A Method to Analyze Tail Buffet Loads of Aircraft

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SUMMARY

In general, aircraft designers have committed large resources to the design of aircraft in meeting performance goals. Despite fulfilling traditional design requirements, many fighter aircraft have encountered buffet loads when demonstrating their high angle-of-attack maneuver capabilities. As a result, during test or initial production phases of fighter development programs, many new designs are impacted, usually in a detrimental way, by the effects of buffet that result in reassessing designs or limiting full mission capability originally desired. These troublesome experiences usually stem from overlooking or completely ignoring the effects of buffet during the design phase of aircraft. Perhaps additional requirements are necessary that addresses effects of buffet in achieving best aircraft performance in fulfilling mission goals.

In attempt to address a buffet loads requirement, this paper describes a reliable, fairly simple, but quite general analysis method to use in the initial design phases of fighter-aircraft program. The method is very similar to the random gust load analysis that is now commonly available in a commercial code, which this analysis capability generally employs with some key modifications. The paper describes the theory and the implementation of the methodology. The method is demonstrated on a JSF prototype example problem. The demonstration also serves as a validation of the method, since, in the paper, the analysis is shown to nearly match the flight data. In addition, the paper demonstrates how the analysis method can be used to assess candidate design concepts in determining a satisfactory final aircraft configuration.

1.0 INTRODUCTION AND BACKGROUND

A major design objective since the late 1960's for fighter aircraft is to achieve exceptional agility through large angle-of-attack (AOA) maneuvers. At these large-angle attitudes, the aircraft encounter highly adverse flow conditions. Generally, the flow condition that is particularly problematic are of the vortex type emanating from various surfaces on the forward parts of the aircraft such as engine inlets, wings, or other fuselage appendages. Modern fighter aircraft, especially with thrust-to-weight ratios of higher than one, can generate very high-energy vortices at high AOA maneuver conditions. From a water-tunnel-model test in figure 1, the buffet mechanism is illustrated by the gas bubble trail that immerses the tails in buffet flow.

Classic, high-energy vortices can damage aircraft when they become unstable and "burst." Initially exhibiting highly organized smooth flow with high circular velocity in a tight radius, when burst, the vortex transitions into a flow characterized by a much larger diameter, less organized, and far more turbulent. The frequency content of the vortex undergoes a transition, as well, from very high frequency ranges, i.e. in acoustic range, down to frequencies that are dangerous and destructive to the aircraft. The burst vortex "buffets" the tails and imparts its energy in the form of unsteady pressures that resonate with the structural modes of the aircraft tails. The high dynamic response damages the impacted structural surfaces and shortens their fatigue life.

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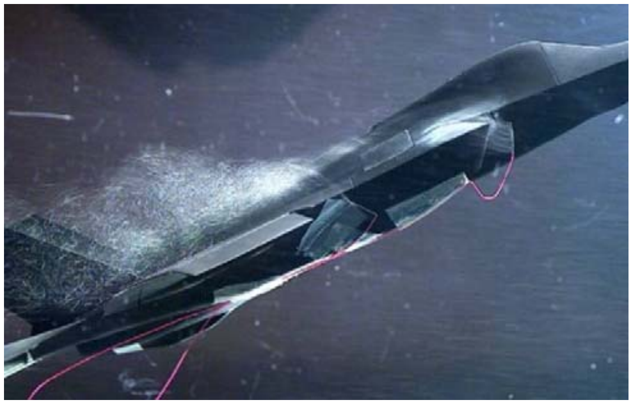

Figure 1. Water tunnel test showing the buffet mechanism with typical vortex burst. (Courtesy of LM Aeronautics)

Although not covered in this paper, the frequency content of the burst-vortex flow is low enough to even aversely impact the flight control of the aircraft during some high attitude maneuvers. The affects of buffet become a critical issue in term of handling qualities and aiming of weapon systems of fighter aircraft. The modeling discussed in this paper can also be applied in design of flight control systems and simulation model of aircraft flight dynamics.

Various forms of tail buffeting have been an ongoing research problem in aircraft for a number of years. Buffet phenomena have originally been documented to occur in propeller-powered aircraft with single vertical tail at the aircraft centerline.[1-4] More recently for a single vertical tailed aircraft, Cunningham has investigated buffeting on the F-111 fighter.[5] With U.S. military's emphasis in developing twin-tailed fighters, buffeting loads on aft aerodynamic surfaces are a more common problem for this class of fighter aircraft, especially, during high angles-of-attack maneuver conditions. In terms of buffet, probably the most notable problem of a twin-tailed design was the F-18. Although the leading-edge extensions (LEXs) of each wing improve low speed performance of the aircraft, they also prove to be very efficient, high-energy vortex generators. In the path of these vortices, the outwardly inclined fins of F-18 are immersed in turbulent wake producing large buffeting loads on the fin and rudder surfaces. The F-18 has brought the tail-buffet problem to the forefront for twin-tailed fighters, if judged by the amount of research conducted and papers generated by aircraft companies, universities, governments, and the military.[6-11]

In 2001, during the contract competition phase of the Joint Strike Fighter (JSF) program, Lockheed-Martin (LM) attempted one high angle-of-attack maneuver of its X-35 prototype. Upon reaching 18 degrees angle of attack, a Mach number of 0.75, and a dynamic pressure of 325 psf, the "knock-off" g-load limits on the tails were reached due to buffet, thus ending the maneuver. Extraordinarily large buffeting loads were also seen on the F-22 during the flight clearance phase of its program. Because of these circumstances, predicting buffeting loads early in the design phase became a top priority to the JSF program and establishes a new precedence for future fighter development programs.

In the past, the buffet environment has reduced the airframe fatigue life and system reliability of several legacy aircraft. This situation was brought on largely because tail buffeting loads were generally ignored in the design process of twin-tailed fighters. There are several reasons for the oversight of this aspect in the design of fighter aircraft: first, the methods to characterize and scale buffet force data into a form suitable for analysis and design of aircraft have not been available; second, quantifiable buffet data characterizing the buffet forces of aircraft is configuration dependent and not normally available during the initial design phase of a fighter development program; and third, no readily available and cohesive analysis method could be used to predict buffeting loads during the initial design of fighter aircraft.

To address the first issue, a number of recent papers have been published to characterize buffet pressures.[6-11] Because buffet is a random process, these papers show that the pressure time-history data can been reduced to power spectral density (PSD) and cross-spectral density (CSD) form. From these papers, the frequency distributions and intensities of the PSDs and CSDs are shown to be both functions of aircraft configuration and angle of attack, which are not scaleable functions. In addition, through its phasing information, CSD functions characterize the temporal or spatial correlations at various points along a surface as the buffet pressure move across it.

During water tunnel tests of both the F-22 and JSF (see figure 1), significant correlation of the buffet pressure measurements between the leading and trailing edges of the vertical tails was observed. More conclusively through experimentation, Lee and Tang[12] have shown results from F-18 fin buffet tests that buffet pressures move essentially as a uniform, wave-front across each surface span. When measured at various points along the chord-wise direction at a given span station, the movement of waves can be quantified very nearly by pure time-delays. Moses[8-11] investigated the time delays of the differential unsteady pressures on the vertical tails in great detail, which enabled the modeling of buffet pressures on the F-18 and F-22 empennage for buffet loads assessments and active control studies.

This high degree of correlation allows a simplifying assumption to be employed in the present method that previous buffeting loads prediction methods[13-17] (Cunningham et al[13] and Bean and Lee[14]) did not employ, namely the use of a single PSD and transport lags to replace multiple CSDs. Further, this analysis method allows the pressure data taken only from one point on the surface to form a PSD to characterize the pressures over the entire lifting surface. This approach both simplifies and makes the method more general and, as a bonus, substantially reduces the amount of buffet data that ordinarily needs to be taken during model testing to perform buffet analysis.

An important contribution provided by reference 8 is the methodology to scale buffet pressure data obtained from wind tunnel tests into a form that can be applied to a full-sized aircraft buffeting loads analysis. This and other papers describe successful scaling techniques.[6,7] Fortunately, they all show that PSDs and CSDs can, to a very reasonable accuracy, be scaled with respect to aircraft size, frequency, speed and dynamic pressure.

Satisfying the second issue of this paper, actual buffet data was obtained from wind-tunnel tests of a 12% JSF model conducted in August 2002 and again in January 2003 at the Lockheed-Martin’s Low Speed Wind Tunnel facility in Marietta, Georgia. To comply with one of the critical assumptions of the method, the pressure data gathered during these tests were obtained from nearly rigid, scaled wind-tunnel models with very stiff fins and rudders. The analysis method makes the assumption that the measured pressures only come from the effects of the buffet flow. This assumption is necessary because the method is capable of computing its own “self-generated” pressures produced by the motion of the modeled structure in the computed unsteady flow.

This paper addresses the third issue of predicting buffeting loads. Basically a random gust response analysis, or PSD analysis, can be modified to perform the predictions. The excitations producing the loads in the analysis method are random quantities that are defined by a PSD. Unlike a gust PSD (such as the von Karman), which is independent of the geometry of the vehicle configuration, the frequency of the buffet pressure PSDs varies with the type of aircraft, its angle of attack and speed.

The standard random gust response analysis such as that existing in NASTRAN is suitable for performing an analysis. One challenge, however, in using the 'standard' gust analysis is that gust *velocities* are the input excitations rather than buffet *pressures* that are available from buffet wind-tunnel tests. This problem is remedied by recognizing that gust velocities on the aerodynamic surface are converted to pressures by the aerodynamic influence coefficient (AIC) matrix. The paper gives a procedure that allows buffet pressures to be applied directly to the affected surface.

2.0 DESCRIPTION OF THE BUFFET ANALYSIS METHOD

The analysis method is composed of, first, reducing the buffet pressure time-history data to PSD form, second, verifying that the buffet pressure is a Gaussian distributed random process, third, scaling the pressure PSDs and, fourth, applying both the measured buffet PSDs and smoother analytically generated buffet PSDs as the excitations in a buffet aeroelastic response analysis.

2.1 Time-History Data

For the twin-tailed JSF test at the Lockheed-Martin's Low Speed Wind Tunnel facility, only the fin on the left side of the model was instrumented for buffet measurements. A photo of the model during testing is shown in figure 2. Most all the pressure time-history data for the test was taken with unsteady pressure transducers, which were located co-incidentally on both sides of the fin. Because the overall objective of the test was to survey the unsteady pressures on the entire fin for a baseline model and a model with various fencing systems, 12 pairs of transducers were employed in the pattern of 4 rows of 3 transducers on the inboard and outboard surfaces. All the surface and differential (inboard minus outboard) pressure time histories were reduced to PSD and CSD forms for review. Many cases were scaled to aircraft flight conditions for comparisons with flight data for the F-18, F-22, and X-35. Following the data review, the differential buffet pressure to be used in the predictions was selected from the pair of sensors at the mid-chord pair near and mid span station.

Figure 2. 1/12th scale wind-tunnel model during buffet testing. (Courtesy of Locheed-Martin Aeronautics)

2.2 Generating Buffet Pressure Power Spectral Densities (PSDs)

The PSDs were generated by an estimation technique using the Fast Fourier Transform (FFT) algorithm. Generally in the technique, the overall, differenced, time-history record with the mean removed is subdivided into many smaller records. To gain a larger number of averages for a better PSD estimate, the smaller records are overlapped by 50% of previous small record. To improve signal estimation, a Hamming window was applied to each of the smaller records. After signal-conditioning the time-history records, they were transformed by FFT into frequency-domain records. The raw PSD of the each smaller record were computed when the complex components of the each frequency-domain record were multiplied by their respective complex conjugates. The estimate of buffet pressure PSD is the average of all the raw PSDs generated from the smaller records.

It is prudent to examine the intensity level of the buffet PSD estimate, since some PSD methods may generate two-sided PSDs giving half the power for the positive frequencies. The proper intensity level for one-sided PSD, which is needed for the subsequent PSD load analysis, can be checked easily by finding the square root of the integral of PSD over the frequency range of the distribution and comparing its value with the variance obtained from the overall time-history record. The two values should be equal. The PSD estimate is used in the analysis method after the appropriate scaling is performed.

2.3 Verifying the Gaussian Distributions of the Pressure Time-History Data for Buffet PSD Analysis

To use PSDs in random process calculations in the frequency domain, it is first necessary to examine whether the buffet time-history data exhibits a Gaussian or a normal distributed random process. A quick check of the criteria is accomplished by examining a distribution of the excursions from the mean of the buffet-pressure time history measurements. Although not directly comparable to a Gaussian form, the error-function form requires only the task of sorting the buffet-pressure measurement data and is much easier to generate. Furthermore, the appeal of this form is that it can theoretically be obtained by integrating a Gaussian distribution. Thus, the two curves can be compared, as shown in figure 3, to determine any deviations.

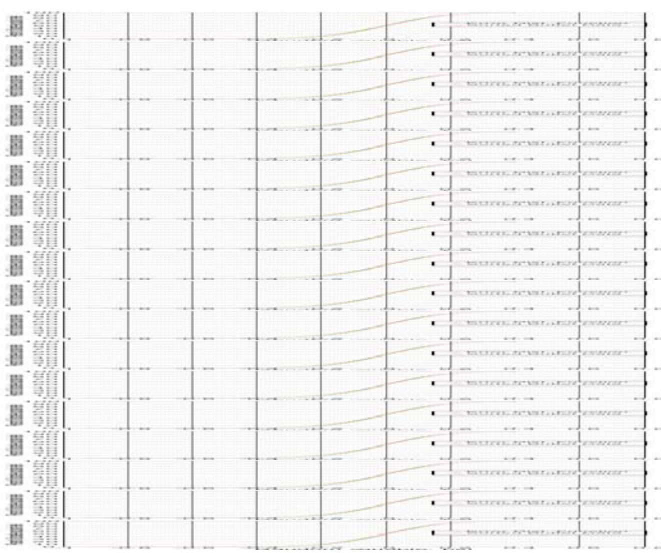

Figure 3. The sorted buffet pressures curve from wind-tunnel data against the error distribution function curve.

To generate the abscissa of the error-function-like distribution, the pressure data (i.e., samples in the time history) are sorted according to their excursion from the mean. The ordinate of the distribution is a percentage of the discrete levels of sorted excursions of the pressure measurements. Figure 3 shows two plots, the first one is of a error function-like plot generated from measured data and the second plot is of the error function obtained from probability theory with the appropriate standard deviation to match that of the measured data. Since the curve of the measured results virtually overlays the theoretically generated error-function curve, a Gaussian distribution of buffet pressure time history measurements can be assumed, and PSD computations used in the buffet analysis.

2.4 Scaling Relations For Predicting Buffet PSD In Analysis

Shapes of the frequency distributions are similar when comparing most buffet PSD results, but are distinctly different if compared to clear air turbulence PSDs found in the atmosphere. Unlike both the Karmen and Dryden turbulences whose magnitudes are analogous to low-pass filters, the buffet PSDs magnitudes resemble second-order damped modal response. Like all atmospheric turbulence models, the buffet PSDs eventually attenuate at high frequencies, matching the attenuation rate of the Dryden turbulence, which is at –2 power rate with frequency as shown in figure 4.

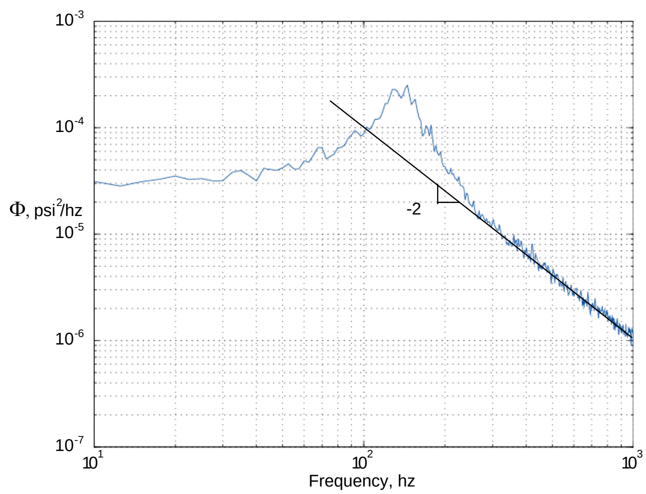

Figure 4. Buffet Pressure PSD from JSF model data at AOA of 22 degrees.

By examining figure 4, a distinct feature occurring in buffet PSDs is the resonant peak prior to the -2 attenuation rate. These peaks are common feature in most buffet PSDs and attributed to the cyclic pressures produced by the buffet vortices. The frequency of the peak is called the vortex-excitation frequency and has been shown[15] to proportionately vary with freestream velocity. The size and the relative location of peaks are functions of aircraft configuration and angle-of-attack and are generally not scaleable quantities. Although, for a given aircraft configuration, Bean and Wood gave good evidence in a study[15] that for a range of angle-of-attack producing high levels of buffet excitation, buffet peak frequencies appear as functions of angle of attack.

In general, scaling methods for PSDs have been developed and employed to accurately predict the buffet pressure PSDs for aircraft size and flight conditions. In a scaling procedure similar to those employed when modeling atmospheric turbulence, such as the von Karman, the wind-tunnel buffet pressure PSDs are scaled in magnitude and frequency to obtain quantities applicable to aircraft load analysis at a particular flight condition. The scaling of buffet pressure PSD frequencies reflects the differences in the frequencies of the flow dynamics for small-scaled model in a tunnel and for a full-sized aircraft at particular flight condition. As shown by experimental test results, very satisfactory frequency scaling can be obtained using the following relations:

$$k = \frac{\omega_m L_m}{V_m} = \frac{\omega_a L_a}{V_a} \tag{1}$$

where,

k = Reduced frequency (dimensionless).
$\omega_{m,a}$ = Radian frequency of the model, aircraft.
$L_{m,a}$ = A reference length of the model, aircraft.
$V_{m,a}$ = Free-stream speed of the tunnel, forward flight speed of the aircraft.

In performing load computations on a structural design, some of the largest loads result when there is sufficient energy in the buffet PSD frequencies that are coincident with the structure's vibration frequency, such as the rudder torsion mode. An important aspect of frequency scaling, which Bean[15] and particularly Zimmerman[6] showed with experimental results, is that the frequency at which the sharp peak occurs, can be computed using equation (1) for other lengths and velocities once the initial relationship (for model or for aircraft) is known through experimentation.

To attain the proper PSD buffet pressures at design flight conditions of full-sized aircraft, Meyn[7] and Zimmerman[6] recommend the following relationship for magnitude scaling, which uses density (for computing dynamic pressure), velocity and length:

$$\Phi_N(k) = \frac{\Phi_m(\omega_m)}{\left(\tfrac{1}{2}\rho_m V_m^2\right)^2}\left(\frac{V_m}{L_m}\right) = \frac{\Phi_a(\omega_a)}{\left(\tfrac{1}{2}\rho_a V_a^2\right)^2}\left(\frac{V_a}{L_a}\right) \tag{2}$$

where,

$\Phi_N(k)$ = Normalized PSD (dimensionless).
$\Phi_{m,a}(\omega_{m,a})$ = PSD of model, of the scaled aircraft.
$\rho_{m,a}$ = Mass density of tunnel's test medium, of air at aircraft's flight condition.

In a cautionary note of using PSDs from wind-tunnel test data, there are some features of the PSD that may not scale to full-sized aircraft. For instance, a general observation found by the author in researching particularly the F-18 buffet literature is that the vortex-excitation peaks of buffet PSD data derived from full-sized aircraft are noticeably more "damped" than those derived from wind-tunnel models. The origin of this damping effect is unknown; however, it is suspected that the effects may come from the flexible structure impacting the buffet flow, since, when making the scaling comparisons in the studies, part of the buffet data came from an aircraft, which is fully elastic. This damping effect may be a consideration in all analytical results coming from full-sized aircraft, but needless to say, more research is needed to better understand the cause of this observed effect.

2.5 Some Equations of the Analysis Method

Most of the equations used in performing buffet load predictions are available in the **MSC/Nastran Aeroelastic Analysis User's Guide** in the *Aeroelastic Frequency Response Analysis* section. This analysis capability has many features available for performing buffet load analysis, but two involving the gust penetration and the direct application of turbulence excitations through PSDs are of particular interest to this method. Since it has been statistically shown that buffet PSDs at lower angles of attack are highly correlated and change little in their distribution shape or magnitude, as a buffet wave sweeps cross a surface, transport lags of the form, $exp(-s\tau)$, can be used to model the penetration effects very accurately. As with atmospheric turbulence, the transport lags are incorporated in NASTRAN gust response solution by employing a downwash equation given by,

$$\boldsymbol{w_j}(\omega) = \cos(\gamma_j)\exp[-\tfrac{i\omega}{V}(\boldsymbol{x_j} - \boldsymbol{x_o})] \qquad (3)$$

where,

$\boldsymbol{w_j}$ = Gust downwash at the aero jth box.
γ_j = jth aero box dihedral angle.

Even though NASTRAN has the capability of performing analysis with excitation PSDs as input for standard random gust analysis, unfortunately the PSDs, can only be applied as downwash velocities in the standard solution sequence. The buffet PSD data is typically derived from measured pressure data and are in the form of pressure PSDs, which precludes using them directly in the standard solution sequence. However, recognizing that the initial computational step in NASTRAN is to produce the pressures at each box location by multiplying the downwash velocities of gust PSDs with the aerodynamic influence coefficient (AIC) matrix, a remedy inside NASTRAN was developed by the authors. Through DMAP modifications, a substitution of the identity matrix for the AIC matrix, used in equations 4 and 5, allowed the application of the transport-delayed pressure PSDs directly to the aerodynamic boxes.

$$[\boldsymbol{Q_{kj}}] = [\boldsymbol{S_{kj}}][\boldsymbol{A_{jj}}] \qquad (4)$$

where,

$[\boldsymbol{S_{kj}}]$= Matrix of the aero box areas
and $[\boldsymbol{A_{jj}}]$= Aerodynamic influence coefficient matrix.

$$[\boldsymbol{Q_{hj}}] = [\boldsymbol{\Phi_a}]^{\boldsymbol{T}}[\boldsymbol{G_{ka}}][\boldsymbol{WTFACT}][\boldsymbol{Q_{kj}}] \qquad (5)$$

where,

$[\boldsymbol{\Phi_a}]$ = Vibration mode shapes
$[\boldsymbol{G_{ka}}]$ = Spline matrix
and $[\boldsymbol{WTFACT}]$ = Weighing matrix of aerodynamic box pressures.

3.0 VALIDATING BUFFET ANALYSIS METHOD BY COMPUTING LOADS EXPERIENCED DURING FLIGHT

As mentioned above, a JSF prototype experienced buffet during one of its flight tests in 2001. Most of the events were recorded by onboard instrumentation. Immediately prior to the buffeting event, the aircraft was flying straight and level at an altitude and Mach number of 26,000 ft. and 0.8 respectively. When the angle of attack was quickly increased to demonstrate flying qualities during sudden attitude changes, the aircraft entered the buffet event. Upon reaching an angle of attack of 18 degrees, the aircraft reach the load limits set by the flight engineers, and the demonstration was promptly ceased. The buffet loads of this event serve as the flight data for validating this analysis method and building confidence in subsequent predictions.

3.1 Aeroelastic Response Loads Model

The finite-element model shown in Figure 5 generated the aeroelastic response model, which is the basis for the analytical model, used to perform the buffeting loads analysis. The FEM represents the empennage flexible modes, which was sufficient for performing loads analysis of the fin and horizontal tail. Appropriate boundary conditions are used to constrain the centerline plane of symmetry and the lateral plane normally attached to the forward part of the aircraft. Vibration modes having frequencies above 100 hz were included in the analysis. In figure 6, mode 11, which is the JSF's rudder torsion mode at 64 hz, is shown. This mode is one of the most critical modes because of demonstrated susceptibility to the fluctuating buffeting pressures. In performing the unsteady aerodynamic and the gust penetration modeling for the analysis, NASTRAN's double lattice method was used to generate aerodynamic coefficients for only the fin and horizontal-tail-surface parts of the aircraft.

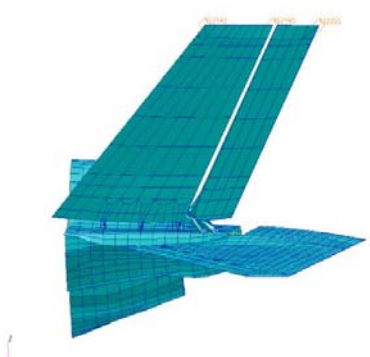

Figure 5. NASTRAN Finite Element Model of Aft Section of Joint Strike

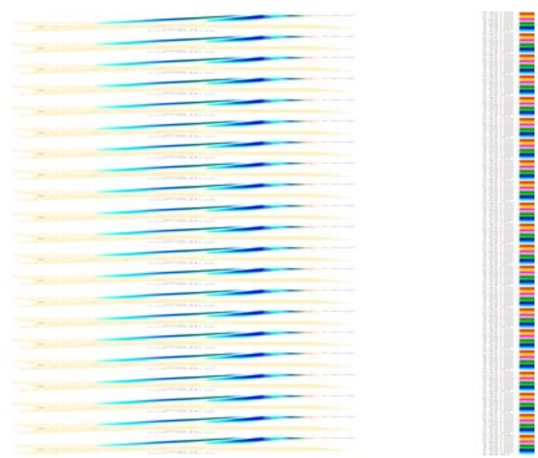

Figure 6. Mode shape of the first rudder torsion mode at 64 Hz. of the JSF.

3.2 Performing Buffet Load Analysis with Measured Pressure PSDs

To demonstrate the method, time-history measurements of the pressures at the leading-edge fin of the wind-tunnel model were reduced to buffet spectra at various angle-of-attack conditions. Before applying these buffet pressure spectrum data to the FEM model of the aircraft, the model-derived pressure spectra at the various angle-of-attack and test conditions were scaled both in frequency and magnitude by equations (1) and (2). The scaled pressure spectra of the buffet data at several angle-of-attack conditions are shown in figure 7.

Subsequently, the PSDs of JSF fin acceleration were computed for each angle of attack, as shown in figure 8. The response measured in flight at 18 degrees AOA is shown to the right of the analysis results for comparison. When comparing the two sets of results for 18 degrees AOA, the maximum value of the acceleration PSD obtained from flight data falls below the maximum of left-hand plot generated from analysis at 18.9 degrees AOA, as expected. In the generated acceleration PSDs, several aspects of the analysis input data should be pointed out. First, the maximum values of the buffet spectra (i.e., vortex frequency) causing the largest modal response (at 20.9 degrees AOA) reside at frequency values much lower than 64 hz, which is the resonant value of mode 11. Second, as illustrated in figure 8, the buffet spectra (for 20.9 degrees AOA) causing the maximum response in mode 11 contains the most power around 64 hz, as shown in figure 7. Therefore, as the angle of attack is increased further beyond 25.2 degrees AOA, the response in mode 11 is expected to subside further.

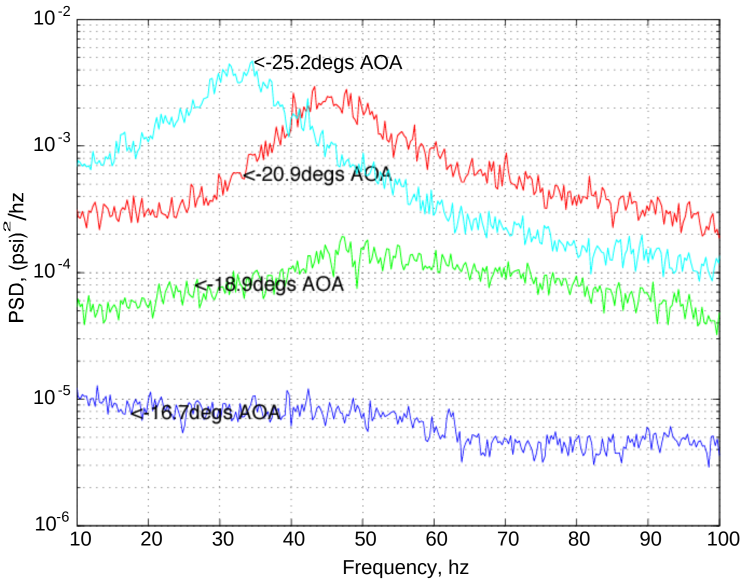

Figure 7. Pressure spectra from LM wind-tunnel tests scaled to buffet flight condition of a full-sized X-35. aircraft.

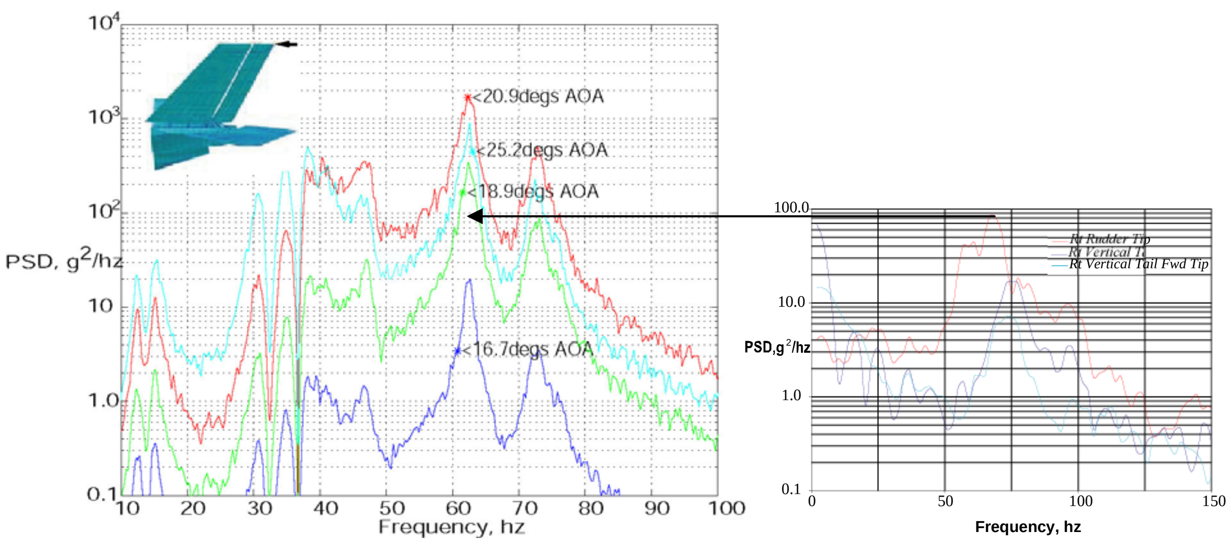

Figure 8. Acceleration PSDs computed by NASTRAN from scaled buffet pressure spectra and acceleration PSDs at 18.0 degrees AOA obtained from X-35 fight data at comparable flight conditions.

3.3 Performing Buffet Load Analysis with PSDs derived from Analytical Functions

As can be surmised from the pressure PSD presented in figure 7 and also the results of figure 8, no wind-tunnel data was available to produce pressure PSD at 18 degrees to attempt to match the flight data. However, using an analytical function (equation 6), pressure PSD estimates can be interpolated from the available wind-tunnel data and used in the buffet analysis to check the agreement with the peak acceleration derived from flight data.

$$\Phi(f) = \sigma_b^{\,2} \frac{1 + \left(\frac{2\pi f}{\omega_n}\right)^2}{\left(1 + \frac{2\delta(2\pi f)}{\omega_d} + \left(\frac{(2\pi f)}{\omega_d}\right)^2\right)^2} \tag{6}$$

Three sets of constants consisting of σ_b, ω_n, δ and ω_d were estimated with an analytical fitting procedure using the three sets of pressure PSD data shown in figure 7 for 18.9, 20.9 and 25.2 degrees AOA conditions. Subsequently, a quadratic interpolation procedure produced a new set of constants for equation (6) to estimate the pressure PSDs at the 18 and 18.2 degrees angle-of-attack conditions, as seen in figure 9. As a reference, the upper three curves can be compared to those seen in figure 7 scaled from the actual wind-tunnel data. Using the same buffet analysis method, the acceleration PSDs were computed for the analytically derived pressure PSDs and their results provided in figure 11.

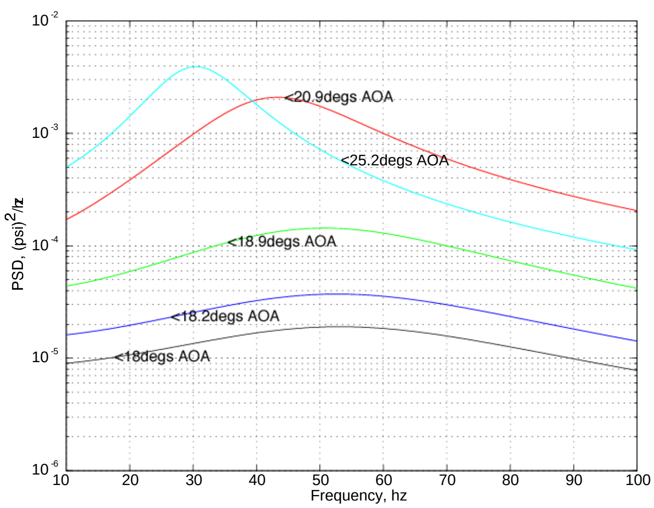

Figure 9. Analytical function plots of pressure spectra obtained by fitting the scaled raw PSDs derived from LM wind-tunnel tests. The 18 and 18.2 degrees PSD plots are interpolated estimates based on fitted analytical functions.

The analysis result using the analytically-derived pressure PSD for 18.2 degrees nearly matches the peak magnitude of the acceleration PSD from flight data, which shows the accuracy of the buffet analysis method. The 18 degree result is also shown with the peak 50% of the 18.2 result. These two AOA values of the analysis are well within the error bounds of the aircraft's instrumentation used to measure AOA. The analysis results for the analytically-derived pressure PSD and the scaled wind-tunnel pressure PSDs for 20.9 and 25.2

degrees AOA agree very well, offering another indication of the potential of this approach.

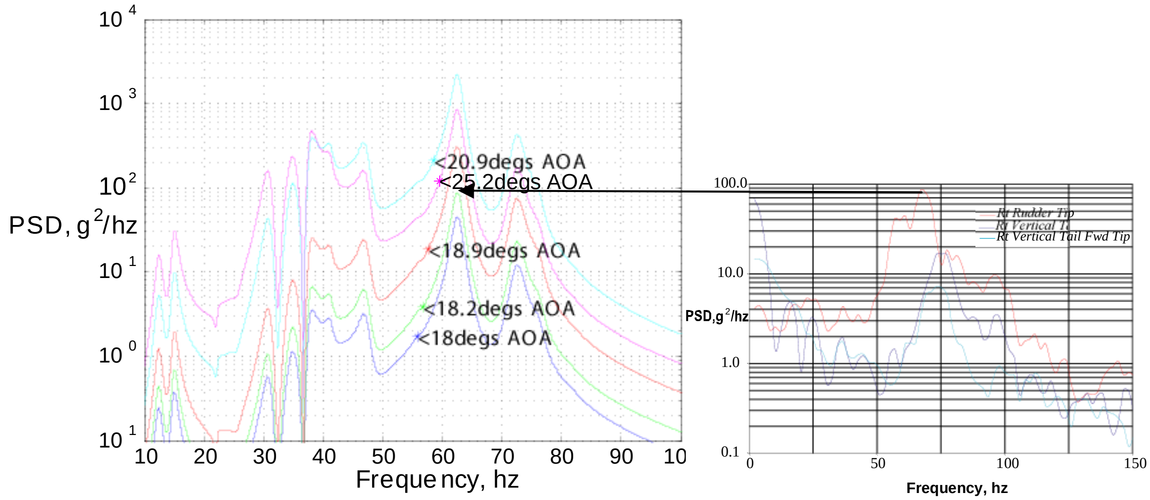

Figure 11. Acceleration PSDs computed by NASTRAN from analytical-function-derived buffet-pressure spectra and acceleration PSDs at 18.0 degrees AOA obtained from X-35 Fight Data.

3.4 More Aircraft Predictions

With the method anchored to existing flight data, buffet loads were predicted for three additional points in the sky: Mach 0.6 at 5000 feet altitude, Mach 0.75 at 14,000 feet altitude and Mach 0.75 at 25,000 feet altitude. For each flight condition, the peak PSD response values near the 64-hz.-frequency mode at the rudder trailing edge tip were extracted and plotted in figure 12 for comparison. These three cases are labeled as the baseline

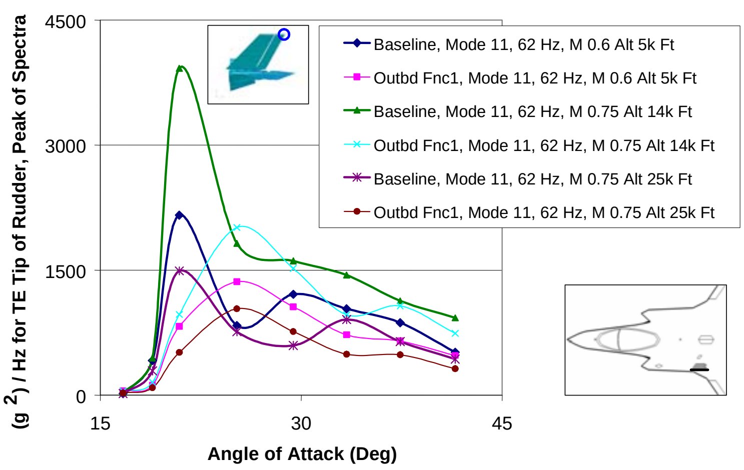

Figure 12. From load buffet analysis, comparing peak response values of the aft rudder tip with angle of attack for the baseline JSF and the LEX fenced configuration at various flight conditions.

in the figure key. Clearly, the trailing edge tip experienced the greatest response with the 64-Hz.-mode-resonance point when the aircraft was flying Mach 0.75 at 14,000 feet, and around 21 degrees angle of attack, followed by the response at the Mach 0.6/5000-feet-altitude case.

In addition to the baseline case, load predictions were calculated for another promising JSF configuration equipped with LEX (**l**eading **e**dge e**x**tension) fence. This configuration was chosen from past experiences of successfully alleviating buffeting loads with the applications of LEX fences on the F/A-18 during some flight conditions. For the JSF configuration, one particular fence location, labeled "Outbd Fnc1", is provided for illustrating further capability of this analysis method. Buffet pressure PSDs obtained from the wind-tunnel data corresponding to this fence configuration were scaled and implemented into the analysis. At most angles of attack, the peak responses of the trailing edge tip of the rudder to buffet were reduced significantly, as illustrated in figure 12. A mild increase in response between 25-28 degrees angle of attack was computed.

4.0 Conclusions

Buffet loads play a critical factor in the design of aircraft. A buffet loads analysis method has been developed that is much simpler to use than previous buffet load methods. Yet this method is very general and uses the solution scheme already employed in NASTRAN's aeroelastic random response method. The method provides a capability to predict and to assess the impact of buffet loads during the design phase of new aircraft development program. The capability to predict the impact of buffet loads early during the aircraft design phase offers the potential to reduce costs to the aircraft development program. As experienced by F-22, the absence of this capability resulted in expensive redesign and costly delays late in its development program.

To provide confidence in its use, the prediction method has been validated by accurately computing the peak and generally the entire PSD load responses against PSD loads obtained from limited flight data. The method was successfully used as a prediction tool in assessing new candidate JSF designs, including notional implementations of LEX fences.

5.0 References

1. Abdrashitov, G., "Tail Buffeting," NACA TM-1041, February 1943 (Translated from Russian, Report 395 from the Central Aero-Hydromechanical Institute, Moscow, 1939).

2. Accident Investigation Sub-Committee: Accident to the Aero-plane G-AAZK at Meopham, Kent, on 21st July, 1930. R. & M. No. 1360, British A. R. C., 1931.

3. White, J. A. and Hood, M. J.: "Wing-Fuselage Interference, Tail buffeting and Flow about the Tail of a Low Wing Monoplane," NACA Report 482, 1933.

4. Hood, M. J. and White, J. A.: "Full Scale Wind Tunnel Research on Tail Buffeting and Wing-Fuselage Interference of a Low Wing Monoplane," NACA TN-460, 1933.

5. Cunningham, A. M., Benepe, D. B., Watts, D. and Waner, P. G.: "A Method of Predicting Full-Scale Buffet Response with Rigid Wind-Tunnel Model Fluctuating Pressure Data," NASA CR 3035, Nov. 1978.

6. Zimmerman, N.H.; Ferman, M. A. and Yurkovich, R. N. and Gerstenkorn, G.: "Prediction of Tail Buffet Loads for Design Application," AIAA paper No. 89-1378, 1989.

7. Meyn, L. A. and James, K. D., "Full scale wind tunnel studies of F/A-18 tail buffet," AIAA Paper 93-

3519, Applied Aerodynamics Conference, August 1993.

8. Robert W. Moses and Ed Pendleton: A Comparison of Pressure Measurements Between a Full-Scale and a 1/6-Scale F/A-18 Twin Tail During Buffet, NASA TM-110282, August 1996, pp. 13, Also presented and included in the proceedings of the 83rd Structures and Materials Panel Meeting of AGARD held September 2-6, 1996, in Florence, Italy.

9. Robert W. Moses and Holt Ashley: Spatial Characteristics of the Unsteady Differential Pressures on 16 Percent F/A-18 Vertical Tails , 36th AIAA Aerospace Sciences Meeting and Exhibit, Reno, Nevada, AIAA 98-0519, January 12-15, 1998, pp. 11.

10. Robert W. Moses and Gautam H. Shah: Spatial Characteristics of F/A-18 Vertical Tail Buffet Pressures Measured in Flight, 39th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference, Long Beach, California, AIAA 98-1956, April 20-23, 1998.

11. Robert W. Moses and Lawrence J. Huttsell, Fin Buffeting Features of an Early F-22 Model, 41st AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference and Exhibit, Atlanta, Georgia, AIAA 2000-1695, April 3-6, 2000, pp. 10.

12. Lee, B. H. K. and Tang, F. C.: "Buffet load Measurements on an F/A-18 Vertical Fin at High-Angle-Attack," AIAA SDM paper no. 92-2127, 1992.

13. Atlee M. Cunningham, Jr., David B. Benepe, Darlene Watts, and Paul G. Waner: "A Method for Predicting Full Scale Buffet Response With Rigid Wind Tunnel Model Fluctuating Pressure Data," Volume I: Prediction Method Development and Assessment, NASA Contractor Report 3035, Contract NAS2-7091, November 1978.

14. D. E. Bean and B. H. K. Lee: "Correlation of F/A-18 Buffeting from Wind-Tunnel and Flight Tests," Journal of Aircraft, Volume 32, Number 6, Nov.-Dec. 1995, pp. 1351-1358.

15. D. E. Bean and N. J. Wood: "Experimental Investigation of Twin-Fin Buffeting and Suppression," Journal of Aircraft, Vol. 33, No. 4, July-Aug. 1996.

16. Healey, M.D.:" F/A-18E/F Vertical Tail Buffet Design, Analysis and Test," AIAA 2003-1886, 2003 Structures, Structural Dynamics and Materials Conference, Norfolk, Va.

17. J. Becker, W. Luber: "The Role Of Buffeting The Structural Design Of Eurofighter," 44th Structures, Structural Dynamics, and Materials Conference, 7-10 April 2003, Norfolk, Virginia., paper no. AIAA 2003-1889**.**

SYMPOSIA DISCUSSION

REFERENCE AND/OR TITLE OF THE PAPER: 19

DISCUSSOR'S NAME: J. Drobik
AUTHOR'S NAME: A. Pototzky

QUESTION:
The buffet load alleviation, by use of a fence, indicates a flow mechanism that is not dissimilar to the F-18 - the movement of vortex breakdown point and diffusion of associated energy. With the constraints of LO (low observable) design for F-35, where a fence is obviously not practical, have you suggestions for a buffet alleviation mechanism?

AUTHOR'S REPLY:
There are probably other solutions, but all I am sure involve system additions modifications, or configuration changes which can be achieved at considerable costs. Some may not provide a "signature". This particular solution mentioned in the paper was a modification which was a cheap "fix" to the buffet load alleviation problem.

DISCUSSOR'S NAME: C. Petiau
AUTHOR'S NAME: A. Pototzky

QUESTION:
The "input" of your calculation seems only the PSD of pressure from wind tunnel measurements. But the theory requires the input of the "cross-spectra". What do you do exactly?

AUTHOR'S REPLY:
We apply one buffet pressure spectrum but apply it to many of aerodynamic "boxes" by using transport lags that model the "gradual penetration" of the buffet waves sweeping across the surfaces. This type of gradual penetration modeling is similar to what is performed in gust response modeling. There are many reasons we use this type of models which are (1) it is simpler since it requires only one spectrum (2) it has been shown in several papers that spectrum sweeping across the computational surface is similar to a transposed lag across the surfaces (3) we can use existing gust load response capability and (4) it is very general in that it can be used even for preliminary aircraft design.

DISCUSSOR'S NAME: E. Dowell
AUTHOR'S NAME: A. Cunningham (for A. Pototzky)

QUESTION:
Is Reynolds number matching important for vertical tail buffet?

AUTHOR'S REPLY:
The effect of Reynolds number for vortex burst induced turbulence is minimal. This is best demonstrated by the success of water tunnel testing that closely replicates flight characteristics. CFD analyses have more problems associated with improper gridding that introduces excessive dissipation of the turbulence.