A practical guide to using MIMO vibration control for MIL-STD-810 single axis transport testing of large, resonant land based military payloads

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Abstract

This paper provides practical information on using a multi-shaker MIMO vibration testing approach for MIL-STD-810 single axis transport testing of large, resonant, land based payloads (up to 6 ton in mass and 20ft in size).Such payloads can often exhibit significant dynamic behaviour within the test frequency range including transients > 50 times control level.

The purpose of the paper is to provide guidance to organisations expanding from single shaker system testing to multi-shaker testing. It shares lessons learnt through hundreds of hours of real world sine and random testing using a 420kN (94,420 lbf) force quad electrodynamic vibration system and MIMO vibration controller in both horizontal and vertical configuration designed for MESA (multi exciter single axis) testing of both military and non-military type payloads. It targets the real world practical considerations of the test engineer/manager when defining and developing a MIMO vibration test facility for large payload testing.

Keywords

MIMO vibration solution, multi-shakers, large resonant payloads, control strategy, MIL-STD-810

1. Introduction

Single shaker single axis testing is very well established as a means of performing vibration tests on an article. However, demand is increasing to be able to use vibration testing on larger or complex shape and heavier structures. In such cases, the use of multiple shakers working in combination may provide a better solution than trying to use a bigger, higher force single shaker. When considering this, it might first be assumed that multi-shaker MIMO vibration testing will be just like single shaker testing but with more shakers and a different vibration controller. In general, original equipment manufacturers (OEMs) can be expected to provide information on their components within the overall solution, for example, the shakers, or MIMO vibration controller, or fixtures, or accelerometers. However, MIMO vibration testing introduces system interactions which should be considered holistically as early as possible in the development of a new vibration system to ensure that the design of the system is optimised and the operational capability is understood.

The following sections provide an overview of considerations for the overall MIMO vibration solution. This includes guidance for the vibration test equipment and fixturing including use of head expanders and slip tables. However, as MIMO testing is a more complex world than single shaker testing, the focus of the paper relates to control loop best practices both in terms of accelerometer selection and control strategy, highlighting the different considerations required when using MIMO control compared to single drive output vibration controllers. Practical learnings are provided on test methodologies to optimise control quickly, to suit test house environments, including key set-up parameters which have been found to significantly influence the control achieved and examples of test results. Finally, the paper looks at how results can be evaluated and reported with respect to MIL-STD-810 G Method 527 and 514.6 guidelines along with suggestions for useful additional data analysis to further understand payload resonant behaviour.

2. Vibration Test Equipment and Fixturing Considerations

The type and quantity of shakers selected for a MIMO vibration system will be dependent upon the size and shape of the payload, not just the type of testing to be performed. It is important therefore to consider the mass distribution of the payload and the likely dynamics, at the earliest stage of system definition. Whilst it may be possible to use different types of shaker together with a MIMO vibration controller, it should be remembered that the less complex the system interactions are that have to be controlled, the better the control is likely to be. As large land-based payloads are likely to have complex dynamics themselves, then the rest of the system should be designed to minimise complexity. Therefore, when selecting the type of shaker to be used, the worst case mass distribution on any shaker should be established in order to rate the overall system requirement. Less obvious to those used to single shaker testing is that the use of multi-point control, common with single shaker testing, is not a typical option for MIMO vibration control. Instead, square control is commonly used whereby the number of control transducers equals the number of shakers. As for single point control on a single shaker, this means that the control points may pass through both resonant and node (anti-resonant) frequencies within the test frequency range. It is, therefore, beneficial to select shakers with additional power capability beyond the theoretical requirements.

How the payload is connected to the shakers requires special consideration. The use of head expanders and slip tables will introduce additional dynamics and, therefore, complexity into the control and therefore ideally should be avoided. However, in practice, when testing different sizes and shapes of payload, the use of vertical and horizontal tables to support different types of payload is often necessary. The vibration controller applies a linear relationship to the drive level required at low level identification runs, which may be dominated by frictional effects and signal noise, to higher force full test levels where friction and noise effects are negligible. All dynamic moving elements within the shaker system should, therefore, be chosen to minimise friction, to avoid the system being overdriven at low frequency. More details are provided on these identification runs in Section 4.1. The dynamics of the payload itself are also an important factor. Large, heavy payloads are likely to experience thermal expansion, static sagging, dynamic bending and twisting modes. In single shaker testing, these payload forces often balance out so that there is minimal external force or moment acting on the shaker. In comparison, with multi-shaker set-ups there is likely to be a resultant force or moment, which must be reacted by each shaker or other structure within the vibration system as shown in Figure 1 below.

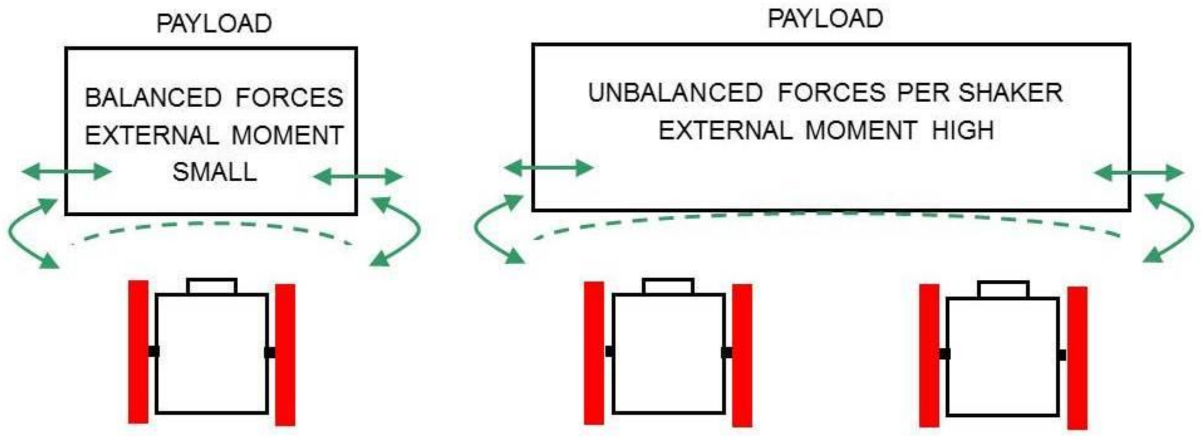

Figure 1. Effect of payload dynamics on single shaker and multi-shaker test set-up

The transfer of payload resonant reaction forces into the shaker system can be reduced by including compliance within the fixtures. Fixtures designed to have high transmissibility in the excitation axis and yet angular and cross-axial compliance can minimise the moments which must be reacted by the vibration system. Therefore, right from the start of developing the system design, it is important to factor in the overall system degrees of freedom, which must be resolved.

3. System Protection

Whilst mechanical design considerations are an important means of ensuring that the high reaction forces associated with large, land-based payload testing are contained, management of the control loop is also necessary. It is recommended that the vibration system includes a means to power up and shut down all shakers synchronously and in a controlled manner both during normal operation and in fault condition, that is, when an interlock or emergency stop occurs. Otherwise, additional strain and damage may be caused to both the payload and the vibration system. Additionally, whilst fixtures should be designed to minimise transfer of payload reactions, the use of cross-axial monitoring accelerometers can be used to protect the shakers from experiencing moments exceeding their limits. However, these should not be relied upon for normal operation, since the control will be notched.

4. Differences Between MIMO Multi-Shaker and Single Shaker Vibration Control Loop

4.1 System Identification Matrix

Typically, prior to running a MIMO Sine or Random vibration test, an identification matrix is run. This defines the interactions including phase relationships between each drive and control response across the test frequency range. It is a random test generally run with no cross spectral relationships imposed between the shakers and is the basis of the initial control applied during a Sine or Random test. As stated in Section 2 above, a linear relationship is assumed between the low level identification run and the full level test, which can be affected by frictional effects, signal noise, non-linear resonances and transients. The linear relationship between low-level and high-level tests is much more important in MIMO testing, than is the case for single shaker testing where control is primarily based on the accelerometer response rather than a pre-stored relationship. This is because single shaker vibration controllers typically have a faster adaptive control due the simpler control requirements. During a random test, the identification matrix is updated, and this can be stored for further runs. This is particularly useful for more complex payloads which do not have linear dynamic responses.

4.2 Cross Spectral Relationships – Phase and Coherence

When performing a single axis test with multiple shakers, it is not simply a case of determining the amplitude profile across the frequency range. At frequencies approaching the first resonance of the system and above, the payload will no longer move uniformly in the excitation axis. Multi-point control is often used with single shaker testing of complex payloads so that the variation in amplitude at different positions is considered using average or maximum control techniques. Similarly, if the phase relationship between accelerometers in a multi-point control test were measured, it would be found that there are phase differences between the different control points. These phase relationships do not affect the control, as only amplitude is considered, whilst the resultant moments are resolved by the vibration table.

When performing single axis multi-shaker testing, the cross spectral relationships between control points are more important since with MIMO control each control point is being driven to optimise not only the amplitude profile but also the phase and coherence between each control accelerometer position. For single axis testing, it is too simplistic to assume that the phase and coherence relationship between accelerometer control points should be zero degrees phase, and close to 1 in coherence across the entire frequency range. This is not representative of real world conditions and in attempting to control to zero phase and high coherence at resonances, this is likely to be over restraining and thus over testing the payload. It is important to understand that a coherence close to 1 should not be considered as ‘good’ nor a coherence close to zero be considered as ‘bad’. Instead, coherence should be thought of only in terms of being high when the payload dynamics allow the control points to be closely coupled and low when they are dissimilar – generally found at resonances and where the payload broadband energy dominates the vibration input rather than the shaker drive input.

4.3 Square Control versus Multi-Point Control

MIMO vibration control considers all drive and control signals simultaneously using a matrix relationship and optimises the drive signal of each shaker in order to achieve the intended amplitude, phase and coherence profiles at each of the control points. The drive from each shaker has an effect on all control points, not just the control most closely linked to it and the closeness of the control to the profiles depends upon the complexity of the system dynamics. Therefore, MIMO control should not be thought of as each shaker simply independently controlling its associated control accelerometer to its test profile but consider the interactions with other control points. This means that if, for example in a theoretical quad shaker system random test, 3 control positions could be closely controlled to their profiles, whilst the 4th control is much higher than the profile due to resonant behaviour, then in a real MIMO test, the 3 control positions will tend to deviate from their profiles in order to bring the 4th control closer. This means that at resonant frequencies, the response of each control channel may seem to be diverging from the profile, however reviewing the weighted average amplitude response across all control channels shows that the overall planar control is optimised. When thought of in this way, MIMO control can be compared to the average multi-point control used with single shaker testing.

4.4 Accelerometer Selection

Typically, MIMO vibration controller manufacturers recommend the use of higher sensitivity accelerometers in order to provide the signal level required for good quality phase control. Therefore, tests, which with a single shaker set-up might typically be carried out using 10mV/g sensitivity accelerometers, may require 100 to 1000mV/g accelerometers in a MIMO system.

Large, land-based payloads generally consist of several components within a modular unit or container. As well as the structural resonances of the unit, the separate components are likely to resonate and may produce transient rattling. When testing large heavy payloads, in a MIMO set-up, it is likely that the moving mass of the payload will be significantly larger than that of the shakers. As a result, the ability of the shakers together with any tables and fixtures to dampen out the transients associated with the payload dynamic behaviour will be quite limited compared with testing small payloads. Additionally, the available positions for control accelerometers may be more limited than when testing with a single shaker using a slip table or head expander arrangement.

This means that the control accelerometer needs to have both high sensitivity and a high acceleration measuring range to accommodate transients without saturating the accelerometer. The requirements for both high sensitivity and high acceleration measuring range are inversely related in accelerometer design. Typically, IEPE accelerometers which have electronics inbuilt within the accelerometer have the relationship;

Sensitivity (mV/g) x acceleration measuring range (g) = 5,000 – 7,000

that is, for an accelerometer of sensitivity 500mV/g, transient accelerations greater than 14g peak will result in saturation of the accelerometer.

Experience has shown that charge mode accelerometers are a better solution when testing with undamped transients. As well as the charge converter electronics being contained in a separate unit remote from the payload dynamics, a much higher acceleration measuring range before saturation is available dependent upon the choice of conditioning amplifier, for example,

Sensitivity (pC/g) x acceleration measuring range (g) = 10,000 – 100,000

5. Control Strategy Best Practices

5.1 Identification Matrix Profile

Care should be taken in developing a suitable random profile for the identification matrix, particularly when this is to be used for sine testing. Experience has shown that using as high a level as allowable, below full test level, especially at known resonances will assist with the controller’s linear calculation. However, if planning to run qualification tests at lower levels then the full test level identification may no longer be suitable. For example, if the identification matrix is run at -3dB of full test level, then this may not be a suitable identification for a qualification run at -6dB of full test level.

Conversely, as the identification matrix is used to determine drive relationships then it may be desirable to minimise the low frequency profile to low displacements so that damage is not caused to the payload during this period. For example, in a push/pull arrangement, the controller must first establish the need to invert the drive signal. If there is a concern with the payload being tested out of phase in this way, then this should be considered within the matrix profile. However, the level should be high enough to avoid frictional effects and signal noise dominating the identification run. Additionally, the identification matrix profile should start at a lower frequency than the actual test range to avoid the control tailing off at low frequency, particularly in sine tests.

5.2 Optimising Control Parameters

With single shaker vibration controllers, the factory settings are often the optimum set-up for the majority of payload test situations, and limited parameter modifications are required other than test specific criteria which may need to be changed such as the required resolution and sweep rate. In comparison, typically MIMO vibration controllers are more sensitive to parameter set-up, which can be payload specific. This may require a more experienced test engineer than required for single shaker testing. For single use vibration systems such as for proving a satellite launch programme, then fine tuning of these multiple parameters can provide benefits to the final control achieved. However, for test house applications where each payload is different, a more pragmatic approach is required.

The key areas found to quickly improve control with minimum set-up time determined through many hours of MIMO testing, are detailed below.

5.2.1 Random Testing

Identification Matrix – the right matrix is key to control, see Section 5.1 above.

Loop Time – a faster loop time increases the equalisation speed and enables deviations in control to be more quickly corrected. Loop time is dependent upon the Degrees of Freedom (DOF) value and the resolution specified. The DOF value determines what proportion of the new control spectrum come from the last accelerometer response. The resolution is the more common parameter to change for different test set-ups dependent upon the test frequency range for a particular set-up.

Phase and Coherence Profiles – Whilst it is simpler to programme in a phase of zero and coherence close to 1 for single axis testing, this means that at resonances, the control loop is trying to force the payload to achieve these profiles against the natural dynamic response of the payload. In order to optimise the amplitude control to test profile, this ‘forcing’ to achieve an unnatural phase and coherence relationship should be avoided. Improved amplitude control can be achieved by inputting the payload’s nominal phase and coherence relationship profiles across the test frequency range either based upon in-service materiel measurement response data or on lower level qualification runs. An alternative approach would be to set the coherence to zero and ignore phase relationships. However, it is important also to protect the vibration system guidance system from reacting out of axis payload motion particularly at low frequencies where displacements may be high. Therefore, where the fixtures cannot accommodate non-planar motion, then coherence should be set high, regardless of payload nominal response for the frequency range where displacements are high enough to damage the system. Profiles should only be programmed to match the nominal response of the payload at frequencies where displacement is small.

5.2.2 Sine Testing

Identification Matrix – As with Random testing the right matrix is key to control, see Section 5.1 above.

Use of Limit Accelerometers – Limit control accelerometers can be used both to protect the system from excessive cross-axial accelerations, and to limit peak accelerations in the excitation axis. Care should be taken to set these limits only to limit true extremes. If the limits are too closely set to the standard test profile, then the control may deteriorate due to the controller ‘hopping’ between true MIMO control and several individual limiting control points.

Bandwidth Filter – As large, land-based payloads typically exhibit transient behaviour then it is tempting to reduce the bandwidth filter to a small size. However, the smaller the filter width, the slower the control update speed will be. This slowing down of the control update is more noticeable with MIMO control where more complex control calculations are performed than with a typical single shaker vibration controller and is likely to increase with the number of shakers in the system.

Compression Rate – The compression rate can have a significant effect on the control response and ideally should be set up with its own test profile across the frequency range, rather than using a controller default setting. For instantaneous transients during a sweep, a low compression speed can be used so that the controller does not over-react to the transient. A higher compression speed may be used where there is a shift in accelerometer responses and a fast correction of the drive amplitude is required. However, care should be taken when using high compression rates that this does not cause control instability.

Sweep Rate – It may be appropriate to reduce the sweep rate at certain frequencies to enable the controller to correct the drive amplitude more gradually. In combination with Compression Rate, this can be used to optimise the control response.

6. Evaluation of Test Results

Multi-shaker testing is an area where knowledge of expected performance is growing and MIL-STD-810G includes sections with guidance specifically related to this type of testing. However using multi-shakers to test large, resonant land-based payloads is still quite unusual with test tracks being a more common approach. The multiple resonances and transients that can be present with these types of payloads mean that the standard tolerances may not always be achievable and so close interaction with the test specifier is recommended. However, good quality testing is feasible so long as the requirements of the test specifier and the practicality of controlling a large resonant payload are understood. An example of typical test results is provided in Appendix A.

6.1 Amplitude – Use of Averaged Control

For the example of a 4 poster vibration system, the MIMO vibration controller controls each corner of the payload to optimise the overall planar control of the payload being tested. This makes it more difficult to understand how to apply the tolerances stated in MIL-STD-810G Method 514.6, since for multi-point control, the control signal is normally a composite signal either using average, maximum or minimum control strategies.

However, MIL-STD-810G Method 527 Annex D Section 3 explains how the signals can be viewed in a composite sense by averaging the accelerometers in a common axis. In the case of MIMO control, this is not used for the control method itself but as a way of clearly representing and evaluating the results. The outputted composite control signal is the average peak amplitude in Sine or average acceleration spectral density (ASD / PSD) in random of the 4 individual signals. These signals may be considered to have equal weighting, for a common amplitude profile or be a weighted average where profiles differ. The desired MIL-STD tolerances of +/-10% for Sine, and +/-3dB for Random can then be applied to this averaged result to understand whether the payload is controllable within 'Pre-defined' Standard tolerances.

6.2 Amplitude – Individual Control Signals

AECTP 400 provides additional guidance regarding allowable extremes for the individual signals. This means that regardless of whether using maximum, minimum, average, or in the case of MIMO, a calculated average, the extremes for the individual signals are identified. For Sine testing ±25% tolerances are recommended for the individual signals for frequencies up to 500Hz, whilst for Random testing the sum of the individual out of tolerance bandwidths should be limited to a maximum of 5% of the total test control bandwidth. These guidelines have been found to be useful as indicative tolerances for the individual control signals during MIMO testing.

6.3 Calculation of RMS

In the case of large, resonant payloads significant broadband energy may be generated by the payload itself during the test which is outside of the frequency range that is controlled by the vibration systems.

The standard approach for calculating the RMS value of a random ASD is to consider the area under the curve between the start and end control frequencies only, for example, for the graph below (Figure 2) the RMS is calculated for the frequency range f_1 to f_2 only. Any energy measured above f_2 is filtered from the calculation. However, it is also useful to capture data up to a higher frequency, for example, 4 × max test frequency to understand an ‘overall payload rms’ as this is indicative of how lively the payload response is and whether it is structurally degrading during the test.

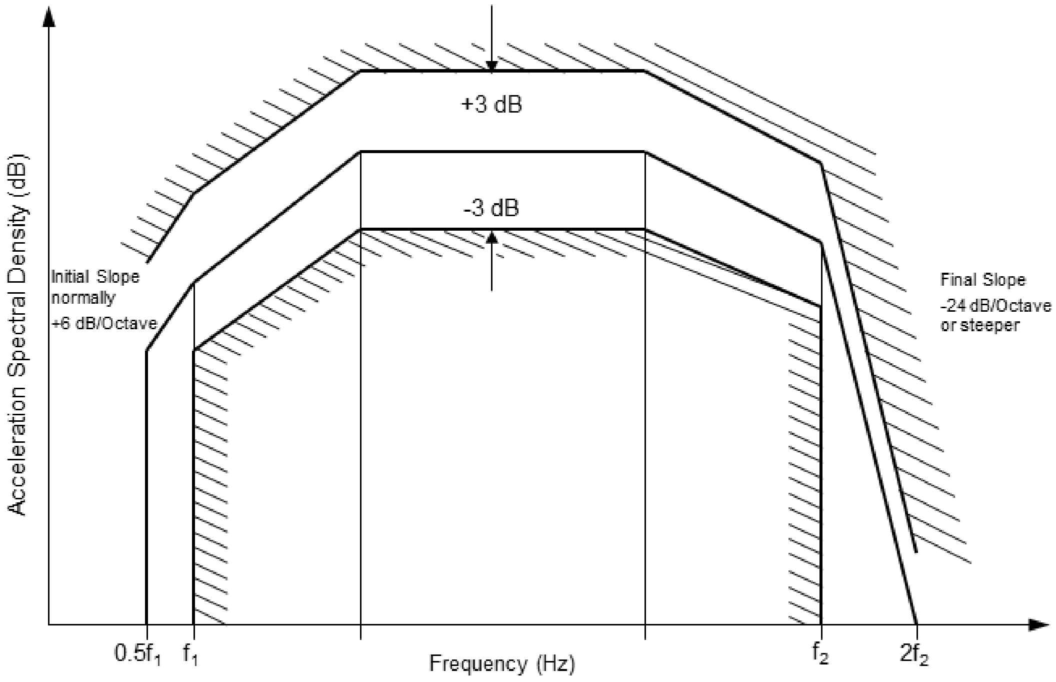

Figure 2 – Random Test ASD profile

Even with lively payloads, it is generally feasible to achieve ±10% tolerances for both the average and the individual signal RMS values within the test frequency range f_1 to f_2.

6.4 Consideration of Cross Spectral Density – Phase and Coherence

Due to the payload’s dynamics, all control points may tend not to move together at all frequencies. Without in-service materiel measurement response data, the expected phase and coherence can be estimated by performing lower level payload characterisation tests such as -6dB of the test profile and then monitoring the performance at full level against this norm (essentially initially determining the response by running a low-level qualification run). A shift in the phase or coherence generally indicates a change in the payload's behaviour, assuming that there are no other problems within the control loop.

For sine, the relative phase relationships of the individual control signals are measured. It has been found that using an indicative tolerance of ±10 degrees is suitable. As might be predicted, this tolerance is normally achievable outside of resonances, however, through resonant frequencies higher phase differences will be measured.

For random tests, the phase and coherence are examined. At low frequencies the coherence between control signals should be as high as possible to avoid damaging the shaker system. Where the coherence is normally high, for example, greater than 0.5, then reductions in coherence of 0.2 or more and changes in phase greater than ±10 degrees are investigated further. Where the qualification run indicates that the nominal coherence is less than 0.5, then no tolerances are applied to coherence or phase, assuming that no damage can be caused to the shaker system.

In general for large, resonant payloads, typical deviations from high coherence would be:

- A drop in coherence centred around the first resonant mode typically 10 – 40Hz for large payloads
- Spikes in coherence at other higher frequency payload resonances
- A tail off in coherence to 0.2 or lower at higher frequencies, for example, above 150Hz

corresponding to a tail off in the drive required if the test energy is predominantly generated by the payload broadband response.

6.5 Involvement of Test Specifier / Design Authority

It is not always possible to maintain control of a payload within the standard predefined tolerances as described above, particularly in sine sweep testing at resonance frequencies. Therefore, it is important to develop an approach for quantifying and dealing with excursions. MIL-STD-810 G highlights the importance of establishing appropriate tolerances for a given payload. Predefined tolerances cannot be generically applied to all potential payloads. Instead, tolerance and test level variations may need to be reviewed and agreed for individual payloads requiring the involvement of the test specifier or design authority.

6.6 Evaluation of Out of Tolerance Results

Broadband Peak Signal – Review of the broadband peak signal during a sine test can provide a good indication of whether transient responses are dominating the control and if the accelerometer may be saturated.

Drive Signal – Drive signals can be compared to each other and to low level characterisation runs in order to understand whether the acceleration levels measured are predominantly shaker system generated or are a payload response with minimal shaker drive input.

Control Signals Time Histories – It is beneficial to capture the individual control signals using suitable data acquisition equipment so that any areas of poor control can be investigated further. At an amplitude excursion, the relative displacement between the control signals may be analysed to understand whether this is likely to overstress the payload or vibration system.

Broadband Response – To understand the cause of the excursion, the FFTs of the individual signals at the excursion frequency may be examined to determine what level of broadband energy is distorting the signal and the payload videoed to visibly understand the sources of this broadband energy.

7. Conclusions

There are significant benefits using a multi-shaker testing approach for large, complex shape payloads and the control achievable can be a much more representative simulation of dynamic behaviour than is achievable with a large single shaker set-up. However, in comparison to single shaker vibration testing, a new approach is required for MIMO Multi-Shaker testing with the vibration system solution being considered as a whole, not just as separate components. This paper shares some of the important areas to be reviewed including;

- Shaker selection
- Controller selection
- Payload dynamics and effect on overall system degrees of freedom
- Method of payload connection
- Choice of accelerometers
- Intended control strategy – number and location
- Means of determining test profiles including phase and coherence
- Expectations of test specifier
- Test engineer requirements

To ensure optimal operational capability of the facility, these should be considered right from the start of the development of a requirement specification and through the design stage.

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About the Authors

Claire Flynn is a mechanical engineer with 19 years of experience. She joined LDS Test & Measurement, now Brüel & Kjær VTS, in 2008 as a Project Engineer and managed over 100 special engineering projects for electrodynamic vibration test systems from initial concept to commissioning. Having gained an in-depth knowledge of vibration applications, Claire's current position enables her to develop and share best practices for vibration solutions to meet customers' expanding needs.

Alex Williamson As Head of Engineering for the LDS range of shakers, Alex has significant experience in developing vibration test system technology, growing core business research and development capability, and solving complex problems with both new and bespoke customer solutions.

Tim Bidwell has over 30 years extensive engineering experience, of which 14 years have been within the R&D engineering group for LDS product range, focusing on vibration test system operation, specification and performance rating. Tim is currently responsible for providing design and technical direction to support innovation and development within the engineering teams of Brüel & Kjær VTS.

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APPENDIX A Example of Typical Test Results for Single Axis Multi-Shaker Testing of Large Payload

Test Set Up – 420kN Quad Electrondynamic Shaker System – Horizontal Configuration used to test a 3 Ton mass 8 Foot Iso Container. Square control test strategy used with one control accelerometer close to each corner of the iso container.

Figure A1 – Set up of horizontal test for 3 Ton 8 Foot Iso Container

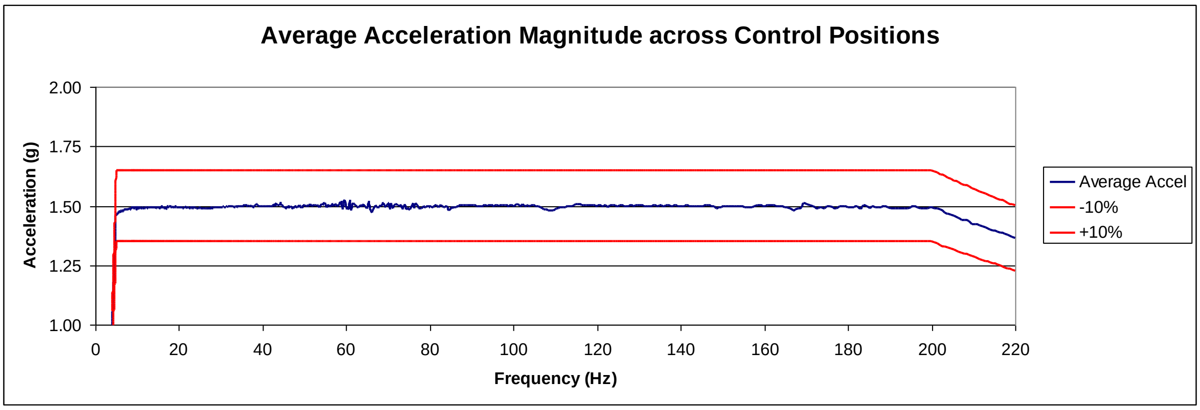

Figure A2 – Characterisation Sine Sweep Composite Average Acceleration Plot

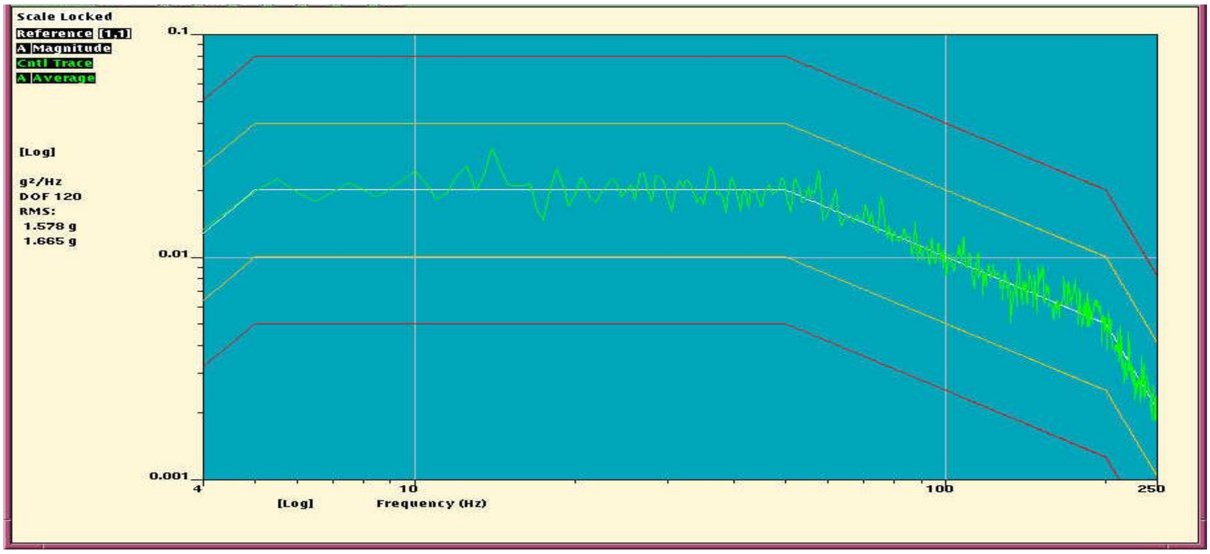

Figure A3 – ASD Average Control Plot

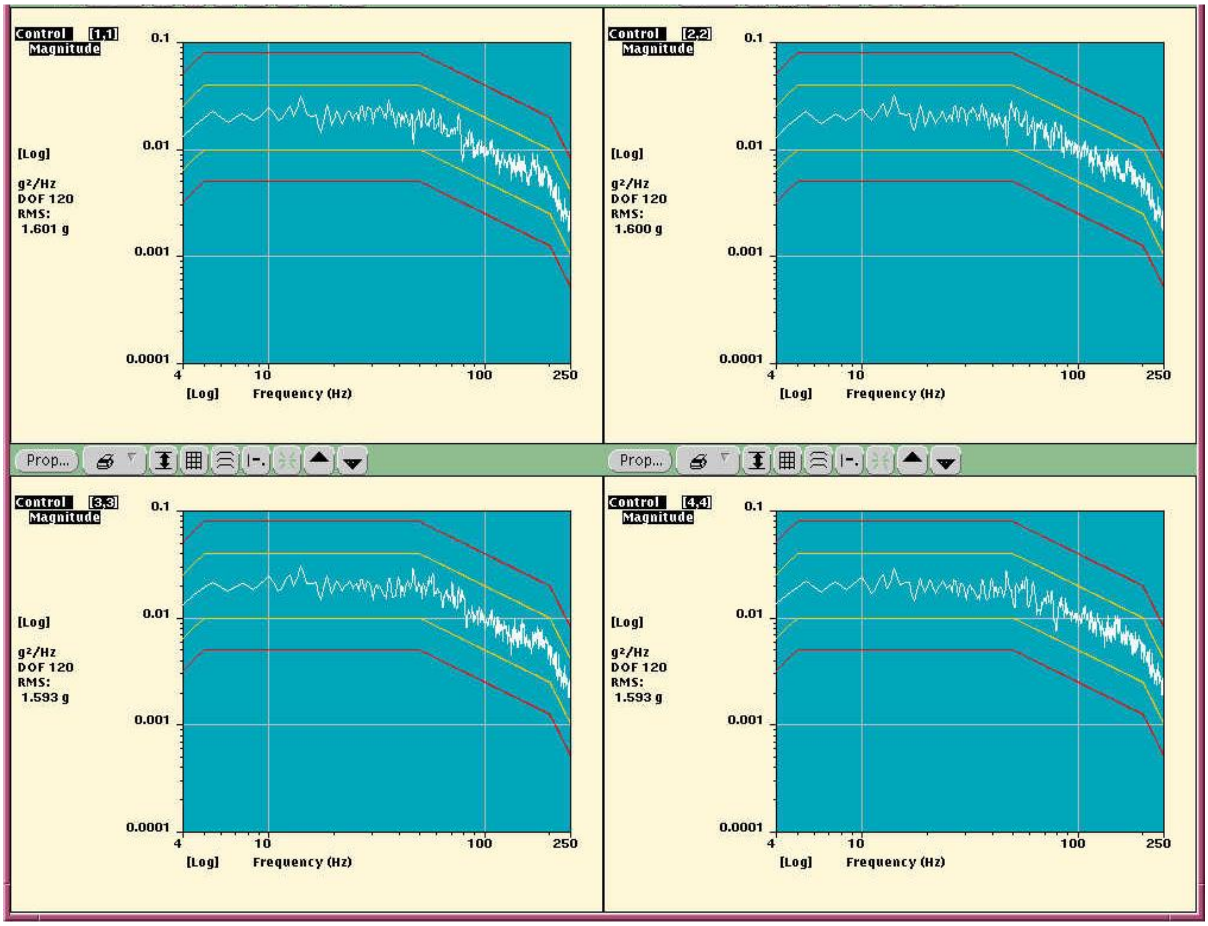

Figure A4 – ASD Individual Control Plots

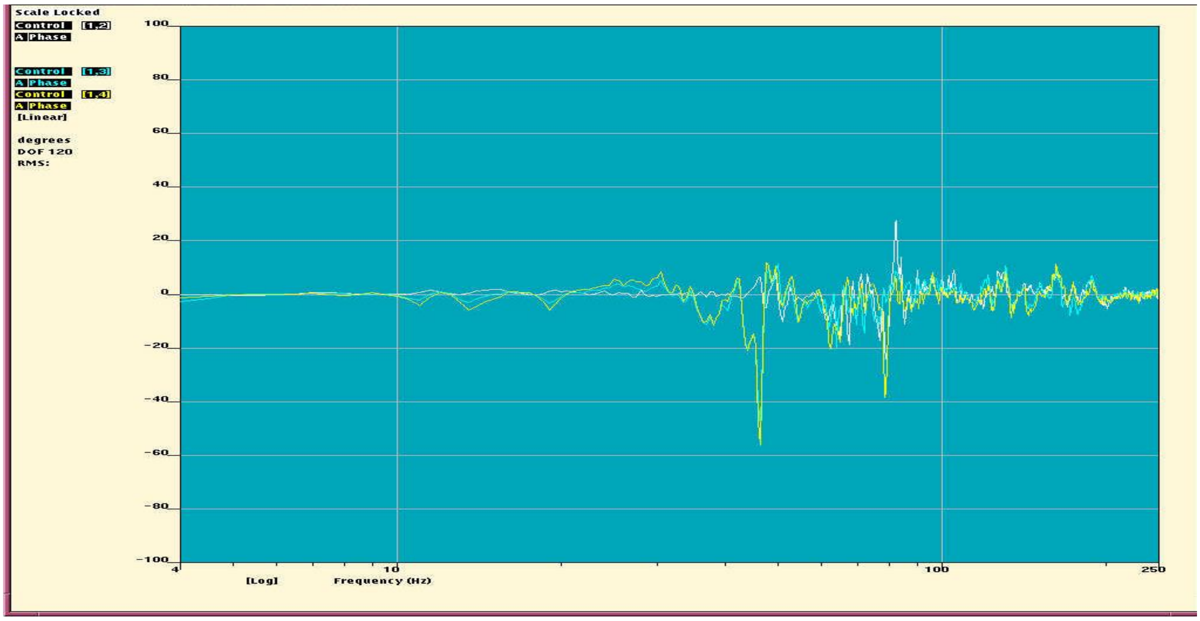

Figure A5 Relative Phase at Control Positions

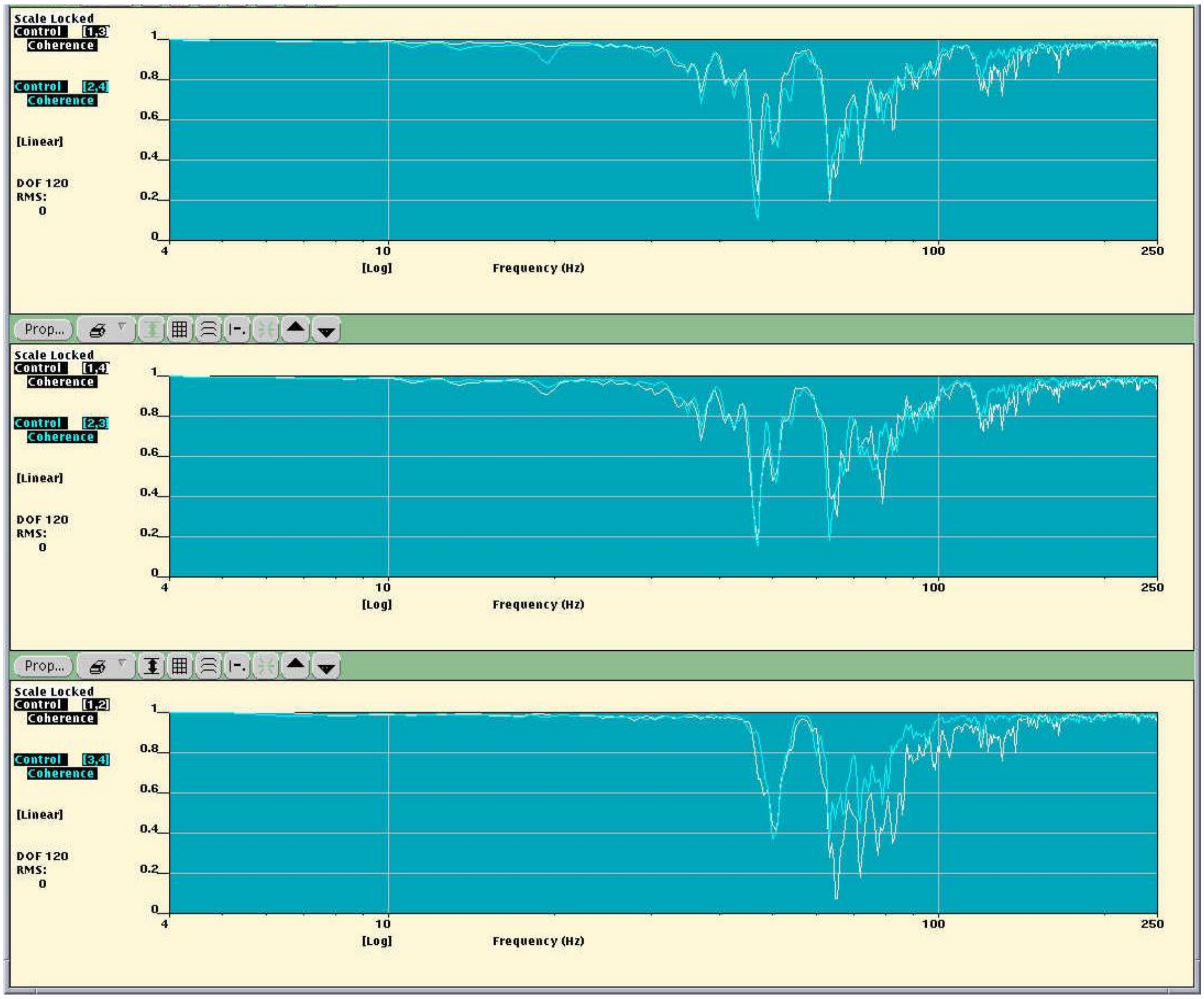

Figure A6 – Relative Coherence at Control Positions

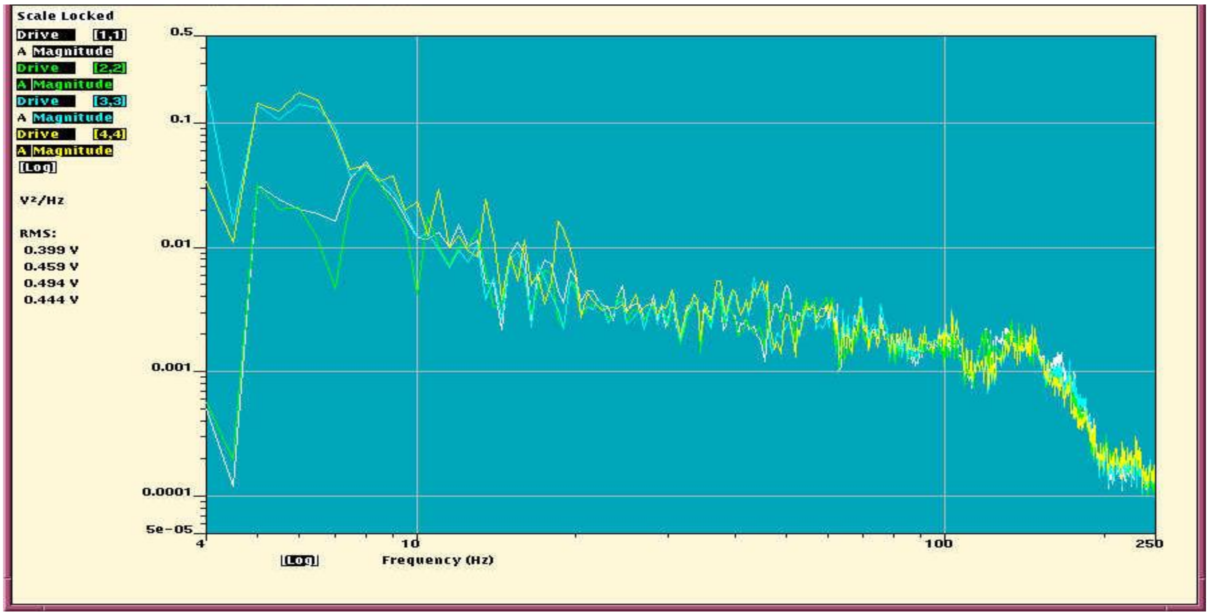

Figure A7 – Individual Drive Signals Plot