VIBRATION AND AEROELASTIC CLEARANCE WORK FOR JASSM INTEGRATION ONTO THE F/A-18A/B

David Conser, Carl Mouser, Hugh McCann
Defence Science and Technology Organisation
david.conser@defence.gov.au;carl.mouser@defence.gov.au;hugh.mccann@defence.gov.au

Keywords: *Flutter, Store, Vibration, Flight Test*

Abstract

Australia acquired the Lockheed Martin (LM) AGM-158 Joint Air-to-Surface Standoff Missile (JASSM) and has integrated it onto the Royal Australian Air Force (RAAF) F/A-18A/B (referred to as F/A-18 herein) aircraft. This process required the aeroelastic envelope for the aircraft/missile to be quantified such that a flight clearance could be issued. In addition, the JASSM vibration environment for F/A-18 carriage had to be quantified and compared to vibration qualification testing. This work is discussed herein and was carried out in Australia using assets based at RAAF Base Edinburgh and scientific and engineering expertise from the Defence Science and Technology Organisation (DSTO) and the Aerospace Operational Support Group (AOSG).

1 F/A-18 Flutter

Aeroelastic flutter is a dynamic instability characterized by oscillations of rapidly growing amplitude that can lead to serious damage or destruction of the aircraft. The F/A-18, like most fighter aircraft, is susceptible to flutter-like behaviour at certain flight conditions whilst carrying heavy under wing stores [1]. Unlike most aircraft, for this configuration the F/A-18 dynamic instability behaviour is not a classical flutter, but rather a Limit Cycle Oscillation (LCO) type response. This instability is not unique to the F/A-18 and is common to other thin-wing fighters such as the F-16 [2]. Due to the nature of the aeroelastic response experienced by the F/A-18, an aeroelastic clearance was required based upon flight testing. This flight test program is discussed in the following sections.

1.1 Limit Cycle Oscillations

The current analytical flutter models for the F/A-18 are linear, both in the structural dynamics and aerodynamics modelling. This presents problems when trying to model F/A-18 LCO at certain points within the possible flight envelope of the aircraft. LCO is a non-linear phenomenon that was identified during the early phases of F/A-18 development. Classical flutter theory, based on linear modelling, assumes there is a point (the flutter point) where the total damping in the system will be equal to zero. At this point, LCO will occur but any increase in dynamic pressure would lead to divergent oscillations. Because of the non-linear behaviour of the F/A-18, an increase in dynamic pressure past the LCO point does not necessarily lead to a rapidly divergent behaviour, rather the LCO is maintained for a wide range of increasing dynamic pressure, albeit with a slowly increasing amplitude.

A significant amount of testing was conducted by the United States Navy (USN) to assess ramifications of flight in an LCO regime. It was found that the most significant impact was on human factors, thus impacting the pilot's ability to fly the aircraft and perform routine cockpit functions. As a result, the aircraft response has been characterised as a function of aircraft lateral acceleration, as measured by an accelerometer installed in the vicinity of the pilot seat, with allowable acceleration limits defined.

1.2 Active Oscillation Control

The F/A-18 susceptibility to LCO was identified during the initial development and full scale testing phase of the aircraft. The manufacturer of the aircraft McDonnell Douglas Corporation, now Boeing, introduced a modification to the flight control system, known as the Active Oscillation Control (AOC) [1]. The AOC worked with the existing flight control system to drive the ailerons in response to the lateral acceleration sensed in the forward fuselage using a fixed, non-adaptive, control law. The minimum Mach number at which the AOC is active was based on flight test results and experience gained from testing a wide range of stores. Thus, the flight control system of the F/A-18 controls the activation of the AOC which is dependent on the store configuration as well as the Mach flown.

1.3 Flight Flutter Test Program

Considering the LCO phenomenon and AOC issues, the RAAF and DSTO embarked on a flight flutter test program to provide a safe envelope for carriage of the JASSM onboard the F/A-18. The program was the first of many involved in certifying JASSM carriage and was required before separation/jettison and noise and vibration clearance flights could be flown.

In preparation for the flight trials, training was provided by the USN to several RAAF flight test engineers, DSTO flutter engineers and a RAAF test pilot. This training led to the development of flutter flight testing procedures to be followed by both airborne and ground-based flight test crew. The procedures were further developed by a series of work-up flights and other clearance programs, culminating in a JASSM flight flutter test program conducted between May 2008 and March 2009, with several significant breaks within this period to address other RAAF needs requiring the test aircraft.

The flight test program aimed to quantify LCO response of the aircraft and determine the airspeed at which this response grew to an unacceptable amplitude. Given the dangerous implications of airframe LCO response potentially becoming unstable and leading to the possible loss of the aircraft and aircrew, an F/A-18 chase aircraft was mandated and all flights were monitored real time at the ground station using a series of sensors installed on the test aircraft. Basic flight parameters, such as airspeed, altitude, Mach and normal acceleration (N_z) and aileron angle (to track AOC response) were monitored. The response of accelerometers installed at the wing tips and wing mid-span, the JASSM Mass Simulation Vehicles (MSVs, mass and inertially representative inert test assets) and the fuselage (lateral acceleration) were also monitored. An abnormal response in any key sensor would lead to an immediate termination of the test point, with the pilot returning the aircraft to a known safe condition.

1.4 Automated LCO Amplitude Tracking

To aid in monitoring the aircraft, an automated LCO monitoring capability was developed to track the LCO amplitude. This provided immediate feedback to the ground-based engineers on LCO status and if pre-defined limits were being approached.

Aircraft data was available in real time at the ground station via a telemetry link to the aircraft. This data was received and converted to engineering units by a commercial telemetry system, was sent out on the Ethernet network and was accessible to all computers on the ground station network. DSTO developed custom software that would capture the data stream, determine the amplitude of the LCO and display it in real-time.

For the purposes of this flight test program, the LCO amplitude was defined as the amplitude of the dominant frequency present in the data over a 2 Hz bandwidth where the LCO phenomenon occurs. A linear-least-squares fit was used to determine the amplitude of a sine wave at 0.1 Hz frequency intervals within the 2 Hz window. The maximum amplitude and the corresponding frequency were then taken as the

LCO amplitude and frequency. Given this calculation was conducted in real-time using data acquired at 312 Hz, the frequency resolution at which the amplitude was calculated was a compromise between providing immediate results to test engineers and accurately determining the aircraft response.

The LCO amplitude was displayed on the test director's and flutter engineer's terminal to provide continuous monitoring during the conduct of the flight test (Fig. 1). The display also changed colour to indicate the magnitude of the LCO amplitude relative to pre-defined maximum allowable limits. In addition, real time response traces of several key channels were available to the flutter engineers to monitor the response and growth in amplitude of several key components (i.e. wing, JASSM).

Indicates acceleration level at specific frequency

Fig. 1. Real Time LCO Amplitude Monitoring Window

Each test point was terminated if the LCO amplitude reached a response level considered greater than was acceptable for normal F/A-18 operations. The airspeed/altitude combination at which this response occurred was then used to determine the final flutter-free envelope of the F/A-18 when carrying the JASSM.

1.5 Results From Flight Flutter Testing

A total of 19 flights were flown to fully define the allowable F/A-18 JASSM flight envelope. This flying covered a range of altitudes, starting at 30,000 ft, where an initial understanding of the dynamic response of the aircraft was obtained at low risk due to lower dynamic pressures. The flying progressed to lower altitudes where airframe aeroelastic response increases and specifically, LCO amplitude increases as Mach number approaches the transonic region. Fig. 2 shows an example of the type of response seen as the airspeed is slowly increased towards the LCO limit. This plot highlights the typical behaviour observed and the rate at which the limit is approached. Also highlighted in this figure is the single frequency nature of the response. The envelope shown on the figure is a single sinusoid fit to 0.5 second windows of data. It is apparent that as the amplitude increases, the response becomes dominated by a single frequency, with response at other frequencies becoming very small. The two inset plots show the response before the onset of the LCO and at the peak of the LCO response, for upper and lower inset plots respectively. These plots clearly indicate the broadband nature of the response prior to entering LCO and the predominately single frequency nature of the LCO response.

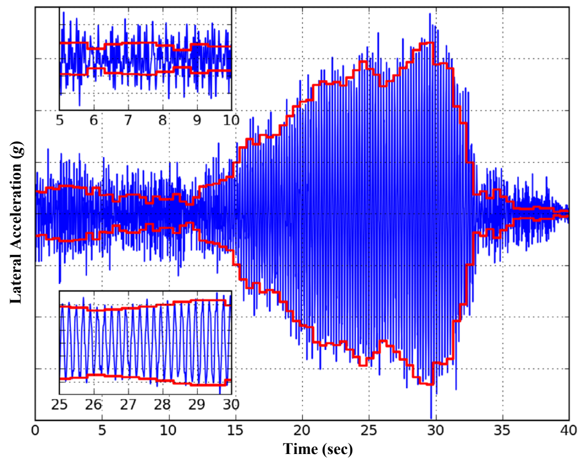

Fig. 2. Aircraft Lateral Acceleration as Airspeed Approaches the LCO Limit

For each test point flown, the LCO amplitude was plotted as a function of airspeed for various altitudes and fuel states, as fuel weight affects wing structural dynamics. A sample plot is shown in Fig. 3. As can be seen from this figure, the LCO amplitude asymptotes are at a clearly defined airspeed. It was this airspeed that was used in the determination of the safe carriage envelope boundary. Note that below the airspeed at which the acceleration increases sharply there are several airspeeds with a reasonably high response. These responses are either transient responses induced by pilot stick raps used to initiate the vibratory response or a change in the LCO response which lags the change in airspeed as the aircraft is rapidly slowed once the peak LCO response is reached.

At the conclusion of the flight flutter testing a safe flight envelope was recommended for the F/A-18 carrying JASSM and the integration program was able to continue with other flight testing required to clear the JASSM for F/A-18 carriage.

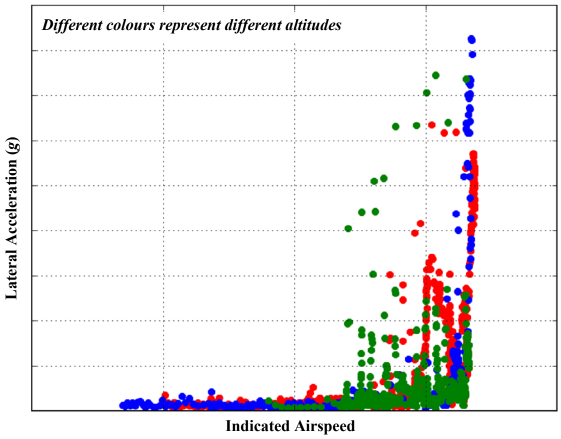

Fig. 3. Aircraft Lateral Acceleration vs. Airspeed

2 JASSM Noise and Vibration

2.1 Background

JASSM procurement utilised a *Function and Performance Specification* (FPS) that included noise and vibration (N&V) requirements. These addressed transportation, F/A-18 captive carriage (CC) and free flight. MIL-STD-810F [3] (also referred to as 810F) was the FPS N&V environmental standard basis.

The JASSM N&V certification levels represented composite spectra derived from other fighter and bomber aircraft. Test spectra for the various components were provided to Australia by LM. Initial assessments indicated that acoustic certification was of less concern. Thus, this paper focuses on CC vibration.

MIL-STD-810F states that there are four primary store vibration sources. These are engine noise peaking at takeoff initiation, aerodynamic turbulence distributed over its surface in flight (non-buffet), aircraft induced vibration (buffet vibration) and vibration generated by internal materiel and local aerodynamics. The first three sources can differ with carriage platform and can be addressed in an N&V flight test program, with the last occurring after store release and addressed by LM in free flight vibration testing.

To measure F/A-18 CC vibration, a JASSM instrumented test vehicle (ITV, Fig. 4 and Fig. 5) was procured from LM for use in an N&V flight test program. The ITV has the same shape, mass properties and was manufactured to be as statically and dynamically similar as possible to a production JASSM. The wings and tail do not deploy and inert components are used. It is also equipped with a Telemetry Instrumentation Kit (TIK) and 100 measurement channels. For N&V analyses, these included 56 accelerometers and 9 microphones sampled at 6720 Hz. The accelerometers covered all major JASSM components. The TIK system transmits measurements via telemetry (TM) to a ground station for reception and processing.

Boeing F/A-18 store N&V flight test reports, in particular their store vibration, shock and acoustic noise requirements report [4], helped guide JASSM flight test N&V planning and data analyses described herein.

2.2 Ground Vibration Testing

A limited ground vibration test (GVT) program was conducted to assess the ITV function, AOSG ground station reception/processing and to measure modal properties of the F/A-18 wing/pylon/JASSM.

The GVT configuration was as shown in Fig. 4. A photo of a test setup using shakers is shown in Fig. 5. Testing uncovered a problem with the ground station's commercial telemetry and data processing system that resulted in data overflows/loss and incorrect time stamping. This discovery before flight testing allowed alternative processing plans to be developed.

Modal test results identified predominant response frequencies of the system prior to flight testing. These were useful in interpreting N&V response. As an example of results obtained, a bending mode is shown in Fig. 5.

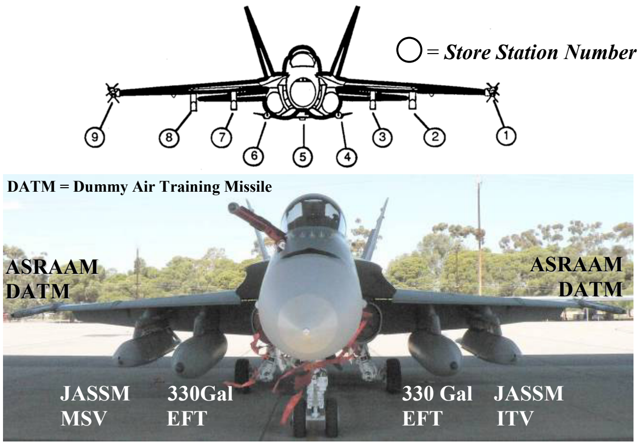

Fig. 4 GVT and Clearance Station Configuration

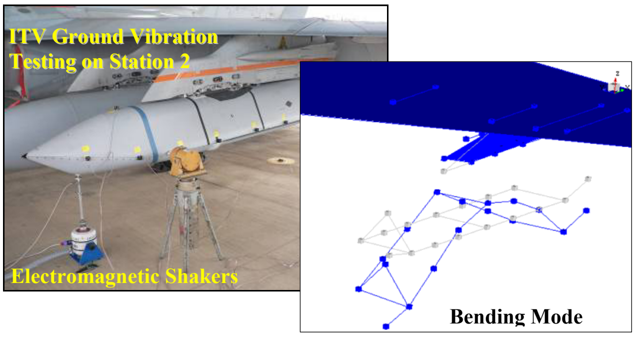

Fig. 5 F/A-18 GVT Setup with ITV Sample Results

2.3 JASSM N&V Flight Testing

A RAAF F/A-18 instrumented flight test aircraft was utilised for N&V testing. Flight testing aimed to measure the captive carriage N&V environment of critical JASSM equipment. The Mach, airspeed, altitude and N_z flight envelope considered was based on missile specifications and applicable flight clearances. JASSM contractual carriage requirements specified an N_z limit lower than aircraft limits. As limits of the basic aircraft applied to JASSM carriage and were desired operationally, the N&V flight test program had to accommodate a broad N_z carriage range.

DSTO and AOSG provided the technical and engineering expertise, flight test engineers, test pilots and assets required for the N&V flight test program. Two LM engineers also attended the first eight flights flown to support ITV operation and real time data and missile structural integrity assessments.

Given a JASSM flight clearance was required on both outboard pylons, the outboard station used for ITV carriage was considered. This was of interest given JASSM asymmetries caused by the vertical tail (Fig. 6). Discussions with DSTO fluid dynamicists indicated flow between the JASSM and the inboard external fuel tank (EFT) was expected to produce higher energy flow based on previous DSTO computational fluid dynamics (CFD) studies. One such result is shown in Fig. 7 for dual MK83 carriage, with the flow phenomenon involved discussed in [5]. Given this, Station 8 carriage (Phase 1) was selected for ITV carriage as it exposed the ITV tail to this flow. A flight was also flown with the ITV on Station 2 (Phase 2) for investigative purposes.

Fig. 8 shows a sample from JASSM CFD modelling performed after N&V testing to further investigate flow characteristics. Supersonic flow is shown at the aft end of the JASSM, with in-flight vibration response in this area of the JASSM demonstrating Mach effects in the transonic flight regime.

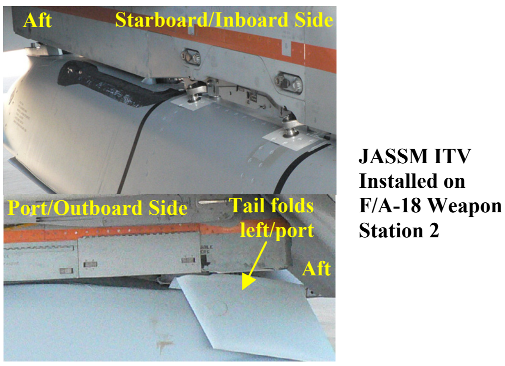

Fig. 6 JASSM Aft Asymmetries Due to Tail

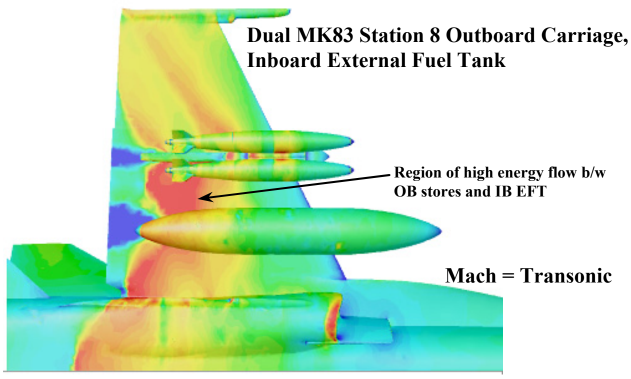

Fig. 7 DSTO CFD Work used to Choose Station 8

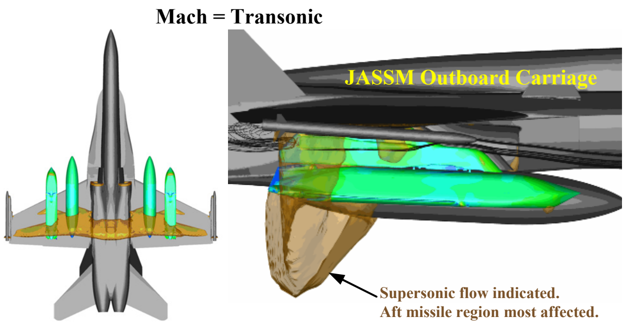

Fig. 8 DSTO CFD of JASSM Outboard Carriage

A comprehensive matrix of test points was derived for the N&V flight test program. Key flight parameters influencing F/A-18 store vibration (Mach, Altitude, Dynamic Pressure (Q) and N_z) were drivers, with conditions expected to yield high vibration targeted. A total of 75 Mach-Altitude-N_z points in the sky (PITS) were defined for the two test phases. The manoeuvres flown at these PITS included dynamic/transient and steady state manoeuvres to achieve the required N_z, depending up the PITS and purpose, as well as Level Accelerations and Decelerations (LADs) to obtain nominally steady state data for a given altitude over a range of Mach numbers.

A total of 13 flights were flown. The first 12 (Phase 1) carried the ITV on Station 8. A 13th flight was flown in the Phase 2 configuration. The number of flights was driven by ITV TM reception issues, especially during transient/dynamic manoeuvres. The lack of an ITV onboard recording system meant that TM loss had a significant impact on the program.

2.4 Vibration Data Processing & Analyses

Time periods corresponding to PITS manoeuvres were processed. Fig. 9 shows these periods in red for Flight 11. Flight parameters recorded on an aircraft tape system, as well as aircraft telemetry data, were also provided for N&V analyses. Telemetry data was instrumental in fixing numerous anomalies present in the tape data.

Given the amount of ITV data and telemetry issues, data integrity checking and 'cleaning' was a very time consuming part of the N&V data analyses. While sometimes tedious, the task should not be underestimated in scope or in its importance to program success.

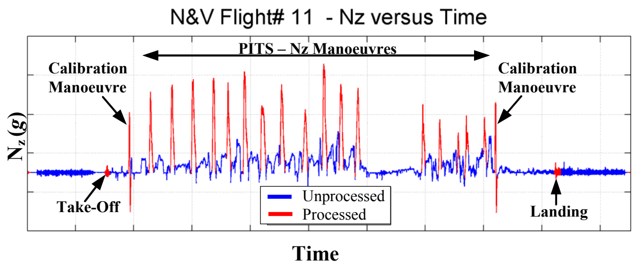

Fig. 9 Flight Periods Analysed for N&V – Flight 11

The spectral analysis approach used by DSTO utilised 2048 point Fast Fourier Transform (FFT) analyses to create Power Spectral Densities (PSDs). While yielding a frequency resolution of only 3.28 Hz, this was deemed adequate for derivation of vibration environments. Choice of this smaller FFT block size also maximised the usable amount of data.

These narrow band PSDs were also converted to 1/3rd octave PSDs and used to define composite PSDs for consistency with Boeing methodologies [4]. As with Boeing, final composite PSDs also omitted 'outliers' at each spectral line based on DSTO defined criteria.

PSDs and composite PSDs were calculated for each of the four flight environments; non-buffet, buffet, take-offs and landings. Various flight parameter statistics and acceleration root mean square (G_{rms}) values were also calculated and stored for each PSD.

Fig. 10 shows sample PSD results. These demonstrate differences present in the four environments. While buffet is dominant at low frequencies, take-offs produce the most vibration at higher frequencies.

PSD G_{rms} response values were also compared to F/A-18 flight parameters to study response trends. One such plot is provided in Fig. 11. This plot also demonstrates the high take-off vibration levels present.

Take-off vibration levels were unexpectedly high compared to in-flight results, see Fig. 11. Fig. 12 shows Flight 1, 5-2000 Hz G_{rms} measurements for each ITV accelerometer normalised by its maximum G_{rms}. The response trend evident is consistent throughout the store and was seen in take-off data for all flights.

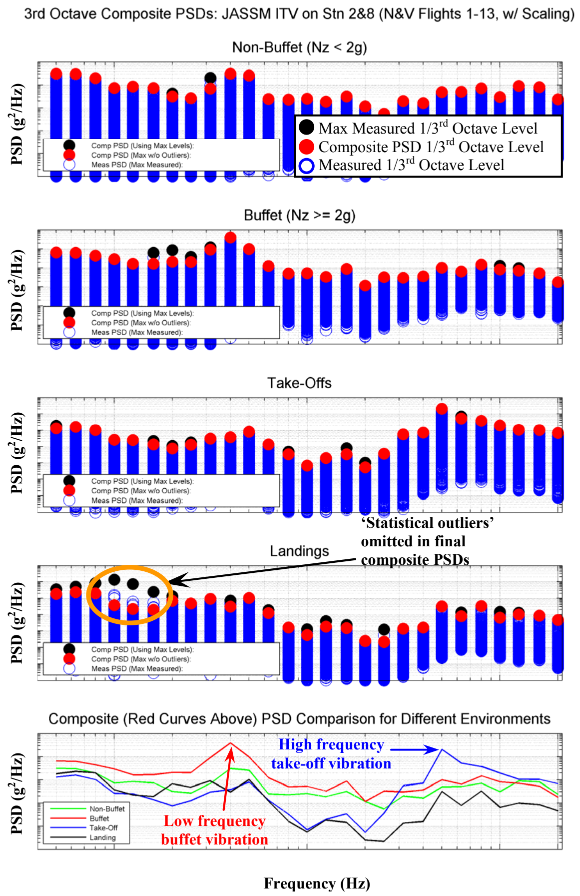

Fig. 10 Sample 1/3rd Octave PSD Results

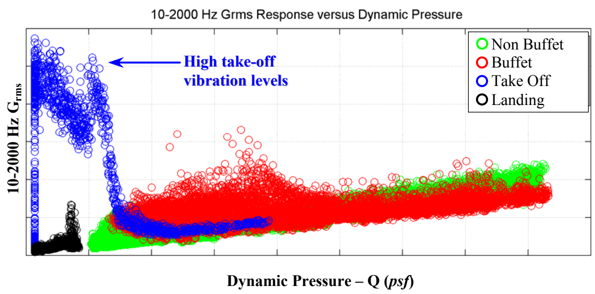

Fig. 11 10-2000 Hz G_{rms} vs. Q – All Environments

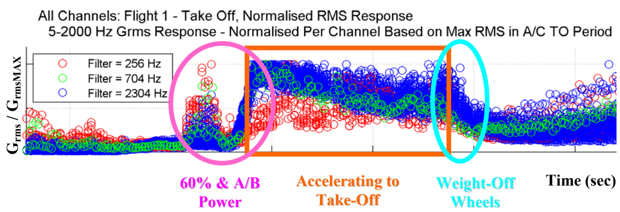

Fig. 12 Normalised Take-Off G_{rms} vs. Time for Flight 1

To investigate possible response differences for Station 8 and 2 missile carriage, G_{rms} values for straight and level flying (LADs) at various altitudes were assessed. LADs provided quasi-steady state conditions deemed more conducive to response comparisons and included transonic flight where the presence of recovery shock waves, often forming near the aft of the store, produces an aerodynamic excitation source that could differ with pylon station.

To investigate this, 10-2000 Hz G_{rms} vibration levels were plotted against Mach number to assess Station 2 and 8 response trends and differences. Fig. 13 shows such response comparisons at an aft JASSM location, normalised by dynamic pressure, for 15,000 and 25,000 feet altitude. Clear differences between Station 2 and 8 are apparent within the transonic Mach flight regime. These differences are deemed beyond statistical scatter and are likely caused by local aerodynamic differences related to configuration asymmetries.

To address Station 2 versus 8 response differences, a conservative scaling approach was taken which utilised curve fitting to scale lower levels to the higher of the response levels present on either station. This ensured that all data was used and the highest measured LAD G_{rms} response levels were used in vibration damage assessments.

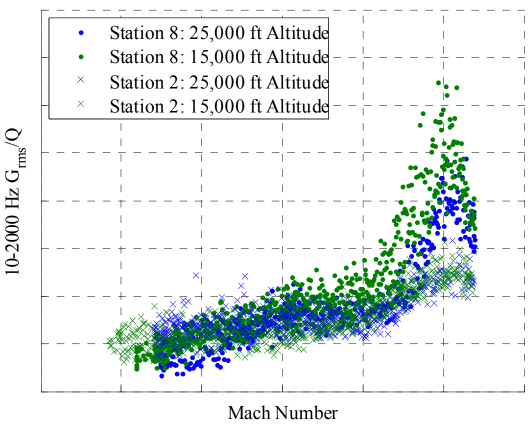

Fig. 13 Station 8 vs. Station 2 LAD G_{rms}/Q vs. Mach

2.5 Vibration Response Characterisation

Parts of the flight envelope were either not flown or had limited amounts of data. As a result, response was predicted for these regions. To facilitate this, response trends versus flight parameters were assessed using available aircraft data. The following parameters were used.

- Take-Offs: G_{rms} = f {airspeed (*knots*)}
- Landings: G_{rms} = f {airspeed (*knots*)}
- Non-Buffet: G_{rms} = f {Q (*psf*)}
- Buffet: G_{rms} = f {N_z (*g*), Q (*psf*)}

Data were collated into flight parameter regions or bins per vibration environment. The size or range of these bins was a compromise between adequately maintaining random vibration response trends and obtaining enough data to achieve a level of statistical significance.

Time weighted G_{rms} predictions were made for bins without adequate data, with predictions only used instead of measured values if a more severe yet 'plausible' level resulted. Examples of response trend plots assessed are provided in Fig. 14. As can be seen, broadband non-buffet G_{rms} response varied linearly with dynamic pressure. Thus a linear prediction was used for non-buffet response.

Fig. 14 also shows a contour plot of G_{rms} versus N_z-Q for buffet flight. As the most important JASSM vibration qualification concerns were discovered to be below 100 Hz, 5-100 Hz G_{rms} data was used for predictions. In reality 3-D surface fits were used to predict buffet response. A surface fit with limited extrapolation applied is shown in Fig. 15. Given extrapolation was needed to cover the full envelope, primarily at lower dynamic pressures, rules were necessary and derived to address 'unrealistic' predictions.

A response distribution was also required for each bin to represent the range of vibration levels experienced. For a bin with more than 40 spectral estimates (deemed statistically 'adequate' based on the N&V database), the measured response distribution was used. In bins using a prediction, a response distribution was selected by identifying the most damaging (using Section 2.6 methods) of the five most populated bins for that channel. This ensured a well populated and conservative damage distribution was used in vibration compliance studies. The selected distribution was normalised by its time weighted G_{rms}, and scaled by the predicted G_{rms} to derive the response levels analysed for the bin.

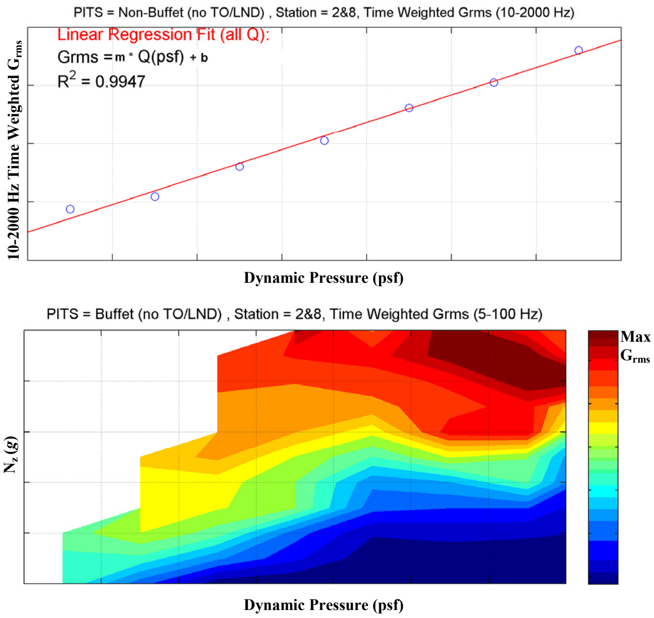

Fig. 14 Non-Buffet & Buffet G_{rms} Trends vs. Q & Nz-Q

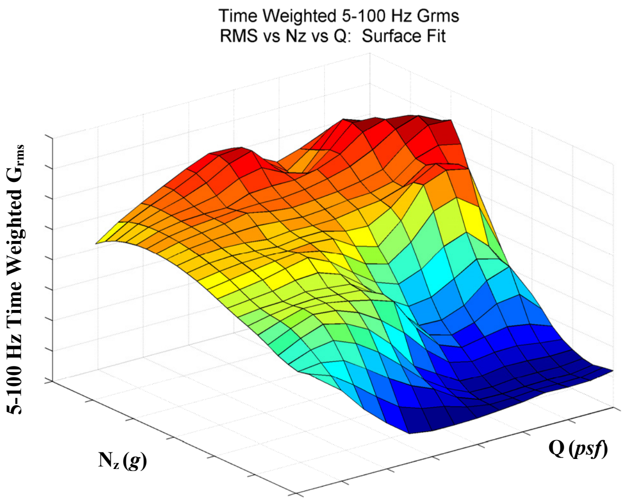

Fig. 15 5-100 Hz G_{rms} Surface Fit to Flight Data

2.6 JASSM Vibration Damage Analyses

To determine vibration damage exposure for each equipment item, time for each of the four flight environments was required as a function of selected vibration characterisation parameters (i.e. airspeed, N_z, Q).

Several predicted mission profiles or usage data sources for JASSM carriage were evaluated. The FPS required a JASSM captive carriage life of 'X' hours. Thus, damage was predicted for X hours of each usage data source and compared to predicted damage results for associated vibration certification programs.

The method used to calculate vibration damage is derived from simple damage theory defined in MIL-STD-810F. The 810F damage or time equivalency technique is an industry standard approach for these assessments. However differences in the equation's exponent, something which is derived based on the components or materials analysed, are common. A variant of the 810F equation, utilizing G_{rms} instead of PSD and a different exponent per Boeing store N&V analyses [4], is provided in Eqn. (1). This is a damage equivalence or time compression equation derived from the Eqn. (2) damage equation. These equations are the basis for JASSM vibration damage analyses.

$$\left(\frac{T_1}{T_0}\right) = \left(\frac{G_{rms\,0}}{G_{rms\,1}}\right)^{6.5} \qquad (1)^1$$

Where: T_1 = Time spent at level G_{rms1}
T_0 = Time spent at level G_{rms0}
G_{rms1} = Level applied for time T_1
G_{rms0} = Level applied for time T_0

As derived from the following damage equation.

$$Damage = Time * G_{rms}^{\ 6.5} \qquad (2)$$

F/A-18 N&V flight test G_{rms} levels and usage times, scaled to X captive carriage flight hours, were used in Eqn. (1) to calculate the equivalent time (i.e. the time yielding equivalent damage) if the flight time was spent at the applicable buffet/non-buffet composite PSD G_{rms} level. The resulting equivalent time and the buffet/non-buffet composite PSD 1/3rd octave levels were then used to calculate damage using Eqn. (2). Take-off and landing damage was calculated 'per event' using measured N&V flight test data from the 13 flights and composite PSDs. This was then scaled to the number of flights required to achieve X flight hours. Eqn. (3) follows from Eqn. (2) and represents the manner in which total captive carriage damage was calculated from each flight environment. This was done for each usage data source at each measurement location.

$$Damage\ (freq) = \sum_{i=1}^{4} T_i * G_{rms\,i}^{\ 6.5} \qquad (3)$$

Where: i = Flight environment (take-off, non-buffet, buffet and landing)
T_i = Equivalent time calculated at composite PSD level G_{rmsi} per environment i
G_{rmsi} = Composite PSD G_{rms} level, as a function of 1/3rd octave band, per environment i

2.7 Vibration Damage Results/Assessment

While '*Damage*' herein refers to vibration induced damage, the method used only allows 'damage exposure' or 'damage potential' to be calculated, with damage only resulting if the structure or components exposed to the vibration are susceptible to it. This can only be determined conclusively through testing. Thus, if the predicted in-service total vibration 'damage' of a component exceeds that of its qualification testing, it does not necessarily mean that the item will fail during fleet service. Rather, such a result indicates that there is no certification test basis to guarantee it will not fail, thus highlighting a risk requiring further consideration and engineering assessment.

[1] *The MIL-STD-810F exponent of 4.0 on PSD level [3] becomes 8.0 when using G_{rms}. For this application, the 810F equation was less conservative than using the exponent of 6.5 used by Boeing in store N&V analyses.*

The total damage predicted at a given location was compared to damage predicted for corresponding qualification test spectra. Sample damage results, normalised by the qualification test damage, are provided in Fig. 16 for one usage data source analysed. This usage results in less total damage for this location at all frequencies than the corresponding certification test. This also shows the difference in damage contribution based on flight environment.

The usage source selected was also important to the damage results obtained, with inclusion of high N_z buffet and or high Q usage time increasing damage at low frequencies, with the peak in Fig. 16 damage corresponding to response of missile bending modes.

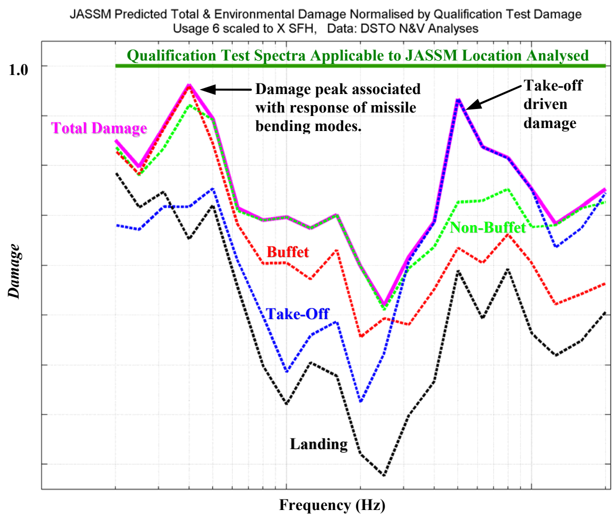

Fig. 16 JASSM Predicted Damage vs. Qualification

3 Conclusions

An Australian F/A-18 JASSM captive carriage vibration flight test and analysis program was successfully conducted through a highly collaborative program involving DSTO, AOSG and RAAF personnel. Flutter testing and analyses were completed to define a flutter free flight envelope for JASSM carriage. Given this, a successful captive carriage N&V flight test program was completed. Using ITV vibration measurements from this testing, DSTO successfully completed all analyses required for JASSM F/A-18 captive carriage vibration compliance assessments, with these results provided to the Australian JASSM Project Office.

4 Acknowledgements

As both the flutter and N&V programs were major tasks involving vast resources and a significant number of personnel, the authors wish to acknowledge all staff members at AOSG, DSTO, the AIR 5418 Project Office, Lockheed Martin, the Tactical Fighter System Project Office and CDG who played a role in making these programs a success. Those of specific note at DSTO are Shane Dunn, flight flutter test engineer, and Regina Blyth and Stefan Schmidt, fluid dynamicists responsible for CFD work presented herein.

5 References

[1] Trame L, Williams L, Yurkovich R. Active aeroelastic oscillation control on the F/A-18 aircraft. *AIAA Guidance Navigation and Control Conference*, Snowmass, CO, August 1985

[2] Denegri, C. Limit cycle oscillation flight test results of a fighter with external stores. *Journal of Aircraft*, Vol. 37, pp. 761-769, June 2001

[3] MIL-STD-810F, *Department of Defense Test Method Standard for Environmental Engineering Considerations and Laboratory Tests*, 1 January 2000.

[4] Croppi JM and Jordan CJ, F/A-18 A/B/C/D Vibration, Shock, and Acoustic Noise Environmental Measurements and Requirements and for External Stores, McDonnell Douglas Aerospace report *MDA 95A0107*, 1 May 1996.

[5] Fairlie, BD and Caldeira, RH. Prediction of JDAM separation characteristics from the F/A-18C aircraft, *37th AIAA Aerospace Sciences Meeting and Exhibit*, AIAA-1999-0126, 1999.

6 Copyright Statement