COMBINED UNSTEADY AERODYNAMICS AND STRUCTURAL RESPONSE ON AUXILIARY POWER UNIT FLAP DOOR: STRENGTH AND FATIGUE JUSTIFICATION METHOD

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Abstract: The present work details a methodology to consider the unsteady aerodynamic excitation based on WTT (Wind Tunnel Test) and to combine it with FEM (Finite Element Model) analysis in order to justify the strength and fatigue of the APU (Auxiliary Power Unit) flap door to forced vibrations at critical flight conditions by means of scaling factors. The methodology was then validated and extended with Flight Test results and good correlation is shown.

1 INTRODUCTION

In the aerospace industry it is normal practice to justify vibrations requirements (CS-25.301, CS-25.305 and CS-25.1309) for design by means of qualifying the system versus a standard spectrum as RTCA-DO160 or MIL-STD810.

This methodology here-in can be used as a compliant for non-aerodynamic structures, but when the mechanical system is embedded into high speed airflow, the physics changes due to the effect of fluid-structure interaction and in this instant, the vibration spectrum could be no longer conservative: the real response of the structures could be higher than the response obtained on the shaker table. Therefore unsteady aerodynamic excitation should be considered properly in these kinds of systems.

The available CFD models did not show good correlation between tested and calculated unsteady pressures, so these results could not be used to calculate the unsteady vibrations contribution to the stress of the components. The present work shows a methodology to consider the unsteady aerodynamic excitation based on WTT and to combine this information with FEM analysis in order to justify strength and fatigue of the APU flap door to forced vibrations. The methodology was then validated with Flight Test results.

2 EQUIPMENT DESCRIPTION

As an example of the proposed method, this paper focuses on the Auxiliary Power Unit (APU) inlet door (APU Flap). The APU Inlet is located at the Aircraft rear end. When opened in flight, the APU air inlet door is subjected to unsteady aerodynamic excitation that may lead to vibrations of the door. These vibrations are due to aerodynamic vortex shedding which drive resonance frequencies of the inlet assembly. Hereafter, this resonance response due to vortex shedding will be referred to as door forced response. The APU air inlet is illustrated in Figure 1. The inlet duct provides the flow path of air to the APU.

Figure 1: APU air inlet design, FEM and location in the aircraft

Mode shapes of the flap door are shown in Figure 2:

Mode 1 is a bounce mode that is the most significant contributor to the overall deformation and stresses in elements.

Mode 2 is a torsion mode with the left and right side of the door deflection out of phase and a neutral axis running front to back along the door center.

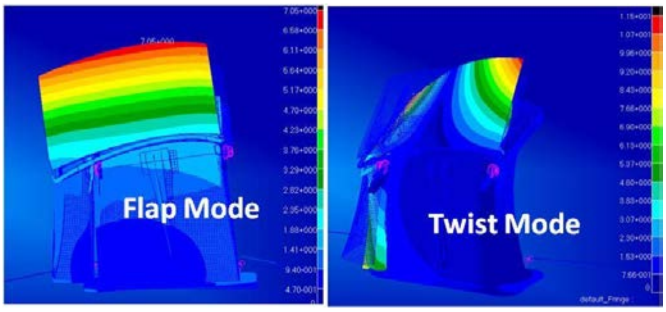

Figure 2: APU air inlet flap mode shapes.

Figure 3: Icing test used for damping calculation

The damping of the system is based on a testing done during an icing test (Figure 3). Data were collected at 3 accelerometer locations on the door (Figure 3). The door vibration response was captured as an acceleration signal and converted to displacement. These signals were then converted to the frequency domain using a FFT algorithm. Single degree of freedom response curves were fit to the resonant frequencies to assess the damping.

3 STRENGTH AND FATIGUE JUSTIFICATION METHODS

The methodology for strength and High Cycle Fatigue justification (HCF) of the APU flap door was needed to justify the full flight envelope extrapolating from WTT available data. The method is based on a system of scale factors applied to the steady analysis results. The Table 1 summarizes the stress combination used in each analysis:

<table>
<tr><th></th><th>HCF</th><th>Strength</th></tr>
<tr><td>STEADY</td><td>Steady stress factored from scale factors calculated from displacement relationship between test and FEM modal analysis.</td><td rowspan="2">Steady Stress as a sum of:
1) Steady Stress factored from FEM based on Test derived steady loads, plus
2) Half amplitude of Vibratory Stress from Test response mapped to FEM dynamic</td></tr>
<tr><td>UNSTEADY</td><td>Vibratory stress from FEM scaled modal analysis of test response</td></tr>
</table>

Table 1: Stress combination for steady and unsteady loads.

This methodology requires the previous stress analysis performed for the critical load cases defined in the phase design:

Case	Mach	h(ft)	APU Flap angle (deg)	F Resultant (N)	Hinge Moment (Nm)	Hinge Moment (lbs-in)	Effective lever arm (ins)	Actuator load (lbs)
1	M_1	h_1	Alpha	F_1	M_1	M_1	l	F'_1
2	M_2	h_2	Alpha	F_2	M_2	M_2	l	F'_2
3	M_3	h_3	Alpha	F_3	M_3	M_3	l	F'_3

Figure 4: Air Intake Flap Design Aerodynamic Loads

The overall stress state requires the evaluation of the mean and alternating loads and stresses. The mean loads and stresses are calculated from the pressure loads from WTT cases extrapolated to the critical flight conditions.

To obtain the alternating loads and stresses a scaled modal analysis approach was used as shown in Figure 5. The process starts by evaluating the WTT APU inlet door responses (6 door accelerations, actuator load) at various conditions linked to specific flight conditions.

As described later, appropriate factors are applied in the analysis to account for uncertainty.

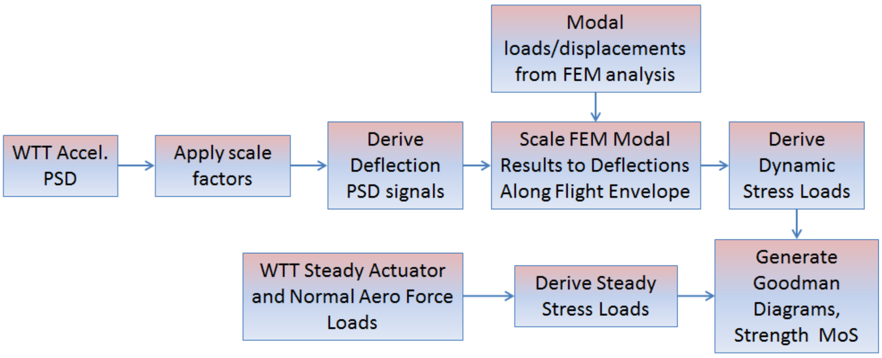

Figure 5: FEA analysis flowchart

The acceleration Power Spectra Density (PSD) signals are converted to deflection PSD signals using standard sinusoidal equations of motion. As described before, there are primarily two distinct response frequencies. These frequencies correspond to the inlet door bounce flap mode frequency and the door twisting mode frequency, respectively.

The RMS deflection responses are then calculated for these two modes by breaking the response curve into two distinct frequency ranges.

These RMS deflections at the accelerometer locations are then mapped to the FEM for the two predominant mode shapes (door flap, door twist). This mapping process is discussed in more detail in section 3.1.2.

3.1 Input Loads

The aerodynamic forces are quantified using the WTT data this aerodynamic force is split into a mean (steady) and a fluctuating (unsteady) part.

3.1.1 Static forces:

The method for generating static stress consists on determining the aerodynamics loads in the whole A/C envelope and the determination of the stress response to this excitation of the flap structure using FEM.

The values of the static door loads are obtained by the integration of the pressure probes situated along the door profile. CFD results are used to estimate the integration surfaces and lever arms associated to the pressure probes in order to obtain the final door moment in the rotation axis.

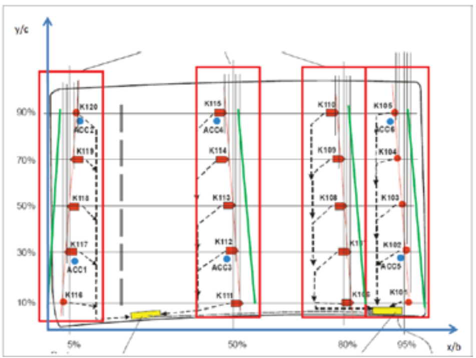

Figure 6: Accelerometer and pressure sensors installed on the WTT.

Then the door moment is equal to the actuator moment in the door rotation axis. So the actuator loads are the door moment loads divided by the actuator arm length.

An uncertainty (multiplication) factor of $\mathbf{K_T}$ is then applied to these loads to account for:

- Aircraft settings angle attack, sideslip, etc ... $\mathbf{K_1}$,
- Simplification of geometry computed by CFD and tested in wind tunnel…$\mathbf{K_2}$,
- Variability in the aircraft movables (A/C control surfaces) deflections vs. the CFD/WTT done with all movables at the neutral position or not movables … $\mathbf{K_3}$.

Finally, $\mathbf{K_T = K_1 * K_2 * K_3}$.

These factors are obtained from CFD results and validated later with flight test data:

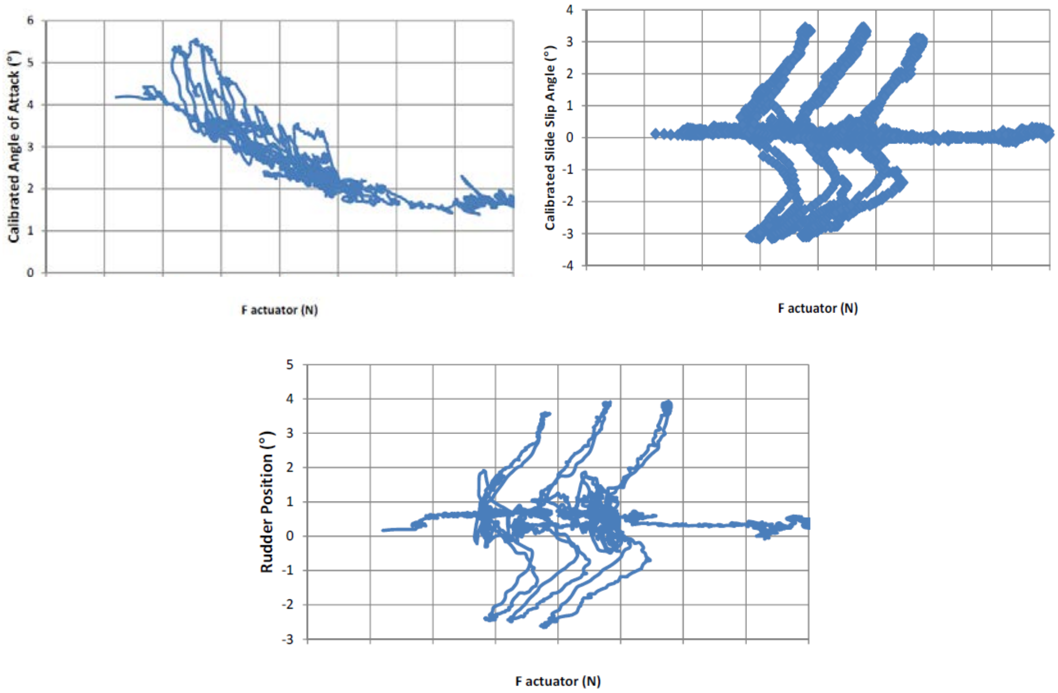

Figure 7: Angle of attack, Sideslip and Rudder deflection effects

3.1.2 Vibratory loads:

The process starts by evaluating the WTT inlet door responses (6 door accelerations) at various flight conditions. The frequency response (FFT) of the actuator load and accelerometers along with the accelerometer PSD for the various cases used in the structural analysis are shown in Figure 8. The actuator load response is plotted to 100 Hz because there is no significant response beyond 100 Hz. Similarly, the acceleration response is only plotted to 500 Hz because there is no significant response past 500 Hz.

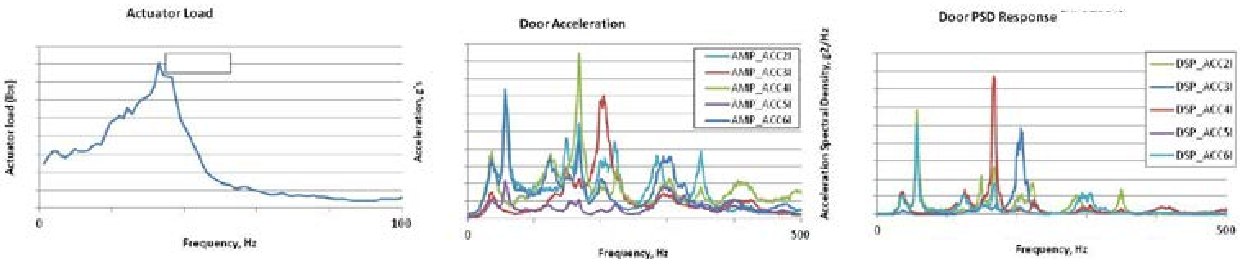

Figure 8: Actuator Load, Door acceleration and PSD response

The acceleration PSD signals are then converted to deflection PSD signals using standard sinusoidal equations of motion as shown in figure below:

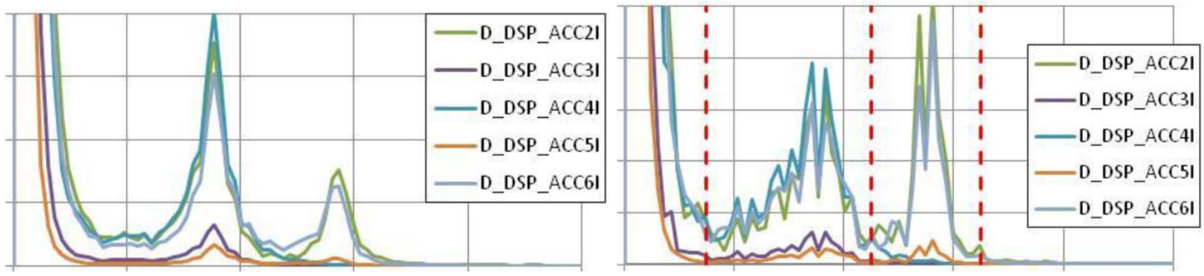

Figure 9: Displacements PSD signals and RMS calculation

All of the response plots show primarily two distinct response frequencies. These frequencies correspond to the inlet door flap mode frequency and the door twisting mode frequency, respectively. The RMS deflection responses are then calculated for these two modes by breaking the response curve into two distinct frequencies ranges (see Figure 9).

These RMS deflections at the accelerometer locations are then mapped to the FEM for the two predominant mode shapes (door flap, door twist).

3.2 Response Analysis

3.2.1 Steady Loads

The steady forces for critical door locations are obtained by scaling the forces from the FEM model for every load case with the ratio of mean actuator force obtained from test and analysis:

$$Steady\_part\_stress = FEM\_part\_stress * Test\_mean\_actuator\_force/FEM\_actuator\_force$$

The results from steady load analysis are used as mean values in the Goodman Diagram.

3.2.2 Response Analysis – Vibratory Loads

Normal mode scaling approach was used to calculate the RMS values of the alternating stress. The alternating stress in the Goodman Diagram calculations were obtained by scaling the stress from normal mode analysis with a ratio between the deflections obtained from normal mode analysis to the deflection measured during tests.

MODAL SCALE FACTOR

The normal mode scaling factor is calculated based on ratio deflection from normal mode analysis to the test deflection. There are 6 accelerometers in the tests, so 6 scaling factors are obtained. For the inlet door flap mode, the maximum ratio among the 3 accelerometers on the door top side leading edge is used for the normal mode scaling analysis. For the door twist mode, since the deflection in the middle accelerometer is very small, the maximum ratio among the two outside accelerometers (2 and 6) on the door top side leading edge is used for normal mode scaling analysis.

	Measurement		FEM Normal Mode Analysis		Test - Load Case				
		Test Accel #	Freq Hz	Amplitude	Freq Hz	Amplitude	Scale Factor	Scale Factor Used	Scaled Results
Flap Mode	Door Deflection	1	f1	A11	f1	B11	C11 = B11/A11	D1 = max[C11-C16]	D11 = D1*A11
	Door Deflection	2	f1	A12	f1	B12	C12 = B12/A12		D12 = D1*A12
	Door Deflection	3	f1	A13	f1	B13	C13 = B13/A13		D13 = D1*A13
	Door Deflection	4	f1	A14	f1	B14	C14 = B14/A14		D14 = D1*A14
	Door Deflection	5	f1	A15	f1	B15	C15 = B15/A15		D15 = D1*A15
	Door Deflection	6	f1	A16	f1	B16	C16 = B16/A16		D16 = D1*A16
Twist Mode	Door Deflection	1	f2	A21	f2	B21	C21 = B21/A21	D2 =max[C21-C26]	D21 = D2*A21
	Door Deflection	2	f2	A22	f2	B22	C22 = B22/A22		D22 = D2*A22
	Door Deflection	3	f2	A23	f2	B23	C23 = B23/A23		D23 = D2*A23
	Door Deflection	4	f2	A24	f2	B24	C24 = B24/A24		D24 = D2*A24
	Door Deflection	5	f2	A25	f2	B25	C25 = B25/A25		D25 = D2*A25
	Door Deflection	6	f2	A26	f2	B26	C26 = B26/A26		D26 = D2*A26

Table 2: Normal Mode Scale Factor Calculation

AERODYNAMIC SCALE FACTORS

The aerodynamic scale factors were developed because the available test data did not cover the entire flight envelope. Specifically, the wind tunnel limit avoided to test to most critical flight conditions. Extrapolation of the test data to flight conditions of interest was accomplished by the defined scaling factors. Different approaches were assessed with a method that utilizes structural response based on measured accelerometer data from WTT. The scaling factors include an escalation factor ($\mathbf{K_{RMS}}$) to take into account the WTT limitation and the full flight envelope on amplitude and frequency. Additionally, another multiplication factor ($\mathbf{K_S}$) is added to the provided scaling factors to account for:

- Uncertainties in the test data (to serve as reference for scaling the CFD data),
- Geometrical simplifications of the geometries computed by CFD and tested in the test
- Movables (A/C control surfaces) deflection (CFD done with movables in neutral position)

The amplitude of the structural response scales with dynamic pressure:

$$PSD_{casei} = PSD_{Testj} * (Pdyn^{casei} / Pdyn^{Testj})$$

$$\mathbf{K_{RMS}} = Pdyn^{casei} / Pdyn^{Testj}$$

		Freq	Case A
Modal Scale Factor		f1	D1
		f2	D2
RMS Factor			K_{RMS}
Ks Factor			K_S
Total Factor		f1	$D1*K_{RMS}*K_S$
		f2	$D2*K_{RMS}*K_S$

Table 3: Summary of Scale Factors

The alternating stresses must be multiplied by a factor to correlate a random vibration test with a sinusoidal vibration test. Since both tests typically simulate the life of an installed component the requirement is to derive a sinusoidal level of equivalent RMS value that will cause the same fatigue damage as a random vibration test. This results in a factor of $\mathbf{K_{alt}}$ that is used to increase the 1σ stress to a fatigue level stress for margin calculations.

To obtain the appropriate cycle count associated with the above alternating stress, the dominant response frequency of the component must be determined. The total cycle count is then the dominant response frequency multiplied by the duration of vibration exposure. The dominant response frequency may be analytically (by modal analysis) or experimentally determined.

- R = 1 sigma (RMS) stress amplitude for random vibration input
- Equivalent Limit Stress = 3R
- Equivalent Alternating Stress = $\mathbf{K_{alt}}$ x R

3.3 Fatigue Analysis – Goodman Diagram Generation

In order to generate Goodman Diagrams, both alternating and mean stresses are needed. The mean stresses are the results of static analysis under steady pressure and alternating load is $\mathbf{K_{alt}}$ **x RMS** value from harmonic analysis.

3.4 Strength Analysis

The sum of mean stress and 3 x RMS unsteady stress is used to check limit strength capability of parts.

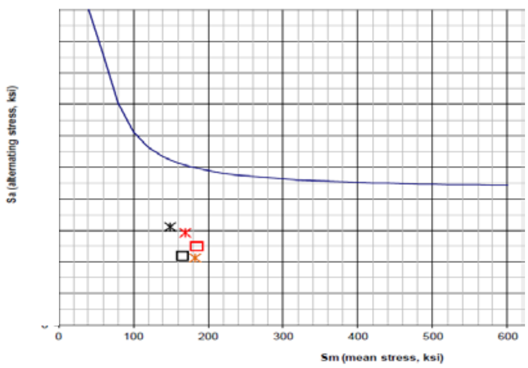

Figure 10: Goodman Diagram for Fatigue Life estimation

4 FLIGHT TEST VALIDATION

4.1 Analysis Process

Flight Test data was captured and processed for several flight points along the full flight envelope to determine the APU inlet door response and component stresses actually seen during flight for a direct comparison to previous explained methodology based on WTT results and conclusions.

The process used to evaluate the FT data and to generate fatigue diagrams and strength MoS are very similar to what was done in previous paragraphs (See Figure 11).

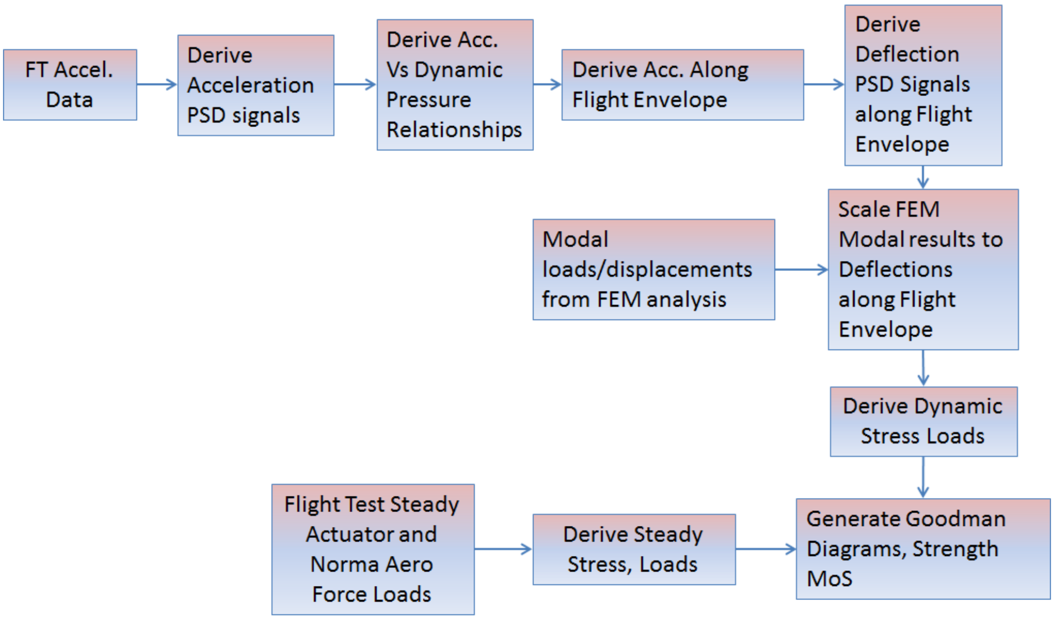

Figure 11: Flight test data processing flow chart

4.2 Flight Test Data

APU inlet door accelerometer locations are shown in Figure 12:

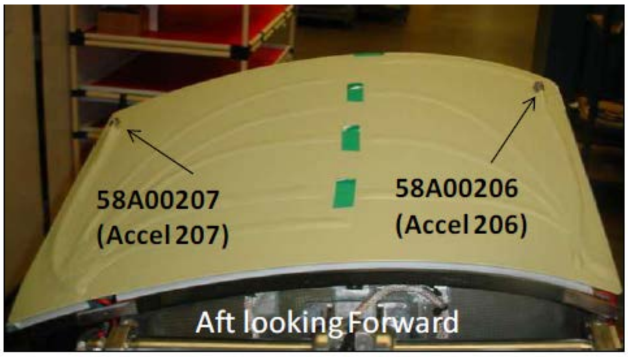

Figure 12: Accelerometer locations on APU flap door for flight test.

The acceleration spectral densities were converted to a Deflection PSD (DPSD) by using the following equation:

$$DPSD = APSD / (2\pi f)^4$$

The response again is more significant for low frequencies and it can be seen that there is no significant response past 100 Hz for the APU inlet assembly.

To calculate the RMS displacement values for each frequency, the area under the curve is calculated. The frequency range used to sum the area under the PSD curve was the same used with WTT data in Section 3.1.2.

Once the area under the curve was calculated, it was used to scale the FEA modal shapes. The stress at each frequency was then summed using a RMS approach to get the overall stress state and multiplied by K_{alt} since this was a random input.

4.3 Response Analysis – Loads

4.3.1 APU Actuator Mean Load

The actuator mean loads and door response acceleration had a strong correlation to the free stream dynamic pressure (Q). The door pressure data was used to predict the actuator loading as a function of the free stream dynamic pressure, as explained in 3.1.1.

Next Figure 13 shows a comparison between WTT data, FT data and the design derived loads from the FT pressure data:

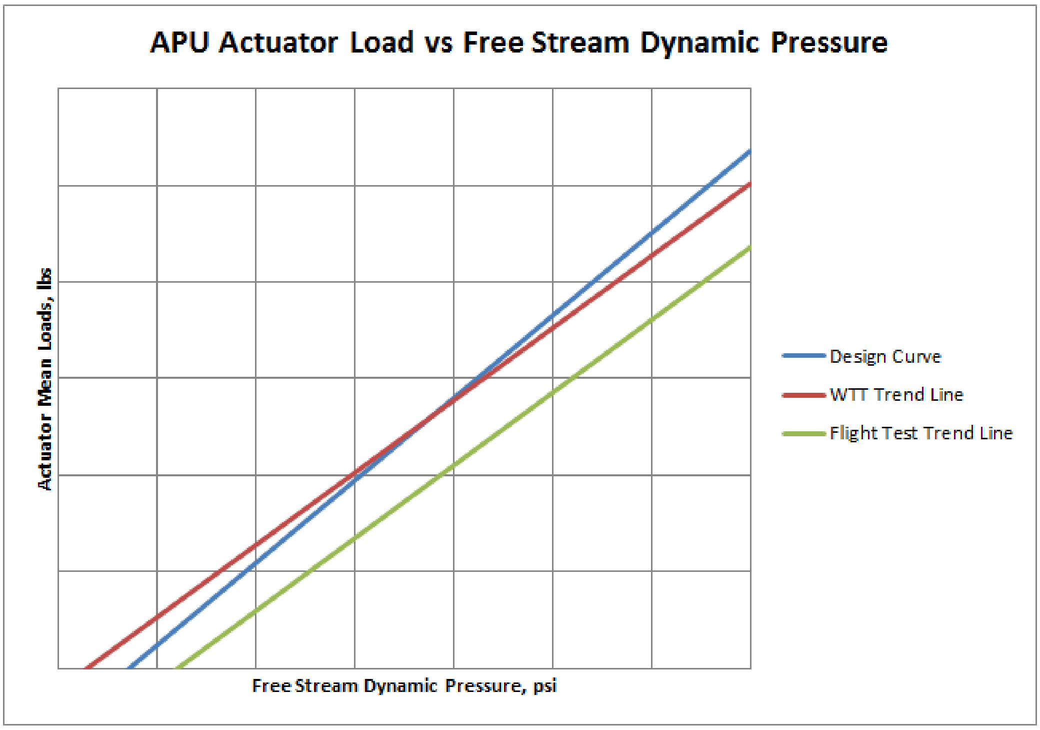

Figure 13: Comparison of Derived Loads vs WTT and FT data.

4.3.2 APU Inlet door vibration loads

The scaled modal analysis approach used to calculate the APU inlet component stresses and the DPSD's shown in section 4.1 again show that main inlet door response can be approached using the first two vibratory modes. The door vibrations are plotted also as a function of the free stream dynamic pressure to see if there is a reasonable correlation.

After post processing the flight test data it can be seen that there is a reasonable correlation between the level of the response and the free stream dynamic pressure for the APU operating conditions.

Figure 14 below summarizes the APU door vibration response (overall, mode 1 and mode 2) as a function of free stream dynamic pressure. The mean trend line is depicted as well as the line that captures the upper envelope of the data for the mode 1 and mode 2 frequency responses. Since the flight test program attempted to capture the worst case conditions, then the upper envelop curve provides a reasonable expectation for the maximum response of the door.

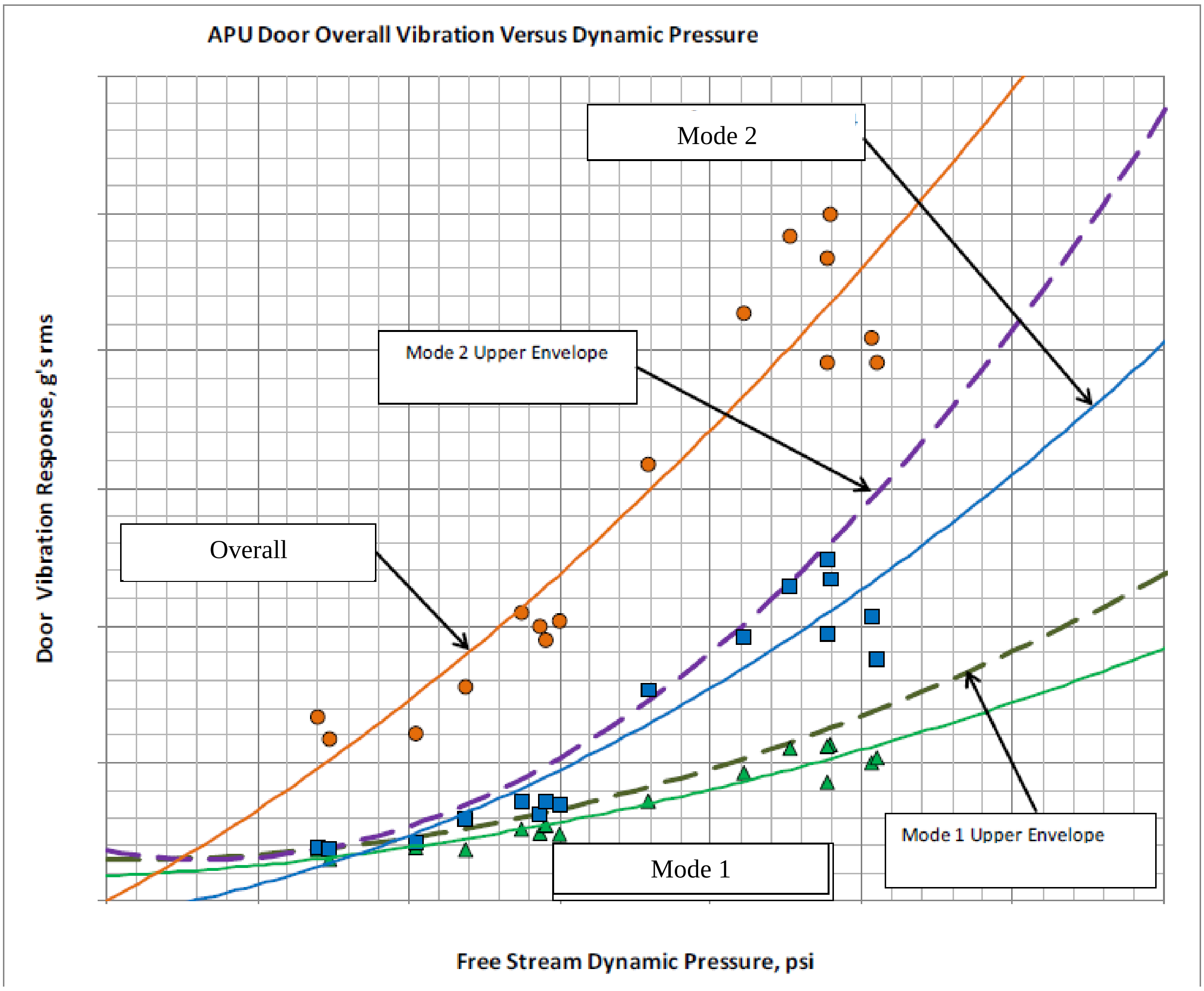

Figure 14: APU Door Vibration vs Dynamic Pressure.

These curves are used to determine the accelerations level for extrapolation to other flight test conditions.

4.4 Response Analysis

The methodology for determining steady and vibratory response for the flight test campaign is related to free stream dynamic pressure as detailed in Section 4.3. This is true for both the steady response (actuator load) and the vibratory response. In all cases, the extrapolated response increases with increasing free stream dynamic pressure.

Strength and Fatigue are analysed with data from the highest free stream dynamic pressure cases and similar results to proposed methodology with WTT data are obtained for the critical components.

5 CONCLUSIONS

This paper shows a methodology based on scaling factors applied to FEM results in order to justify strength and fatigue of critical components of an APU inlet flap door for all the flight envelope conditions.

The scale factors and extrapolation curves are calculated from wind tunnel test data.

Results are then validated with flight test data results and good correlation is found between the real response of the structure and the estimated response using the proposed on scale factors methodology.

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7 COPYRIGHT STATEMENT