A Method to Analyze Tail Buffet Loads of Aircraft

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SUMMARY

Aircraft designers commit significant 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 resulting in reassessing designs or limiting full mission capability. 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.

This paper describes a reliable, fairly simple, but quite general buffet loads analysis method to use in the initial design phases of fighter-aircraft development. The method is very similar to the random gust load analysis that is now commonly available in a commercial code, which this analysis capability is based, 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

Since the late 1960's, a major design objective for fighter aircraft is to achieve exceptional agility through large angle-of-attack (AOA) maneuvers. At these large-angle attitudes, the aircraft encounters highly adverse flow conditions. Generally, the flow conditions that are particularly problematic involve vortices 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.

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 the 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 excite structural modes of the aircraft tails. The high dynamic response damages the impacted structural surfaces and shortens their fatigue life.
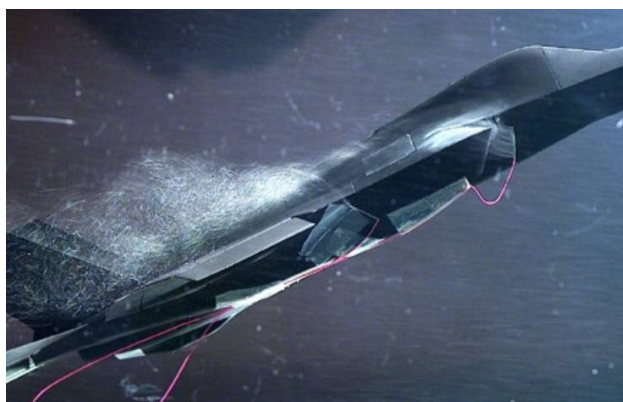
Figure 1. Water tunnel test showing the buffet mechanism with typical vortex burst. (Courtesy of Lockheed-Martin Aeronautics)

Interestingly, the frequency content of the burst-vortex flow can be 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 terms of handling qualities and the aiming of weapon systems of fighter aircraft. The modeling discussed in this paper can also be applied in the design of flight control systems and simulation models of aircraft flight dynamics.

Various forms of tail buffet have been an ongoing research problem in aircraft for a number of years. Buffeting 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 trend 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. The outwardly inclined fins of F-18 are immersed in the turbulent wakes of these vortices, producing large buffeting loads on the fin and rudder surfaces. If judged by the amount of research conducted and papers generated by aircraft companies, universities, governments, and the military, the F-18 has brought the tail-buffet problem to the forefront for twin-tailed fighters.[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 incidents, predicting buffet loads early in the design phase became a top priority to the JSF program, thus establishing a precedent for future fighter development programs.

The buffet environment has reduced the airframe fatigue life and system reliability of several legacy aircraft. This situation was brought on largely because tail buffet 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, which can be categorized by the following issues: 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 existed to predict buffet loads during the initial design of fighter aircraft.

To address the first issue, a number of 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) forms. The PSDs and CSDs are shown to be 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 pressures move across it.

During water tunnel tests of both the F-22 and JSF, significant correlation of the buffet pressure measurements between the leading and trailing edges of the vertical tails was observed. 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 chord. 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 et all[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 buffet loads prediction methods (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 simplifying assumption 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 the method and makes it more general and, as a benefit, substantially reduces the amount of buffet data that needs to be taken during model testing to perform buffet loads 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 buffet 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.

To address 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 consistent with one of the critical assumptions of the method, the pressure data gathered during these tests were obtained from a nearly rigid, scaled wind-tunnel model with very stiff fins and rudders. The analysis method makes the assumption that the measured pressures correspond to the effects of the buffet flow only. This assumption is necessary because the method is capable of analytically computing the induced pressures produced by the motion of the modeled structure.

Regarding the third issue of predicting buffeting loads, a random gust response analysis, or PSD analysis, can be modified to perform the buffet 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 buffet pressure PSDs are functions of aircraft geometry, angle of attack and speed.

The standard random gust response analysis such as that existing in NASTRAN is suitable for performing a

buffet loads analysis. One challenge, however, in using the standard gust response analysis is that gust *velocities* are the input excitations rather than buffet *pressures* that are available from buffet wind-tunnel tests. This challenge is addressed 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 LOADS ANALYSIS METHOD

The analysis method is composed of the following: 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 the 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 pressure measurements. A photo of the model during testing is shown in figure 2. The pressure time-history data for the test was taken with unsteady pressure transducers,
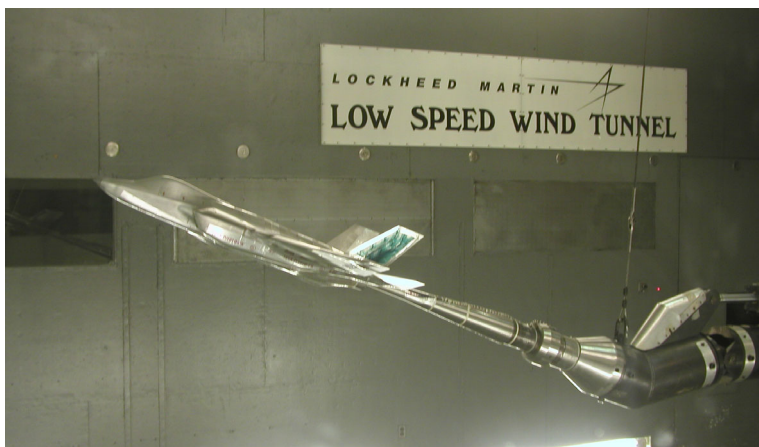

Figure 2. 1/12th scale wind-tunnel model during buffet testing.
(Courtesy of Lockheed-Martin Aeronautics)

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 surface minus outboard surface) 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 X-35. Following the data review, the differential buffet pressures to be used in the buffet loads analysis method was selected from the pair of sensors at the mid-chord near and mid span station.

2.2 Generating Buffet Pressure Power Spectral Densities (PSDs)

The PSDs were generated by an estimation technique using the Fast Fourier Transform (FFT) algorithm. 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, each smaller record is overlapped by 50% with the previous record. To improve signal estimation, a Hamming window was applied to each of the smaller records. After signal-conditioning, each of the smaller time-history record was transformed by FFT into a frequency-domain record. The raw PSD of the each smaller record was computed multiplying each frequency-domain record by its complex conjugate at each frequency. The estimate of the 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 estimation techniques may generate two-sided PSDs, giving half the power for the positive frequencies and the other half the negative frequencies. The proper intensity level for a one-sided PSD only, which this PSD analysis method requires, 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 buffet loads analysis method after the appropriate scaling is performed.

2.3 Verifying the Gaussian-ness of the Pressure Time-History Data

To use PSDs in random process calculations in the frequency domain, it is first necessary to examine whether the buffet time-history data exhibits the characteristics of a Gaussian or a normal random process. An examination of the distribution of the excursions from the mean of the buffet-pressure time history measurements with the error distribution function indicates the degree of Gaussian-ness. Thus, the two curves can be compared, as shown in figure 3, to determine any deviations from Gaussian-ness.
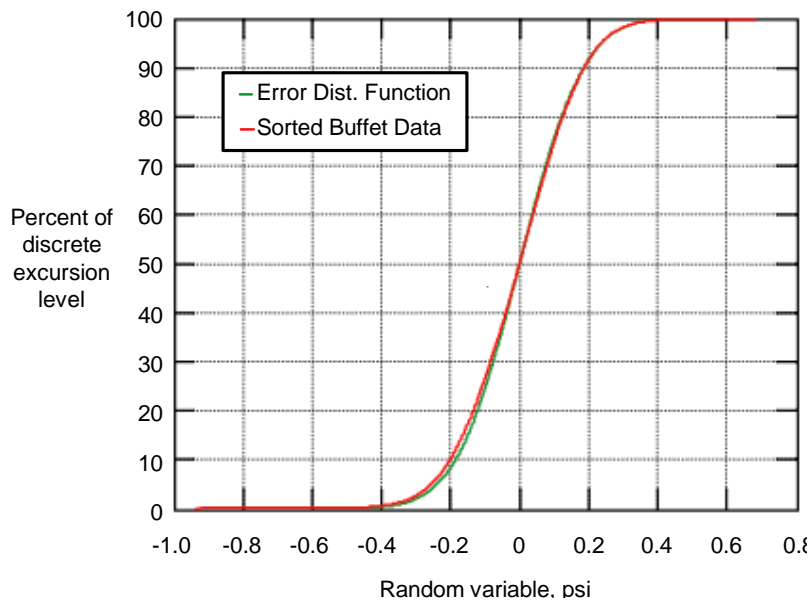

Figure 3. The sorted buffet pressures curve from wind-tunnel data against the error distribution function curve.

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 can be used in the buffet loads analysis.

2.4 Relations For Predicting Scaled Pressure Buffet PSDs

Buffet pressure PSDs differ in character from atmospheric turbulence PSDs. The former has the general characteristics of second-order damped modal response; the latter has characteristics of low-pass filters. Both forms of PSDs eventually attenuate at high frequencies.

Figure 4 contains a log-log plot of a buffet pressure PSD obtained form the JSF model data at an angle of 22 degrees. A distinct feature of this PSD, typical of most buffet pressure PSDs, is a board peak in the magnitude followed by the attenuating magnitude at a -2 slope.
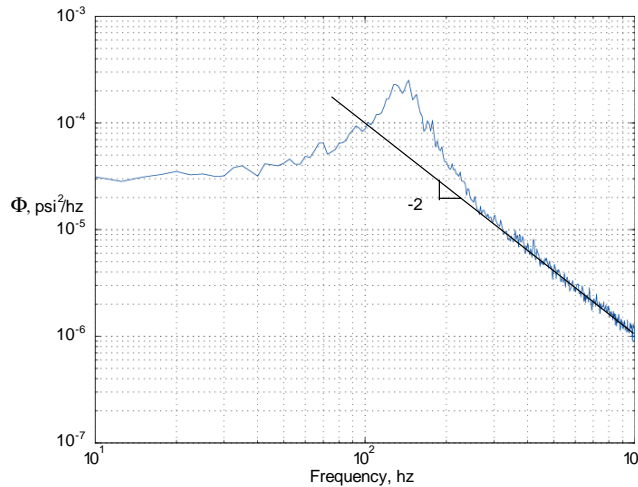

Figure 4. Buffet Pressure PSD from JSF model data at AOA of 22 degrees.

These peaks are 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 to proportionately vary with freestream velocity.[15] The size and the relative location of peaks are functions of aircraft configuration and angle-of-attack and are not scaleable quantities. Although, for a given aircraft configuration, Bean and Wood[15] provide evidence that for a range of angles of attack producing high levels of buffet excitation, buffet peak frequencies appear as functions of angle of attack.

Scaling methods have been developed and employed to accurately predict the buffet pressure PSDs for aircraft size and flight conditions given buffet pressure PSDs from wind-tunnel tests. Wind-tunnel buffet pressure PSDs are scaled with respect to their magnitude and their frequency. The scaling of frequencies reflects the differences in the flow dynamics for a scaled model in a tunnel and for a full-sized aircraft at a particular flight condition. Frequency scaling entails matching model and aircraft reduced frequencies:

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

where,

$k_{m,a}$ = Reduced frequency (dimensionless) of model, aircraft,
$\omega_{m,a}$ = Circular frequency for the model, aircraft,
$L_{m,a}$ = A reference length of the model, aircraft,

and $V_{m,a}$ = Free-stream speed of the tunnel, forward flight speed of the aircraft.
Using experimental results, Zimmerman[6] and Bean[15] validated equation (1).

To obtain PSDs of buffet pressures at the design flight conditions for the full-sized aircraft, Meyn[7] and Zimmerman[6] recommend the following relationship equating the both normalized model and aircraft PSDs:

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

where,

$\Phi_{m,a}(\omega_{m,a})$ = Buffet pressure PSD of model, of the scaled aircraft,

$\rho_{m,a}$ = Mass density of tunnel's test medium, of air at aircraft's flight condition.

A cautionary note regarding using PSDs from wind-tunnel test data: there are some features of these PSD that may not scale to full-sized aircraft. For instance, a general observation found by the authors in researching the buffet literature[6,8,14,16,17] is that the vortex-excitation peaks of buffet pressure PSDs generated from full-sized aircrafts are noticeably more "damped" than those generated from wind-tunnel models. The origin of this damping effect is unknown; however, it is suspected that the effects may come from the buffet flow impacting fully elastic rather than a rigid structure. This damping effect may be a consideration in all analytical results for a full-sized aircraft. Additional research is needed to better understand the cause of this observed damping effect.

2.5 Details of the Buffet Analysis Loads Method

As stated previously, the present buffet loads analysis capability draws heavily upon many features of the well-established power spectral density gust loads analysis capability. Both capabilities employ the standard input-output relationship of random process theory, namely,

$$\Phi_y(\omega) = \left|H_y(\omega)\right|^2 \Phi_x(\omega) \qquad (3)$$

where, $\Phi_y(\omega)$ = PSD of load response,

$\Phi_x(\omega)$ = PSD of turbulence or buffet input,

and $H_y(\omega)$ = Transfer function of the load response due to turbulence or buffet.

In this compact notation, the $H_y(\omega)$ represents solution of the aeroelastic equations of motion and the load output equations. These random process computations are available in NASTRAN. For this paper, a more detailed explanation of the equations and capabilities used in performing loads predictions are available in the **MSC/Nastran Aeroelastic Analysis User's Guide**,[18] specifically, in the *Aeroelastic Frequency Response Analysis* section.

The gust loads analysis capability within MSC/NASTRAN has several features that make it especially suitable for implementing the buffet loads analysis capability, which include the following: (1) the ability to automatically generate the gradual gust penetration model; (2) the ability to apply user-provided turbulence PSDs; (3) the ability to modify the existing solution sequences through DMAP alters; and (4) the ability to generate load response results in a usable form for subsequent processing.

As previously mentioned the buffet PSD data is typically derived from the measured pressure data and are in the form of pressure PSDs, which precludes using them directly in the standard NASTRAN solution sequence

for the Aeroelastic Frequency Response Analysis for gust loads. From the authors' understanding of the theoretical formulations of the NASTRAN's computational procedures to obtain the turbulence-produced pressures from the gust-velocity PSD, modifications to the solution sequence inside NASTRAN were developed and are described to use a buffet pressure PSD instead of the gust-velocity PSD in the existing gust load analysis capability. Thereby, these modifications expand the existing analysis capability to perform buffet loads also.

All the computational modules for generating $H_y(\omega)$ in NASTRAN have been left intact including the modules for computing the gust-velocity loadings. To develop the buffet loads analysis method, only the AMP module was modified. This module is located in the SEAERO section, which is in the uppermost level of the solution sequence. In this location, the initial aerodynamic computations are performed prior to the final gust load response computations downstream. Among the other computations the module performs, the AMP module generates the right-hand-side, aerodynamic-related, generalized loading coefficient matrix. In the generalized coordinates, this coefficient matrix relates the gust-velocity PSD through a set of transport lags from each of the aerodynamic boxes to the aerodynamic forces used in the load equations of motion.

As described in section 2.7 of the **Aeroelastic Analysis User's Guide,**[18] in the first part of the computational process, AMP internally generates the box-level aerodynamic force matrix, $[Q_{kj}]$, as follows:

$$[Q_{kj}]=[S_{kj}][A_{jj}] \tag{4}$$

where, $[S_{kj}]$ = Matrix of the aerodynamic box areas
and $[A_{jj}]$ = Aerodynamic influence coefficient matrix.

Again as given in the **Aeroelastic Analysis User's Guide,**[18] in the final part of the computation, the AMP module uses the $[Q_{kj}]$ matrix to compute the $[Q_{hj}]$ matrix, which is the desired output result,

$$[Q_{hj}]=[\Phi_a]^T[G_{ka}][WTFACT][Q_{kj}] \tag{5}$$

where $[Q_{hj}]$ = Right-hand coefficient matrix for the generalized loadings,
               $[\Phi_a]$ = Matrix of vibration mode displacement,
               $[G_{ka}]$ = Spline matrix,
and $[WTFACT]$ = Weighing matrix of aerodynamic box pressures.

To directly apply the buffet pressure effects to the aerodynamic surface, the identity matrix, $[I_{jj}]$, was substituted with DMAP coding for $[A_{jj}]$ in equation (4), as follows,

$$[Q_{kj}]=[S_{kj}][I_{jj}] \tag{6}$$

The second part of the modifications for the buffet loads analysis that did not require DMAP coding was to include as part of the input data entries the buffet pressure PSD as a function of frequency by using NASTRAN's TABRND1 table format.

These two modifications allowed the aeroelastic frequency response analysis or solution 146 to be also used as a buffet load analysis capability, which incorporate the transport lags modeling the correlated buffet flow across a lifting surface and, more importantly, the buffet *pressure* PSD based on the measured buffet pressures instead of a *velocity* PSD ordinarily used in standard gust load analysis.

3.0 ANALYTICAL PREDICTIONS USING BUFFET ANALYSIS METHOD

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. For this event, the buffet loads analysis method is demonstrated to predict the buffet loads of the flight data. The exercise will serve to validate and build confidence method's prediction capability.

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 buffet loads analysis. The FEM represents the empennage flexible model, 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 below 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
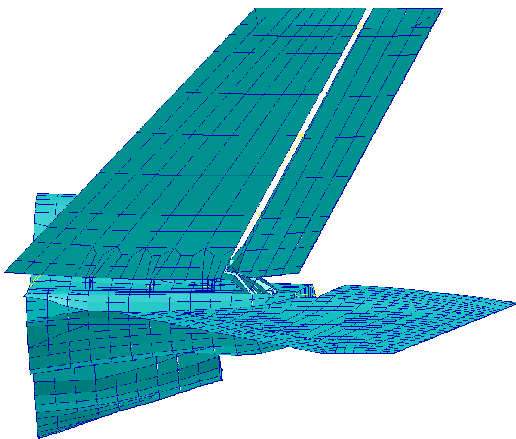

Figure 5. NASTRAN Finite Element Model of Aft Section of Joint Strike Fighter. (Courtesy of Lockheed-Martin Aeronautics)
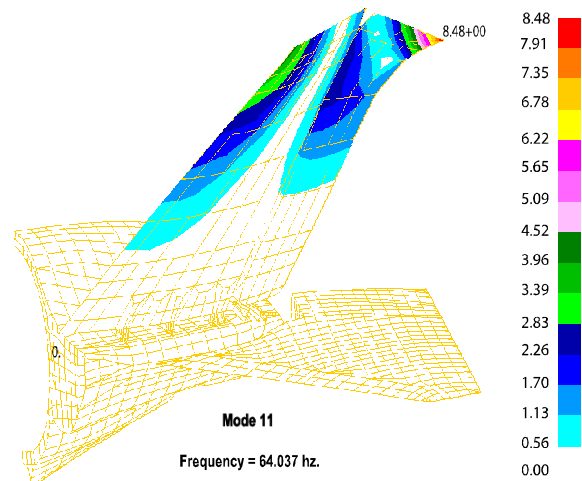

Figure 6. Mode shape of the first rudder torsion mode at 64 Hz. of the JSF.

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.

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.
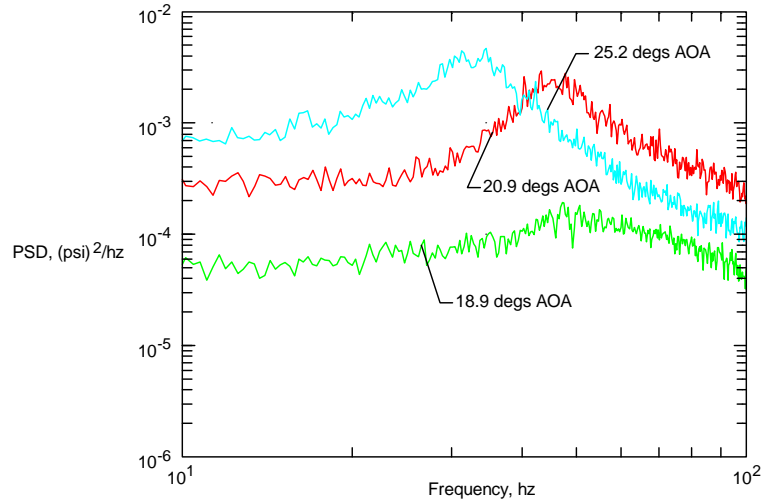

Figure 7. Pressure spectra from LM wind-tunnel tests scaled to buffet flight condition of a full-sized X-35. aircraft.

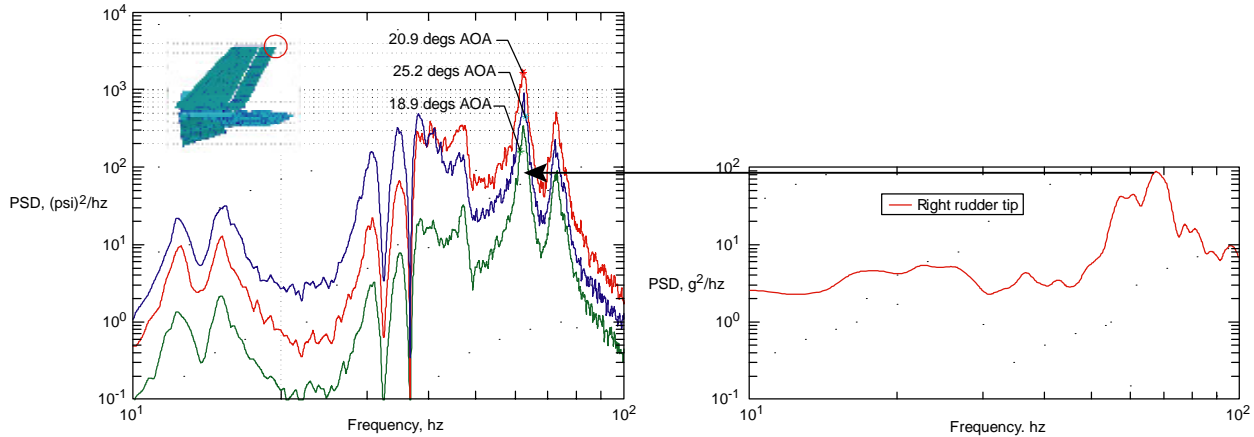Subsequently, the PSDs of JSF fin acceleration were computed for each angle of attack, as shown in figure 8.

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.

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.

3.3 Performing Buffet Load Analysis with Analytical Buffet Pressure PSDs to Validate the Method

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 7), 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.

$$\Phi(f) = \sigma_b^2 \frac{1 + \left(\frac{2\pi f}{\omega_n}\right)^2}{\left(1 + \frac{2\delta(2\pi f)}{\omega_d} + \left(\frac{(2\pi f)}{\omega_d}\right)^2\right)^2} \tag{7}$$

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 (7) to estimate the pressure PSDs at the 18 and 18.2 degrees angle-of-attack conditions, as seen in figure 9. As a reference,
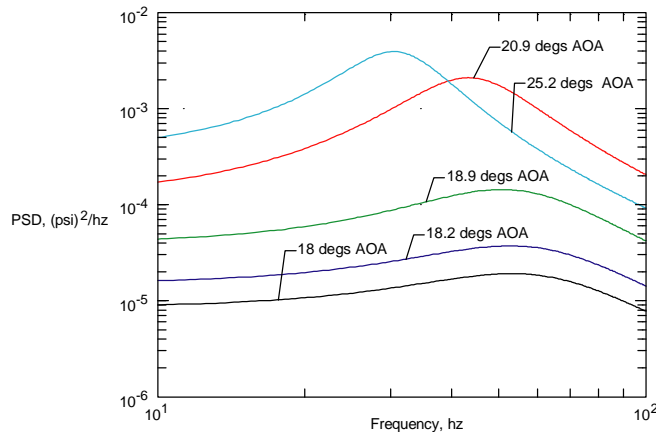

Figure 9. Analytical function plots of pressure spectra obtained by fitting the scaled raw PSDs derived from LM wind-tunnel tests. The 18 and 18.2 degrees PSD plots are interpolated estimates based on fitted analytical functions.

the 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 10. 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 result for the analytically-derived pressure PSD and the scaled wind-tunnel pressure PSD for 18.9 degrees AOA agrees with measured results very well, offering another indication of the potential of this approach.
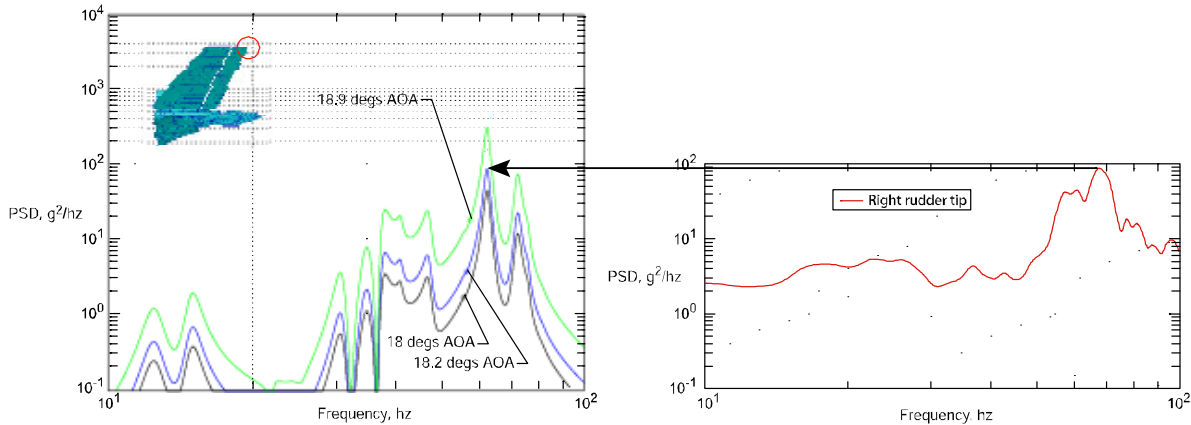
Figure 10. Acceleration PSDs at 18.9, 18.2 and 18.0 degrees AOA computed by NASTRAN from analytical-function-derived buffet-pressure spectra and acceleration PSDs at 18.0 degrees AOA obtained from X-35 Fight Data.

3.4 Additional Buffet Load Predictions for Aircraft

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 11 for comparison. These three cases are labeled as the baseline
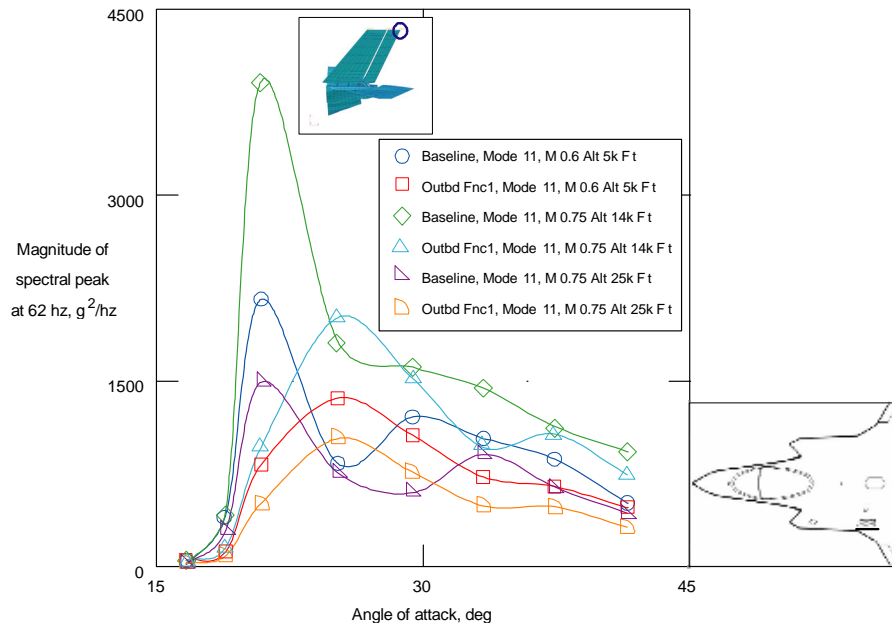

Figure 11. Peak response values of the aft rudder tip with angle of attack for the baseline JSF and the LEX fenced configuration at various flight conditions.

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 11. 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

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