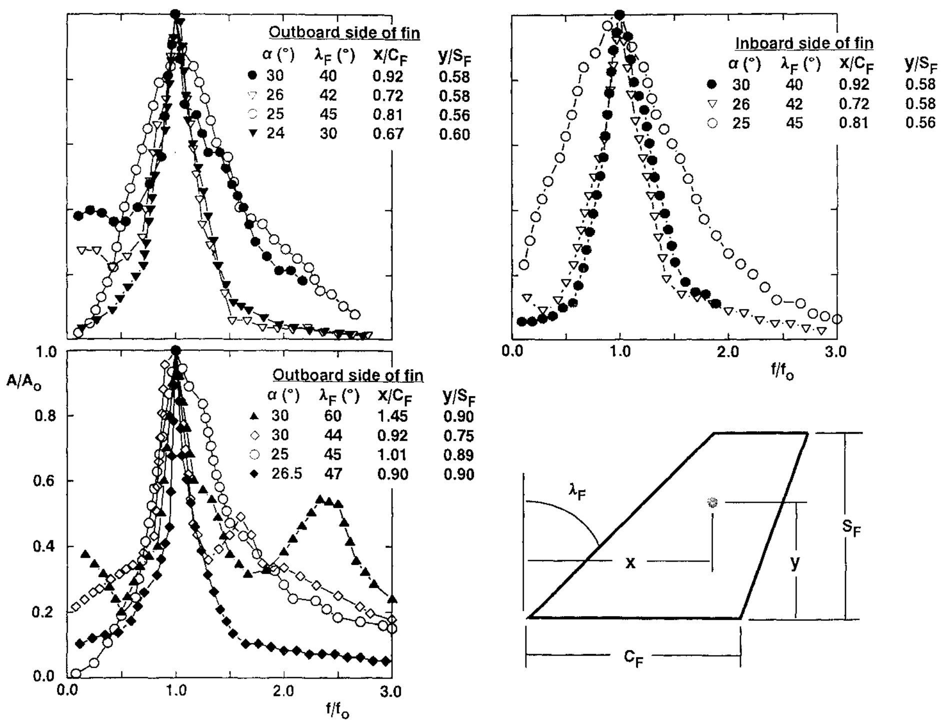

Fig. 1 Amplitude A of power spectral density of surface pressure fluctuation on fin as a function of frequency f, normalized by peak amplitude A_0 and frequency f_0 at which peak occurs.

the tip of the fin, $0.75 \leq y/S_F \leq 0.90$, are shown in the plot at the bottom left. Spectra on the inboard side of the fin are given in the plot at the upper right. It is important to recognize that in addition to the various configurations of fins the nature of the incident vortex and, therefore, its spectral content prior to impingement on the fin will be a function of whether a simplified delta wing configuration or an actual model of the aircraft is employed. Despite the wide range of variability of configurations and experimental conditions corresponding to the investigations of Fig. 1, it is evident that a well-defined peak occurs in all spectra. It must be emphasized, however, that the sampling frequency and fast Fourier transform (FFT) size, which were not generally available, will influence the sharpness of the peaks in each of the A/A_0 vs F/f_0 distributions of Fig. 1. For this reason, it is not appropriate to compare the values of quality factor for different spectra. The general observation that relatively sharp spectra can occur over such a wide range of Reynolds number, as defined in Table 1, suggests that the fluctuations due to vortex breakdown are driven by predominantly inviscid mechanisms.

Predominant Frequencies of Surface Pressure Fluctuations on Fin

Consideration of spectra of the sort shown in Fig. 1, as well as a wide range of other spectra corresponding to the investigations of Table 1, gives the plot of Fig. 2. It shows the dimensionless peak frequency of the pressure spectrum f_0x/U_0 vs angle of attack α, in which x is the distance measured from the effective origin of the vortex to the location of the surface pressure transducer on the fin. For the case of a simple delta wing, x is measured from the origin of the vortex, and for a model of aircraft with a LEX, it is from the apex of the LEX. In the absence of a LEX, it is measured from the junction of the wing with the fuselage. For reference purposes, the data of Gursul,[16] corresponding to pressure fluctuations on the surface of a delta wing without a fin, are indicated on Fig. 2 by thick gray lines and the symbols Δ ($\lambda = 60$ deg) and Δ (75 deg). Furthermore, for purposes of guiding interpretation of data, three curve fits are shown for simple delta wing–fin configurations, designated by Δ_F (~75 deg) and Δ_F (60 deg.) These lines correspond to third-order linear curve fits through all data of fin–delta wing configurations. For the sweep angles $\lambda = 75$ deg or 76 deg, designated here as $\lambda \sim 75$ deg, i.e.,Δ_F (~75 deg), there are two curves, one corresponding to an upper range of frequencies and the other to the lower range. The upper range of frequencies correspond only to the

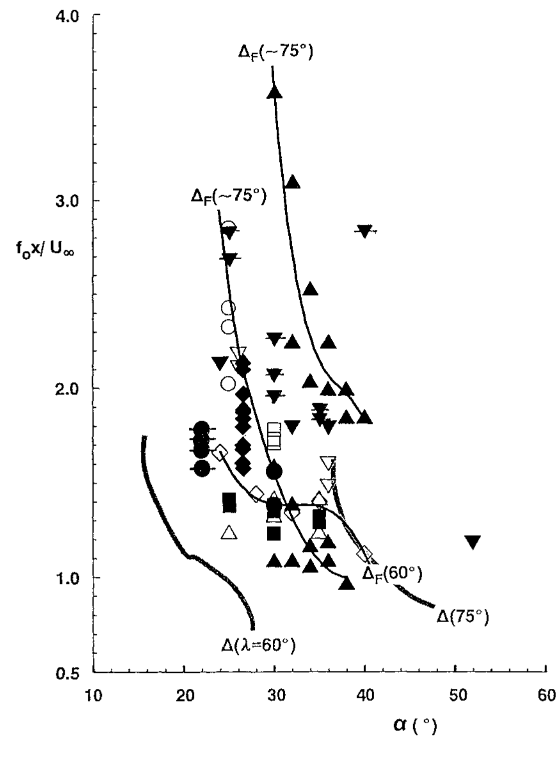

Fig. 2 Dimensionless frequency f_0x/U of peak of spectrum f surface pressure fluctuation as a function of angle-of-attack α; symbols Δ and Δ_F denote wings without and with fins, respectively.

data of Washburn et al.,[2] for which the fin was located downstream of the trailing end of the delta wing, in contrast to other studies where the apex of the fin is upstream of the trailing end. In the investigation of Washburn et al.,[2] there were two predominant peaks: the higher peaks correspond to the upper Δ_F (~75 deg) curve and the lower peaks to the lower Δ_F (~75Δ) curve. In general, all Δ_F curves show the same general trend as the Δ curves for delta wings without fins. That is, the dimensionless frequency f_0x/U_0 decreases substantially with increasing angle of attack α. Although the data corresponding to the F-series model aircraft show no particular

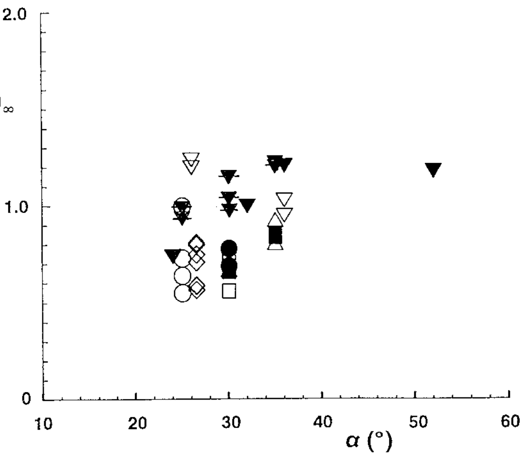

Fig. 3 Dimensionless frequency $f_0 x_b/U$ of peak of spectrum of surface pressure fluctuation as a function of angle-of-attack α; distance x_b is from onset of vortex breakdown to location of pressure transducer.

trend, no doubt, due to the complexity of these configurations, the extreme values of frequency $f_0 x/U_0$ approximately correspond to the extreme values for the simple delta wing–fin configurations Δ_F. The major share of the data lie in the range $1.0 \leq f_0 x/U_0 \leq 3.0$. The fact that these dimensionless frequencies lie within a definable band of dimensionless frequencies $f_0 x/U_\infty$ suggests that the same principal mechanism is responsible for their generation. The occurrence of large-scale instabilities in the wake type bubble, immediately following the onset of vortex breakdown, appears to be the principal excitation mechanism over a wide range of Reynolds and Mach numbers, and it appears that scaling on the basis of x, the distance from the origin of the vortex, is a reasonable approximation for determining the order of the predominant frequency.

For certain experiments listed in Table 1, it is possible to deduce the location of vortex breakdown and thereby determine the distance x_b from the onset of breakdown to the location of the pressure tap on the fin. The plot of Fig. 3 shows that the data normalized on this basis lie in the range $0.5 \leq f x_b/U_0 \leq 1.3$. Recasting $f x_b/U_0$ as $x_b/(U_0/f)$, the distance, x_b appears to be of the same order as an equivalent freestream wavelength $\lambda_0 = U_0/f$. Of course, the wavelength λ of the instability within the vortex increases substantially in the streamwise direction after the onset of breakdown. Further insight into the flow structure is required to relate this wake instability to the data correlation of Fig. 3.

Acknowledgments

The authors are pleased to acknowledge support of the Air Force Office of Scientific Research through Grants AFOSR-91-0055, F49620-93-1-0075, and F49620-94-1-0038.

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Flow Visualization Using Natural Condensation of Water Vapor

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I. Introduction

RECENT interest in transonic axial compressor rotors has driven a need for the development of a flow visualization technique to assess characteristic flow structures that impact rotor performance. Losses associated with blade passage shock waves and/or blade tip vortex–shock interactions are not well understood. Numerous experimental studies, generally involving the measurement of casing surface pressures (steady) or wake pressure distributions, offer little insight into detailed blade passage flow structure. It is clear that measurement of the internal flow structure requires a nonintrusive technique since the disturbance introduced by conventional pressure and/or thermal sensors will alter the natural flow. Furthermore, the adaptation of intrusive sensors is operating turbomachinery presents a formidable engineering challenge. The purpose of the present Note is to describe a planar imaging technique which makes use of condensing water vapor. Implementation of the technique is straightforward in steady flow applications and, thus, offers a cost effective means to visualize high-speed flows. The work presented here was part of pilot study to demonstrate a flow visualization technique which could be adapted to an operating compressor rotor environment.

The use of Mie scattering in flow visualization is commonplace at low speeds.[1] Applications involving higher speeds are less well known but have been demonstrated. Goddard et al.[2] appear to have been the first to successfully introduce smokelines, formed by vaporizing an oil into a transonic flow. Images were recorded on photographic film simultaneously with schlieren images. McGregor[3] considered condensation of water vapor as a means to visualize flows over transonic delta wings. The formation of condensed vapor in those experiments was a result of low stagnation pressures and temperatures used in a closed-loop wind tunnel. Flow pressures and temperatures are not always conducive to condensation except

Received Nov. 30, 1994; revision received Jan. 16, 1995; accepted for publication Jan. 25, 1995.

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