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Schwingprüfung der Rohrleitung eines Flugzeug-Enteisungssystems mit geregelter MIMO Shakeranregung

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Qualification Test of an aircraft piccolo tube using Multiple-Input-Multiple-Output control technology

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ABSTRACT

Wing Anti-Icing Systems (WAIS) are integral part of a wing design. Their presence ensures safety in all-weather conditions. In standard designs, the WAIS are fitted in the slat internal structure and runs throughout its span in between the ribs. Given its critical function, such a system has to pass qualification test. The test specification is dictated by international standards. In the case discussed in this article, the standard adopted is the RTCA DO-160G "Environmental Conditions and Test Procedures for Airborne Equipment". In particular, the work presented here concerns with the Vibration environmental test. The standard prescribes a number of dynamic tests to be carried out on the AIS: random, shock and sine excitation tests have to be performed in order to study their effect on the parts composing the Anti-Icing System. The standard prescribes vibration levels at the attachment locations of the AIS to the wings' ribs. However, one issue specific to the anti-icing system is its dimension. As previously said, this runs the wing span which makes it a very slender body (length >> than cross-section area). Each part of the system is long over 3m. At the same time it has a very light weight. Such a flexible structure becomes very cumbersome to excite with a single shaker setup. And even bigger problem is to ensure a uniform excitation level at the attachment points. In order to overcome such difficulties, it is shown here that it is possible to test this system using Multiple-Output-Multiple-Input technology to ensure that each excitation point is appropriately excited. In this case five exciters (shakers) have been mounted at the 5 locations where the loads are transmitted to the structure (through the wings' ribs). The amplitude levels are maintained at the prescribed levels using a state-of-the-art MIMO closed loop control technology. The results show that the system has been exposed to the right level of vibration at each location reducing drastically the uncertainties related to its operational exposure to both ordinary (e.g. Ground-Air-Ground) and extra-ordinary (e.g. FBO) vibratory loads.

INTRODUCTION

A critical part of the structural qualification test campaign of A/C system is the vibration test. This test has a unique set of challenges that needs to be addressed properly to test verify the functional performance and structural integrity of A/C system when subjected to normal and abnormal vibration environment. However a common issue encountered by supplier of large and light systems is that vibration qualification can only be satisfied by using expensive dedicated test rig and or single axis shaker coupled to large slip table. This paper presents the results of alternative method that was used for wing anti-icing system piccolo line vibration qualification test.

Wing anti-Icing Systems (WAIS) are integral parts of the slat pneumatic line that are designed to protect wing leading edge against ice accretion. Their presence ensures safety in all-weather conditions. In standard designs, the WAIS are fitted in the slat internal structure and runs throughout its span in between the ribs. In order to certify the system at A/C level and given its critical function, such a system has to pass rigorous qualification tests. The test specification is dictated by international standards. In the case discussed in this article, the standard adopted is the RTCA DO-160G "Environmental Conditions and Test Procedures for Airborne Equipment". This standard outlines a set of minimal environmental test conditions (categories) and corresponding test procedures for airborne equipment. The purpose of these tests is to provide a controlled (laboratory) means of assuring the performance characteristics of airborne equipment in environmental conditions similar of those which may be encountered in airborne operation of the equipment (humidity, EMC, vibration, …).

In particular, the work presented here concerns the random excitation vibration environmental test however to complete the qualification test campaign four different test procedures have been applied:

- Random vibration test
- FBO (Fan Blade Out): High Frequency Short Duration
- Low Frequency Long Duration
- Operational Shocks test

The standard prescribes vibration levels at the attachment locations of the WAIS to the wings' ribs. However, one issue specific to the anti-icing system is its dimension. As previously said, this runs the wing span which makes it a very slender body (length >> than cross-section area). Each part of the system is long over 3m but at the same time it has a very light weight. Such a flexible structure becomes very complex to excite using classical single axis shaker with slip table. Another problem with single shaker is to ensure a uniform excitation level at the attachment points. In order to overcome such difficulties, SONACA and LMS took the initiative to use a non-standard procedure for DO160 using Multiple-Output-Multiple-Input (MIMO) shaker control technology to ensure that each excitation point is appropriately excited. Up to five exciters (shakers) have been mounted at the locations where the loads are transmitted to the structure (through the wings' ribs). The amplitude levels are maintained at the prescribed levels using a state-of-the-art closed loop MIMO control technology. MIMO shaker control is a standard practice since "F" revision in 2000 of the MIL-STD-810 (method 527).

In this paper we will first provide the physical principle of the MIMO control. In the second part the results of an experimental test conducted on a CUBE™ with 6 actuators and 6 degrees of freedom aimed at validating the control algorithm and its implementation is been presented. It demonstrates that it is possible to control all inputs independently in such a way to carry out a vibration test with Multiple Exciter Multiple Axis (MEMA), using the terminology of MIL-STD-810G method 527. At last the results of the WAIS piccolo line vibration qualification test making use of Multiple Exciter Single Axis (MESA) random excitation vibration will be presented. The results indicate that the system has been exposed to the right level of vibration at each location reducing the need of using a large shaker.

MIMO CONTROL

Control theories for random signals are ubiquitous in the literature [5-8]. A rigorous mathematical demonstration of the control strategy and algorithm goes beyond the scope of this publication. Here the aim is focused on providing only the physical principle of the MIMO control. Also, in order to simplify the notation, the matricial mathematics involved will be expressed in simpler form.

Consider a general Transfer Function (TF) defined as the ration between the output (O) measured on a system excited by a given input (I),

$$TF = O/I \qquad (1)$$

Without loss of generality, Eqn.(1) can be re-written as

$$H = R/D \qquad (2)$$

Where H is the system's transfer function (which is a function of the frequency) and can measured before and during the test, R is the response (or output) measured during the test and D is the drive (or input) signal. It should be noted that in the context of environmental testing the response refers to the parameter which needs to be controlled because this output has to match a pre-defined target (e.g. taken from a test standard) whilst the drive signal needs to be constantly updated so that the response can follow the target as close as possible. It is also very important to highlight that one assumption of this MIMO control implementation is that the number of responses/controls is bigger than the number exciters. Therefore, the scope of the controller is to update the drive, which from Eqn.(2) is given by

$$D = Z \times T \qquad (3)$$

in which the response R has been replaced by the user's defined reference target T (as ideally this will be equal) and $Z = H^{-1}$ is measured[a]. Z is sometime also referred to (with abuse of language) as the system's impedance. The quality and precision of the control relies on the continuous update of the system's response (impedance) and the new drive is computed as

$$D_{i+1} = D_i + (Z+\Delta Z) \times T \qquad (4)$$

which means that at each iteration the new drive is computed starting from the previous one corrected to take into account the change in impedance (ΔZ).

[a] Note that in general these quantities are matrices and therefore the mathematical operations should require a more rigorous notation, but this goes beyond the scope of this paper

EXPERIMENTAL SET-UP AND RESULTS

Several tests were performed on the CUBE™ at the KUL. The experimental set-up is shown in Figure 1.

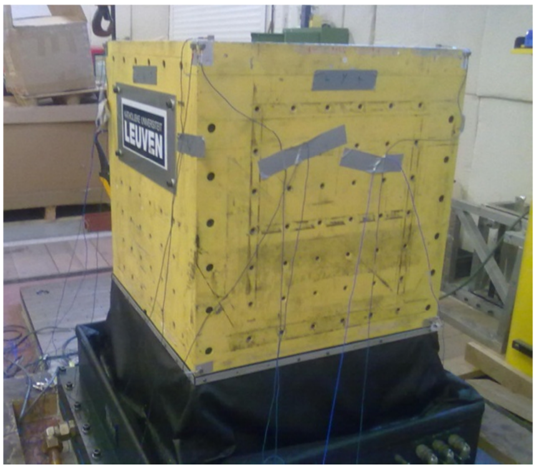

Figure 1: Experimental set-up at the University of Leuven

Triax accelerometers were placed at the Cube's corners. In order to validate the control algorithm and its implementation several tests were performed:

Square and rectangular control

With the former LMS implementation of the MIMO Random control it was possible to conduct a test if the set- up was such that the number of exciters and the number of 'controllers' were the same, i.e. a square control. However, in the vast majority of the cases, the number of exciters is lower than the number of sensors/controllers, a case referred to as rectangular control. Thus, the first test was to verify the control's performance on both square and rectangular controls. The result of this first test was twofold:

- with square control, given the limited number of sensors available, it is very important to choose carefully the locations of the control transducers in order to achieve a satisfactory level of information on the system's movement in all the degrees of freedom. Placing one of the accelerometers in a wrong location can easily cause an important degradation in control quality;
- observability is a smaller issue in a rectangular set-up because the higher number of transducers. On the other hand, in a rectangular set-up the targets are only achieved satisfactorily in a leas-square sense.

Excitation of multiple degrees of freedom at once.

During the measurement campaign with the CUBE™ the control was set to follow a certain profile on different axis (or degrees of freedom) at the same time. This test is referred to in the MIL-STD as Multiple-Exicter-Multiple-Axis (MEMA) test. In particular, Figure 2 shows the results obtained when a reference (control) PSD was assigned for different points on different axis (X and Z). It was also observed that this type of control task was less problematic than controlling one or more axes to zero.

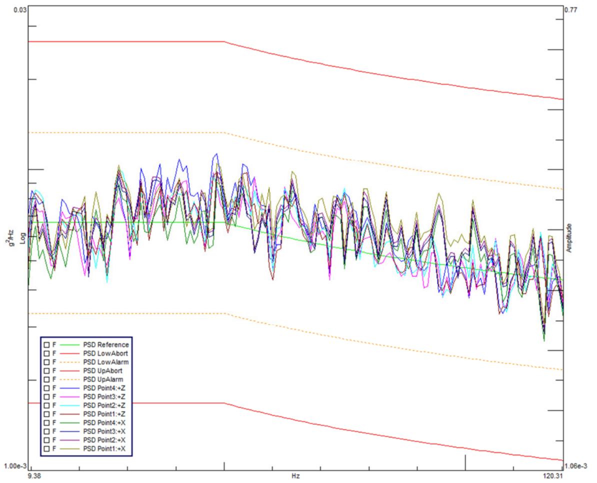

Figure 2: Simultaneous control on multiple degrees of freedom

RMS and spectral limiting

The implementation of the new MIMO control has been carried out maintaining our primary focus on safe testing. In many instances it is of utmost importance to ensure that during the test the structure does never exceed specified response (acceleration, displacement, strain or any other parameter of interest) levels. This is achieved with different approaches:

RMS limiting, whereby the overall test level (RMS) is lowered to suppress the drive over the whole frequency range. An example of this approach is shown in Fig.3. During the test set-up, a limiting value of 0.8g was defined for Point 1. As a result of the all the drives were suppressed over the entire frequency range and therefore both control responses (shown by the blu lines in the top 2 graphs) are below their target level (in green).

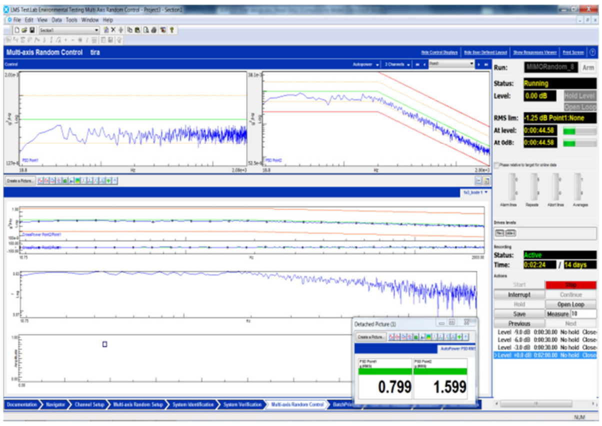

Figure 3: Illustration of RMS limiting

Response limiting (sometimes also referred to as notching) which allows the user to define a maximum level on a specific control or measurement point. Unlike the previous case, the drives are equally suppressed only if the level is exceeded in the specified frequency range on the specified channel. An example is given in *Figure 4* response limiting is defined on point 3 according to this profile the limit (black line) on this channel is lower than the control profile (green line) until a certain frequency. Above this frequency the limit profile follows that of the control channel. The result of the spectral limiting is that all the drives are suppressed in the low-frequency region. The effect is visible in the top plots in *Figure 5* both control responses are below target due to this limiting. However, since the same amount of limiting is applied on all drives the coherence does still match the defined coherence profile.

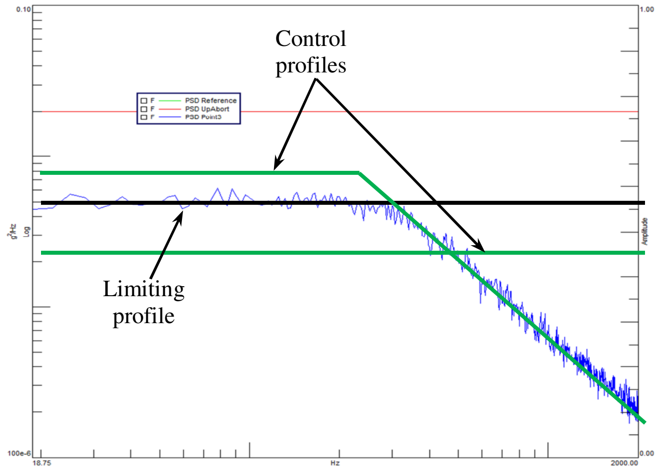

Figure 4 Effect of spectral limiting: the limiting profile for point 3 (black line) is such that until a certain frequency is lower than the control profile, whilst after it follows is (green line).

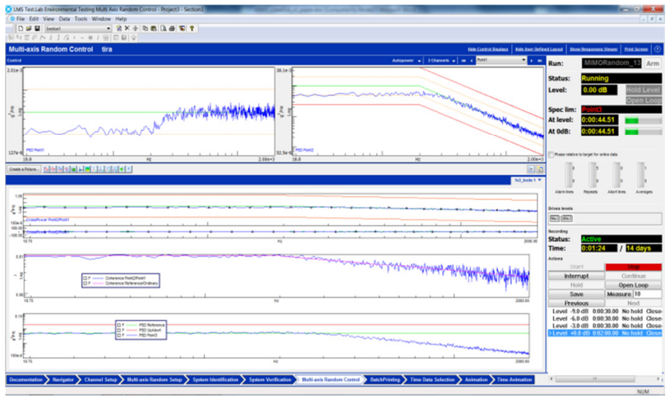

Figure 5 Effect of spectral limiting: The top 2 plots show the control profiles: the drives are suppressed in the lower frequency region (where the black line is below the green) but not in the higher region

WAIS VIBRATION QUALIFICATION SET-UP AND RESULTS

Description of Test Specimen and installation setup

The *piccolo* tube and hoses are designed, certified and manufactured by SONACA and are parts of the whole WAIS-slat pneumatic line. The system is designed to prevent ice formation. Hot air from the engine bleed valve is blown to the wing's leading edge through the small holes along the *piccolo* tubes. A typical *piccolo* line is represented on Figure 6. Note that the tested sections are identified as parts 1,2 and 3.

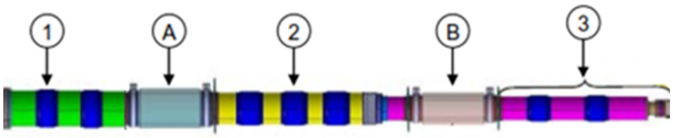

Figure 6: Piccolo line tested elements

__1:__ Piccolo tube / first slat
__A:__ Fist Interslat
__2:__ Piccolo tube / Second Slat
__B:__ Second Interslat
__3:__ Piccolo tube / Third Slat

The piccolo tubes were instrumented with 15 strain gauges and triaxal accelerometers, as represented on Figure 7-9. Gauges (red) were positioned on the most critical areas observed during the three X, Y and Z axes excitation as per FEM analysis. Measurements accelerometers (blue) have been positioned with enough spatial resolution as to capture its mode shapes (and especially the first bending mode).

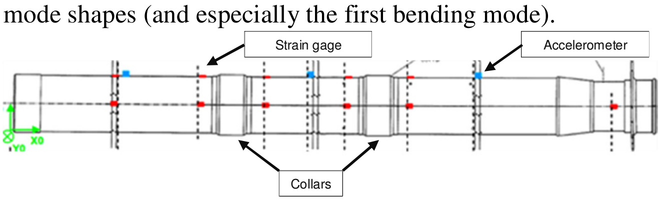

Figure 7: Piccolo tube instrumentation

Figure 8 shows the schematic of the complete test set up: shakers were located at each mechanical interface with the slat and a minimum of one control accelerometers was fixed on the support tooling near the shaker armature. The supports and clamps used to fix the hose were representative of the A/C installation and slat design, including the silicone rings between the slat and its support. A fixed additional support has been added to test the interslat hoses.

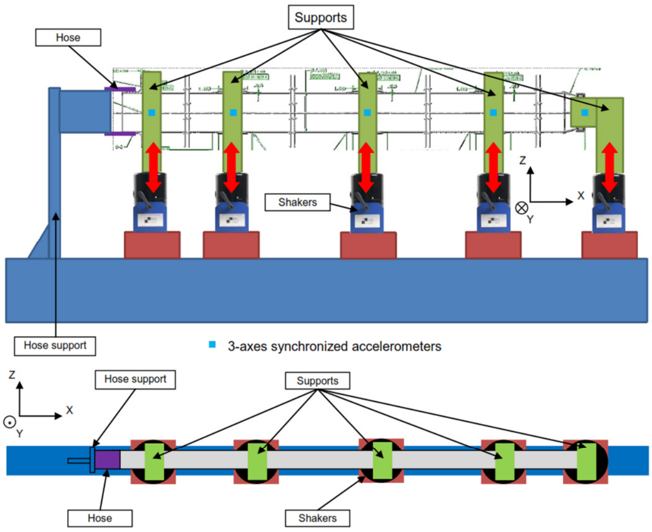

Figure 8: Front view and top of the equipment and tooling under test configuration

This setup offered the advantage to control the acceleration's targets at each leading edge mechanical interfaces independently. This control strategy ensures that each attachment point is subject to the prescribed amount of vibration avoiding under/over-testing. This is very different from the current practice (especially when the test object is large in size) of using one exciter with one test profile and match this with the average of multiple control accelerometers. Although tolerated by most standard, this method can lead to significant differences between the local vibration levels and global (control) averaged acceleration.

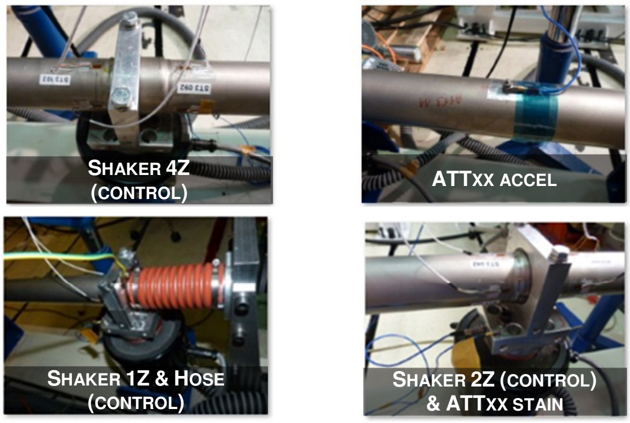

Figure 9: OZ axis Setup & instrumentation

The data acquisition system (LMS SCADAS Mobile 05) included 32 input (to read the strains and the accelerations) and 5 output (to drive the 5 shakers) channels. The Mulitiple-Input-Multiple-Output (MIMO) control strategy was implemented by the LMS Test.Lab solution (described in the previous section).

Description of test specification levels and shaker selection

The test procedure was prepared by SONACA with the collaboration of LMS. Most of vibration levels are standard to the DO160 and involve subjecting each orthogonal axis of the tube to the required vibration qualification level and duration in order to demonstrate the structural integrity. Table 1 shows the typical input levels with five different reference target

Test ref. as per DO160	**Freq. range** Hz	**Accel** g rms	**Accel** g peak	**Vel** m/s	**Displ** mm	**Force** N
Time domain reference criteria						
Shock test	NA	NA	6.0	0.20	2.08	90
Frequency domain reference criteria						
Random perfo. test - 10 min.	10 to 2000	7.96	39.8	0.42	3.8	120
Random endurance test – 3 hours	10 to 2000	11.33	56.7	0.60	5.3	170
FBO sine test 0.167Hz/s	14.52 to 250	NA	10.0	1.07	11.8	150
Special low frequency sine test	Confidential	-	-	-	>12.5	-

Table 1 DO160 Vibration test level and corresponding max force per shaker

The vibration level prescribed by the DO160 standard as such that can be reached with standard general-purpose low-force shakers. However, these types of exciters have a limited stroke (about one inch). As the stoke required for the Special low frequency sine test are above shaker specification and as the analysis demonstrated that within this frequency range the stress levels are not critical the stroke was limited to 1 inch.

The 5 shakers used in this campaign are based on COTS Modal shop K2075E075 systems. Each shaker is capable of providing a max force of 334N, max velocity of 1.8 m/s peak and maximum acceleration of 75g peak.

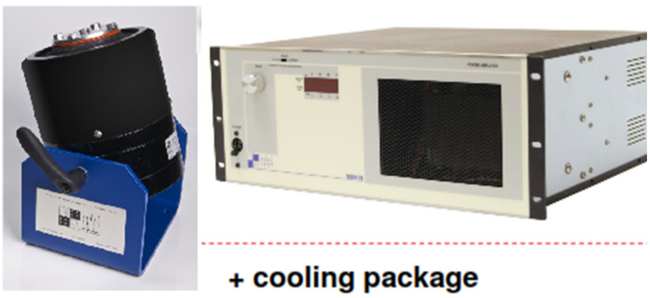

Figure 10: Modal shop K2075E075 systems

Test results

The tests were performed at the Certification and Testing facilities Center (CTC) of SONACA from October 2012 to November 2012. A photo of the test setup is shown in Figure 11. Prior to the qualification test, several low-level sine tests were performed on an engineering model at -12dB, -6dB and full level to verify pre-test analyses and the correct performance of the procedure.

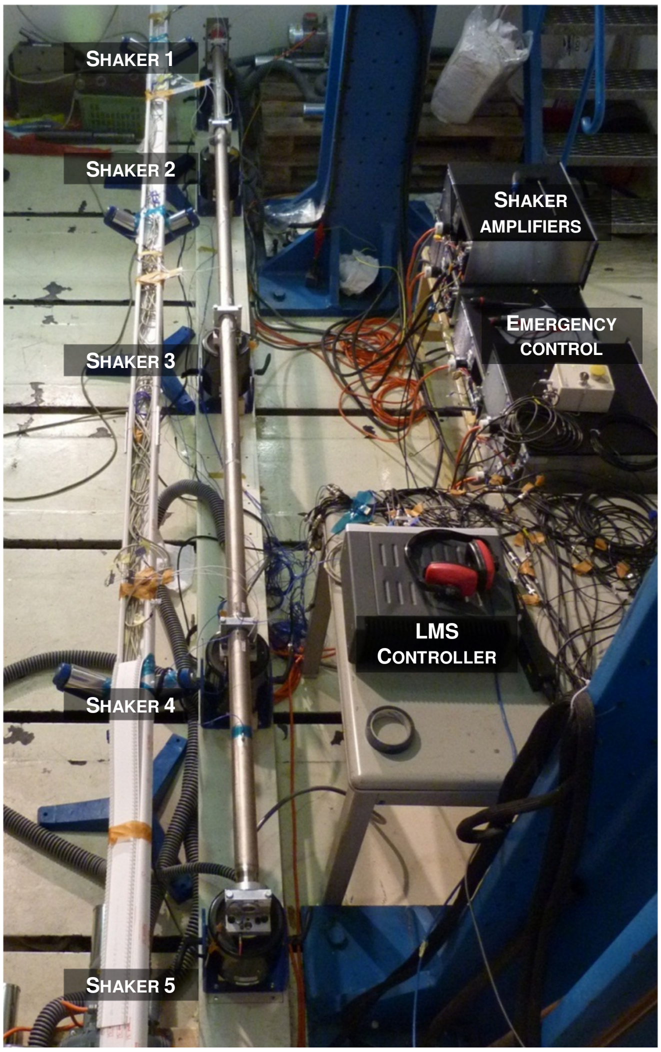

Figure 11 Setup OZ axis piccolo tube

Given that the vibration section of DO160 is based on single axis excitation techniques specific attention has been taken to guarantee that the Multi shaker single axis vibration qualification testing meet all of the same requirements as when performed on a single axis test system. The result section will therefore highlight that comparison.

Figure 112 shows that the 5 shakers PSD control target spectra for the endurance and performance random test remained within the limits specified by the DO160 and were stable.

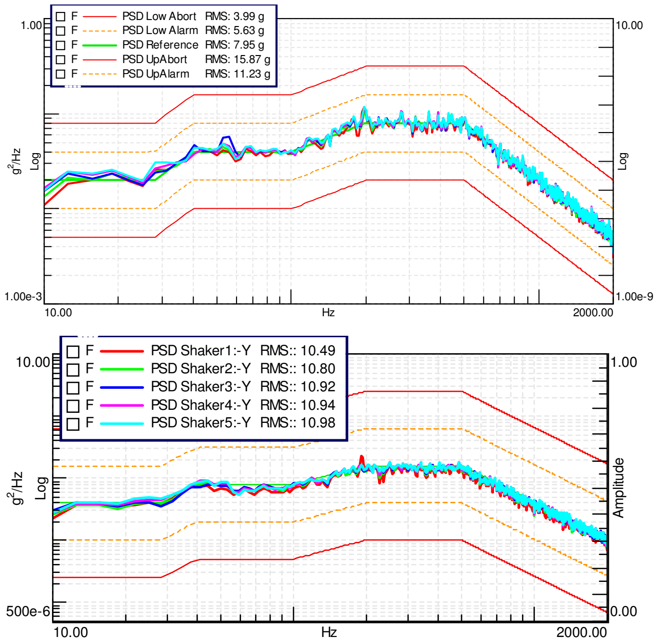

Figure 12 OZ performance (top) and endurance (bottom) MIMO Random test results

A comparison between the linear averaged PSD of the above 5 control target spectra and the control PSD of a similar test using single axis control shows no significant differences as shown in Figure 13.

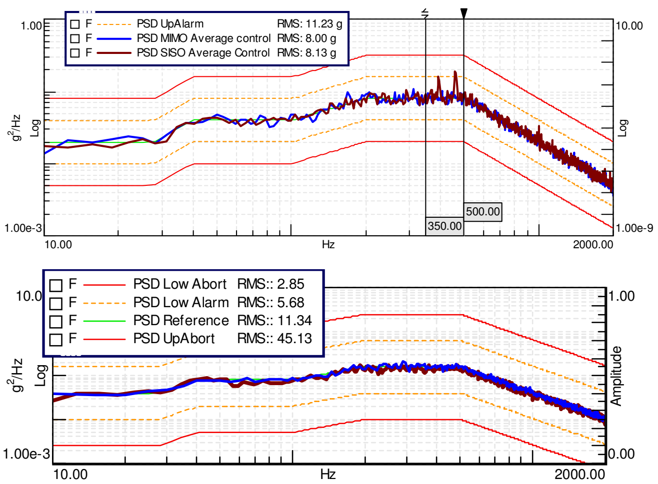

Figure 13 OZ performance and endurance MIMO Random test results vs. OX single axis random test

It should be noted that the comparison of the post-test resonance search results with the initial low level sine sweeps combined with Liquid Penetrant Inspection demonstrated that the structural integrity of the tube structure was preserved and no damage had occurred during the test. This is illustrated at Figure 14 where one can see the minor change in resonance frequency on PSD response from accelerometers located on the tube (3 bottom diagrams):

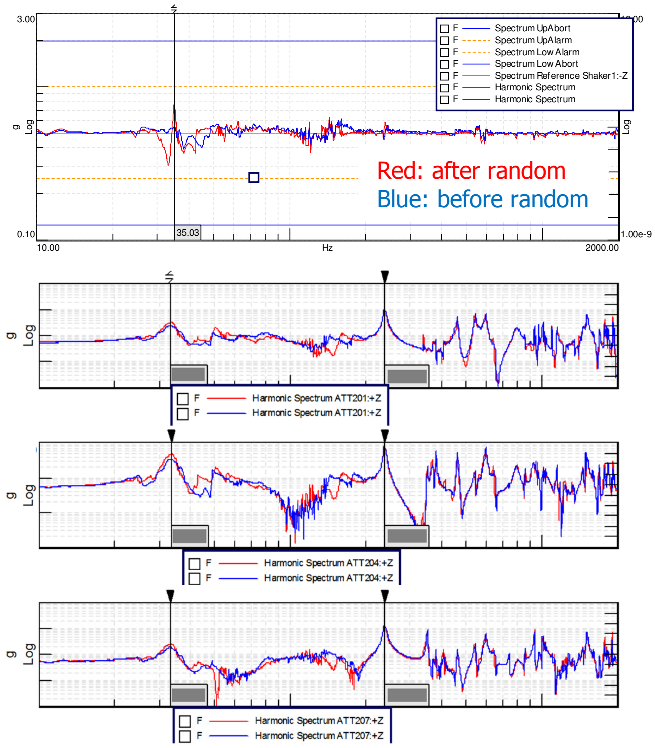

Figure 14 MIMO Sine test results prior and after high level random tests

SUMMARY/CONCLUSIONS

Albeit not yet standardized in the civil aerospace industry MIMO set-ups for environmental testing offer clear advantages when forces need to be injected in large structures, single-point attachments are not possible or a single-axis excitation is not representative of the environment. The testing community is currently debating the adequacy of the current (old) standards and to expand them to take into account advanced in testing capability and control algorithms.

In this paper a new MIMO Random control tool which adds to the Environmental test family product has been presented. The controller has been validated using the test facility at the Katholieke Universiteit of Leuven (KUL) using the CUBE™ installation. In addition it has been proven to be reliable in the context of a qualification test campaign of a piccolo tube.

Results have shown that this rectangular control implementation enables to carry out both MESA and MEMA tests maintaining the important safety features of RMS and response limiting.

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