minimum-time trajectories with three time-zones of azimuth changing. A mild turn at the beginning, an almost level flight, and a final tight turn. An approximation to the problem, with a constant-speed assumption, has been shown to be in good agreement with the exact solution.

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Effect of Leading-Edge Extension Fences on the Vortex Wake of an F/A-18 Model

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Introduction

ONE of the topics of current interest in high angle-of-attack (AOA) aerodynamic research is the interaction between the F/A-18's leading-edge extension (LEX) vortex and the vertical tail surfaces. The resulting buffeting of the vertical tails has led to the development and implementation of a LEX fence for the F/A-18. Recent investigations of vertical tail buffet of the F/A-18 aircraft, both in wind-tunnel tests[1–3] and flight tests,[4] have shown that the LEX fence has little effect on the position of vortex burst, but causes formation of a second vortex near the fence and reduces the dynamic loading on the vertical tail. Brief reviews of the previous studies related to tail buffeting phenomena on twin-tailed aircraft at high AOA appear in Refs. 5 and 6. Data on spectral energy content of the vortex, both with and without LEX fences, will significantly add to the understanding of vortex/tail surface interaction. To this end, an investigation was conducted in the Naval Postgraduate School (NPS) 32- by 45-in. low-speed wind tunnel, using a 3% scale model of the Northrop YF-17, the lightweight prototype from which the F/A-18 was evolved.[7] The results of the hot-wire surveys of the downstream wake with and without LEX fences are discussed, with particular emphasis on power spectral data. Additional details of the investigation appear in Refs. 7 and 8.

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Experimental Program

The NPS tunnel is a closed-circuit, single-return, horizontal-flow wind tunnel with a contraction ratio of 10:1, a test section 1.143 m wide by 0.813 m high by 1.219 m long, a maximum test section velocity of 80 m/s, and a nominal free-stream turbulence level of 0.2%. A yoke assembly attached to a horizontal turntable located in the center of the test section floor permits sting-mounting of the model and variable pitch angles (Fig. 1). The diameters of the sting and the vertical strut were 15.9 and 25.4 mm, respectively, and the distance of the vertical strut to rear of the model was 0.133 m. The 3% YF-17 model having a length of 0.486 m, a wingspan of 0.32 m and a mean aerodynamic chord (MAC) of 0.098 m was chosen due to its close similarity to the F/A-18 and its availability. Dissimilarities between the YF-17 and the F/A-18 were considered minor enough in the investigation of the effects of the LEX fence.[7–9] The model was configured with neutral flap settings and wingtip missiles. Note that the same model was tested in Ref. 5, but without wingtip missiles. The 3% scaled version of the NASA Ames LEX fences was constructed from 0.8-mm-thick balsa wood and installed one on each side of the model near the junction of the LEX and the wing.[8]

Flow visualization by injection of smoke into the test section at low tunnel velocities (5–10 m/s) helped determine the approximate location of vortices downstream of the model. This information was subsequently used to determine locations for hot-wire surveys. The crossprobe was mounted on a traversing mechanism (Fig. 1) that allowed surveying laterally by turning the traversing crank. A spectrum analyzer provided spectrum

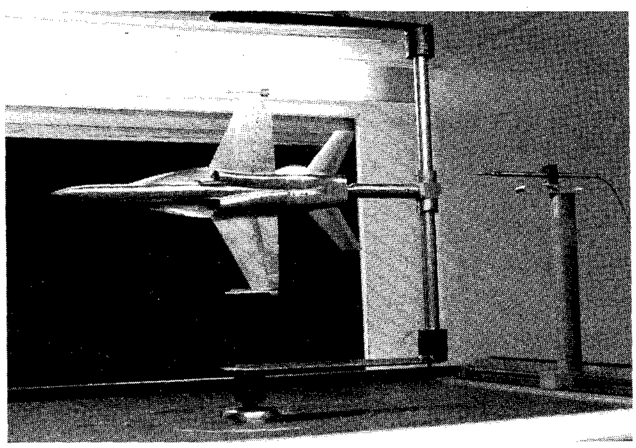

Fig. 1 Model in the NPS wind tunnel with hot-wire probe at station B.

averaging for up to 1024 display frames. The input was resolved into 400 separate frequency filters. The horizontal hot-wire surveys and spectrum measurements were made at several downstream locations, but the results to be discussed below refer to a near downstream location (called station B) 76 mm aft of the model support column at a height 51 mm above the model centerline. At station B, the hot wire probe was located approximately 0.43 model lengths aft of the model. The data were collected at several freestream velocities (10–50 m/s). At 50 m/s, the freestream dynamic pressure was 1537 N/m^2 and the Reynolds number was 3.4×10^5 based on the MAC.

Results and Discussion

The model orientation corresponding to maximum velocity fluctuation in the downstream vortex wake was determined from the mean and turbulence data obtained from horizontal sweeps at station B at a tunnel freestream velocity of 50 m/s and intervals of 1 deg in the AOA range of 20–30 deg. The turbulence data from these surveys indicated that the peak turbulence increased with AOA up to 25-deg AOA, after which it decreased.[7] Although station B is downstream of the vertical tail, this finding is consistent with the observation of Sellers et al.,[5] that at 25-deg AOA the LEX vortices burst in the vicinity of wing-LEX intersection and impact directly on the vertical tails, raising the rms levels of the turbulent fluctuation in that region. The effect of LEX fence was therefore investigated at 25-deg AOA and covered a freestream velocity range of 10–50 m/s.

Figure 2 shows the turbulence data obtained from hot wire surveys at station B at a freestream velocity of 50 m/s for the case of no LEX fence and LEX fence installed. The horizontal axis represents transverse distance X (nondimensionalized with MAC) of survey location from the tunnel centerline. The vertical axis represents the lateral component of turbulence where the rms value has been normalized with the local mean axial velocity at each data point. In view of the estimated measurement uncertainty of ± 0.001, the differences in the turbulence intensity between the case of no LEX fence and LEX fence installed may not be very easily discernible. Disregarding the support column wake, it is seen that the location of the maximum turbulence intensity corresponds to the horizontal location X/MAC = 1.02, and that the intensity is higher with the LEX fence installed.

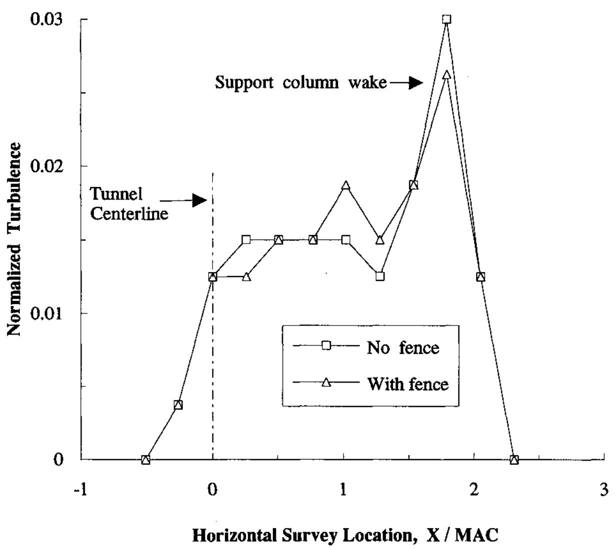

Fig. 2 Turbulence survey at station B with and without LEX fence; tunnel velocity = 50 m/s, AOA = 25 deg.

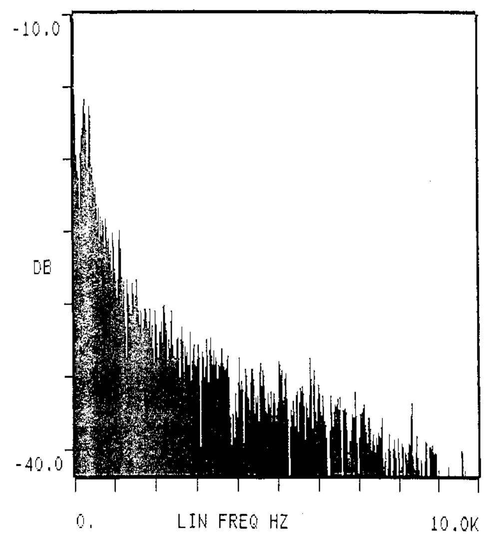

Fig. 3 Power spectra of turbulence at station B without LEX fence; tunnel velocity = 50 m/s, AOA = 25 deg.

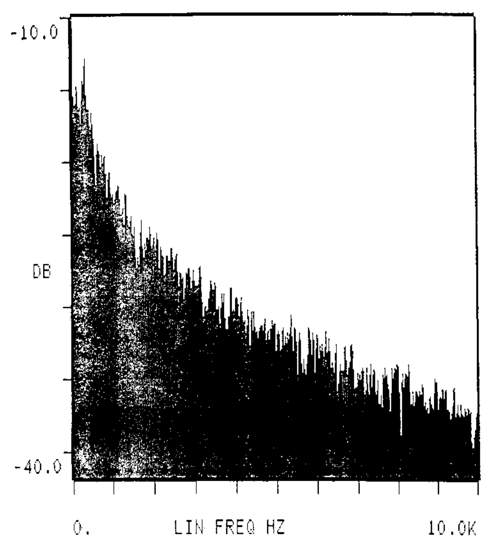

Fig. 4 Power spectra of turbulence at station B with LEX fence; tunnel velocity = 50 m/s, AOA = 25 deg.

Spectra at station B obtained at 25-deg AOA (yielding maximum fluctuation) for the case of no LEX fence and LEX fence installed, at test section velocities of 10, 20, 30, 40, and 50 m/s, were recorded[7] for each case at the location corresponding to maximum turbulence (X/MAC = 1.02). Figures 3 and 4 show typical spectra at 50 m/s for the case of no LEX fence and LEX fence installed, respectively. They clearly indicate a shift in the high frequency turbulence energy content to larger values with the LEX fence installed. Also, the frequency content extends over a wider band. These observations are also valid for the low frequency spectra obtained at lower tunnel velocities (10–40 m/s).[7] Because of the increase in the spectral level with the LEX fence fitted, the integration of the spectral curve will show a higher overall turbulence intensity, which is consistent with the earlier observation based on hot wire turbulence data (Fig. 2).

It should be noted that the above observation at station B (which is based on the lateral turbulence component), assumes that the longitudinal and transverse turbulence components behave in a manner similar to the lateral component. In the absence of any measurements upstream of the vertical tail, the present data are taken as indicative of the redistribution of turbulence to high frequencies. This is in agreement with the qualitative observation of Thompson,[10] that the addition of the LEX fence results in the formation of a secondary fence vortex that interacts with the primary LEX vortex, possibly altering the frequency of any unsteady flow component downstream of the vortex breakdown. The redistribution of turbulence to higher frequencies is a desired feature of adding the LEX fences because, if done properly, it could move turbulence away from the critical low frequencies of the vertical tail. The present data corroborate those of recent wind-tunnel and flight measurements of tail buffet on the F/A-18,[1–4] which have shown that the LEX fence extends the turbulence frequency content over a wider band and reduces the fin tip acceleration considerably.

Conclusions

A low-speed wind tunnel investigation was conducted to examine the vortex wake downstream of a 3% scale model of the YF-17 at high AOAs. The hot-wire and power spectrum measurements were made in the velocity range of 10–50 m/s with and without the LEX fences. The following conclusions are drawn from this investigation:

1) The maximum turbulent fluctuation at a near downstream station just aft of the model occurred with the model oriented at 25-deg AOA.

2) The addition of LEX fences increased the spectral levels and shifted the power spectrum toward higher frequencies.

Acknowledgments

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Turbulent Effects on Parachute Drag

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I. Introduction

ONE of the key indicators to measure the overall performance of fully deployed parachutes is the value of the drag coefficient.[1–3] Recently,[4] a wind-tunnel experiment was performed to measure the time-average value of this coefficient for a "parachute-like body" that was nonporous but "somewhat compliant." The objective of this Note is to compare this experimental result with the predictions of different turbulence models in different CFD implementations. However, no attempt will be made here to compare the local values for the pressure and velocity that were obtained in these simulations. Furthermore, we restrict our study to the steady-state (or time-average) flow around the parachute, although other studies[5] indicate notable time-variations in the value of the drag coefficient due to vortex shedding.

To gauge the importance that turbulent effects have on the value of the drag coefficients, one can use dimensional analysis. This analysis shows[6] that for laminar flow parallel to a finite flat plate the drag coefficient cd is proportional to $(Re)^{1/2}$ (where Re is the Reynolds number), on the other hand when turbulence effects are taken into account we obtain that $cd \approx (u/U)^2$, where u is the turbulent velocity residual in the wake and U is the freestream velocity. Consequently, one is led to expect that turbulent effects will have critical importance in the correct computation of this coefficient.

For parachutes, the need for this study is accentuated further by the fact that the flowfield around parachutes have three length scales. The first is the parachute span that is of the order of 10 m, the second is its thickness that is of the order of 10^{-3} m, whereas the third is related to the wake whose size can exceed 200 m. To resolve the flowfield under these conditions requires careful adjustments of the grid and the turbulence model to obtain convergence of the solution and valid results.

II. Turbulence Models and CFD Tools

To simulate incompressible fluid flow one has to solve Navier-Stokes equations, which in nondimensional form are

$$\nabla \cdot u = 0$$

$$\frac{\partial u}{\partial t} + (u \cdot \nabla) u = -\nabla p + \frac{1}{Re} \nabla^2 u$$

In these equations, u is the fluid velocity, p is the pressure, and Re is the Reynolds number, which is defined as

$$Re = (UL/\nu_0)$$

Here, U and L are the characteristic velocity and length, and ν_0 is the dynamic viscosity of the fluid. The basic modeling assumption is that ν is actually a dynamic variable whose actual value at each point depends on the local flow conditions. Thus

$$\nu = \nu_T + \nu_0$$

where ν_t is the "turbulent viscosity."

Many turbulence models for fluid flow exist in the literature.[7] Of these models the most important from an engi-

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