Chapter 37
Next-Generation Random Vibration Tests

P.M. Daborn, C. Roberts, D.J. Ewins, and P.R. Ind

Abstract This paper describes a radically new approach to the vibration testing of structures in order to demonstrate their endurance under simulated service conditions. The excitation mechanisms of structures in-service typically fall into one of three configurations; (i) excitation from a parent structure through mechanical connections (e.g. during transportation), (ii) excitation from aerodynamic forces distributed over the outer surface of the structure (e.g. aircraft and rockets in flight), or (iii) A combination of (i) and (ii). In nearly all cases, the in-service excitation is multi-directional, yet it is standard practice to replicate these environments with three orthogonal single-axis vibration tests. In addition, a considerable mismatch of the boundary conditions between the in-service and laboratory configurations is common, especially when replicating aerodynamic environments. This paper presents quantitative evidence of limitations with the status quo and demonstrates a superior method; Impedance Matched Multi-Axis Testing (IMMAT). Three noteworthy improvements of the new method are; (i) enhanced replication of the in-service environment, (ii) much shorter test durations, and (iii) a significant reduction in costs associated with random vibration tests.

Keywords Random vibration • Multi-axis testing • Missile • MIMO • Mechanical impedance

37.1 Introduction

Ground-based vibration tests are widely undertaken to replicate the damaging effects of vibration measured in-service. To carry out random vibration tests, environmental test houses typically use procedures developed in the 1960s and 1970s [1–3]. The status quo is to attach the structure-under-test to a high mechanical impedance shaker and to sequentially test the structure in three orthogonal axes. Typically, the direction of the test axis is selected to line up with the principal axis of the structure and is not based on scientific reasoning. This single axis testing methodology arose in the early days of vibration testing due to the technology available and was adequate for the expectations of that time. Some important advancements have been made in some areas; for example the development of Multi-Input-Multi-Output (MIMO) random control has enabled single-axis twin-shaker vibration tests to be undertaken on missile systems, although issues within the test configuration and the requirement for three separate single-axis tests still remains. Other notable advancements in the field of environmental testing are force-limiting techniques and multi-axis testing facilities [4–6], although these are not commonplace by any means.

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There is much literature which demonstrates that traditional vibration tests are overly severe [7–10]. This is to be expected; commercial and military establishments are comfortable with the notion that they are overtesting and therefore ensuring that their structures are robust, safe and serviceable. There is less published material demonstrating that traditional methods can lead to undertesting at some spectral regions [11–13].

The configuration of in-service structures comes in many varieties with the excitation mechanisms typically falling into three broad categories:

(i) Excitation from a parent structure through mechanical connections (e.g. during transportation).
(ii) Excitation from aerodynamic forces distributed over the outer surface of the structure (e.g. aircraft and rockets in flight).
(iii) A combination of (i) and (ii).

One of the critical features of the vibration experienced by a structure is the local mechanical impedance of the excitation medium and/or the parent structure. The impedance of a large shaker system rarely matches the impedance of the parent structure in (i) and is vastly different from the free-flight aerodynamic conditions in (ii). In addition, in-service structures typically experience multi-directional excitation whereas the laboratory test is usually carried out in one axis with the location/region of the excitation location(s) being entirely different from the in-service excitation locations. The compounded mismatches between the laboratory and in-service configurations lead to unrealistic random vibration tests.

This paper quantifies the deficiencies of some current state-of-the-art random vibration tests and proposes considerable improvements using a case study which falls into category (iii), though most of the paper is relevant for any structure which experiences random vibration.

37.2 Objectives

The objectives of the research were as follows:

(i) To quantify the limitations with current methods of random vibration tests.
(ii) To propose a technique that can yield significant improvements.
(iii) To quantify the improvements of the new technique over current methods.

In order to meet the above objectives, a case study was carried out—replicating the induced vibration of an underwing missile during captive air carriage. Many of the methods described in this paper, and the subsequent conclusions, can be applied to most structures and are not specific to underwing missiles. In fact, they are applicable wherever random vibration tests are carried out.

37.3 Case Study: Underwing Missile

An underwing missile falls into category (iii) stated in the introduction and an example of an underwing missile is shown in Fig. 37.1. In flight, the missile is excited by two mechanisms—aerodynamic forces distributed over the outer surface of the missile and from the parent structure through mechanical connections. The nature of the vibration response is heavily dependent on the local impedance of the parent structure; in this case the launcher rail and the wing at the attachment region. To allow greater freedom within this research, a dummy 1/3rd scale model of the missile was manufactured out of aluminium and nylon and is shown in Fig. 37.2. The approximate dimensions of the 1/3rd scale model are: length = 1,200 mm, outer diameter (cylindrical section) = 60 mm and inner diameter (cylindrical section) = 54 mm. The mass was approximately 3 kg.

The case study was designed to mimic a real-world missile vibration test program by executing the following procedure:

(i) Carrying out a flight trial.
(ii) Generating a test specification based upon the data in (i).
(iii) Carrying out a vibration test in accordance to the test specification from (ii).

Activities (ii) and (iii) from the above procedure were carried out according to the current state-of-the-art technique for missile vibration testing; the twin-shaker single-axis MIMO random vibration test. Activities (ii) and (iii) were then repeated using a new method proposed here; the Impedance Matched Multi-Axis Test (IMMAT) which will be described fully in Sect. 6.

Fig. 37.1 Underwing missile (*picture courtesy of the Federation of American Scientists*)

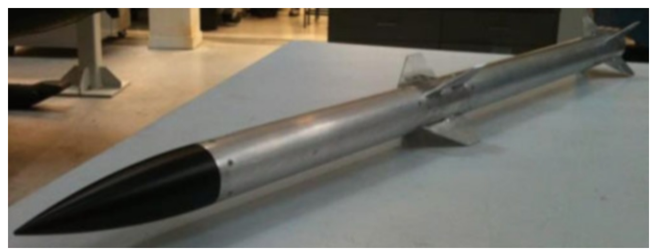


Fig. 37.2 Scale model (1/3rd) of underwing missile

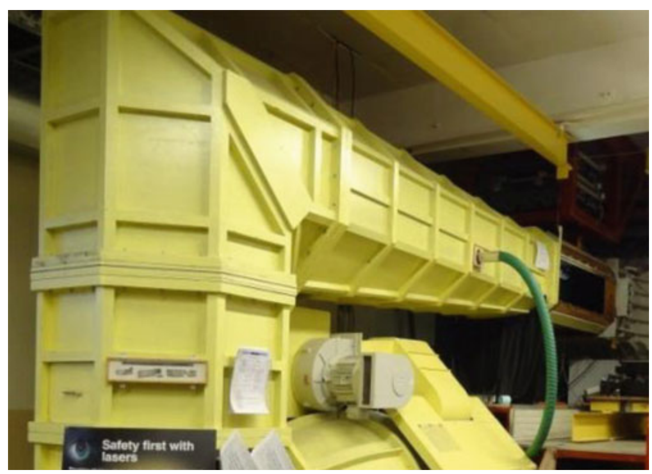


Fig. 37.3 Wind tunnel facility at the University of Bristol

37.4 The Flight Trial

In order to understand the anticipated service environment for a missile system, it is necessary to measure the dynamic response during flight trials. This will give the specification writer the information required to generate a test specification. The test specification will then be used to control the laboratory test for that particular missile system.

For this case study, it was not practical to carry out an actual flight trial with the dummy missile so the aerodynamic environment was provided by a wind tunnel facility within the Aerospace Department at the University of Bristol (Figs. 37.3 and 37.4). The missile was subjected to multiple wind speeds and orientated at various yaw angles (Fig. 37.5). For simplicity, only data from the maximum wind speed (88 m/s) and at 0° yaw angle is used in this research.

During the wind tunnel testing, thirteen accelerometers were attached to the missile, some of which are shown in Fig. 37.6 along with the axis definition. The accelerometers were distributed over the outer surface of the missile at six locations (1–6)

Fig. 37.4 Wind tunnel facility with dummy missile attached

Fig. 37.5 Missile inside the wind tunnel at some specified yaw angle

Fig. 37.6 Dummy missile showing some of the attached accelerometers, the launcher rail and the axis definition

along the X axis. At the tail end of the missile (position 1) a tri-axial accelerometer sensed in all axes (X, Y and Z). At positions 2–6, single-axis accelerometers sensed in Y and Z only. The duration of the wind tunnel testing was 50 seconds to allow a suitable number of averages to be taken. The acceleration time histories were converted to frequency domain power spectral densities (PSDs) and Fig. 37.7 shows some examples of the PSDs obtained during the wind tunnel testing. It should be noted at this stage that only random vibration is considered during this case study and no attention has be given to other forms of dynamic motion such as mechanical shock.

37.5 The Twin-Shaker Single-Axis Vibration Test

The twin-shaker single-axis vibration test is the current state-of-the-art for missile testing and it was felt that it should be investigated as part of this case study. In a twin-shaker test it is possible to excite one axis only. To certify a system fully in all axes, it is necessary to carry out three individual tests in three orthogonal directions. For simplicity, only Z direction excitation is considered in this case study (Fig. 37.8).

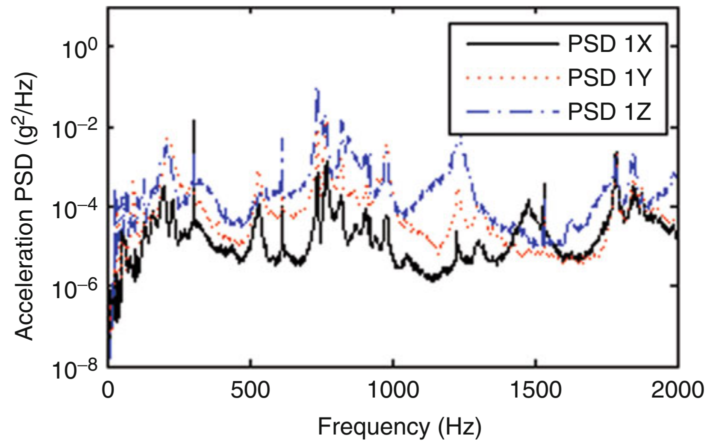


Fig. 37.7 Example PSDs obtained during wind tunnel testing

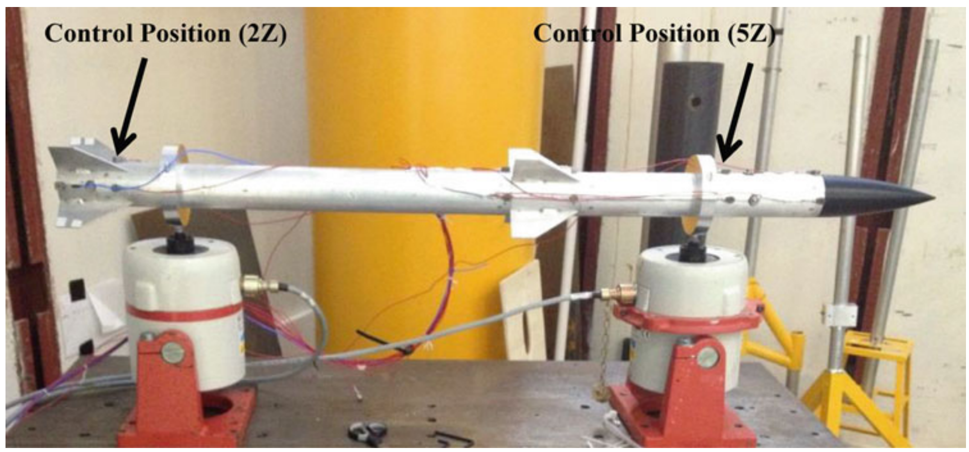


Fig. 37.8 Twin-shaker single-axis vibration test

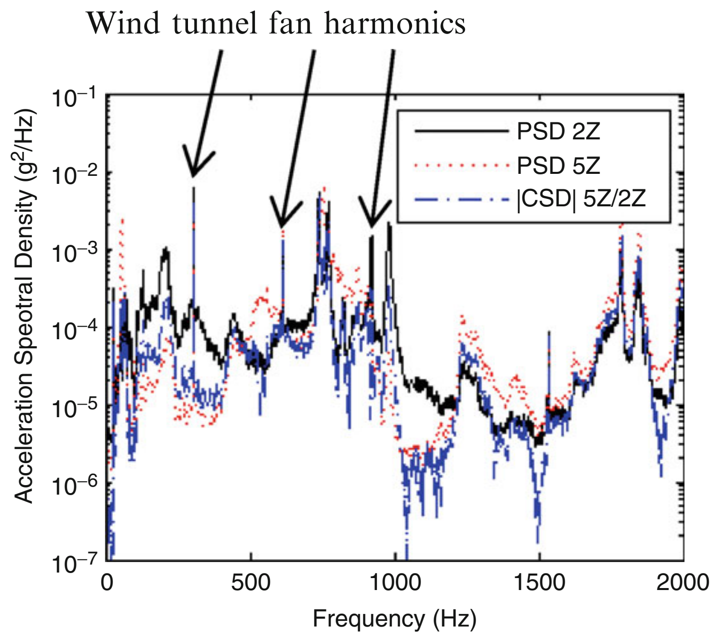
Prior to carrying out the vibration test, it was necessary to generate a test specification. As the vibration test involved two shakers (Fig. 37.8), the test specification must be suitable for MIMO random control. It order to replicate current practice, two response positions (2 and 5) were selected to control the test and were situated close to the two excitation locations (Fig. 37.8). The test specification consisted of two PSDs and one cross spectral density (CSD). The PSDs and CSD in the test specification were obtained directly from the wind tunnel environment at the control accelerometer positions and are shown in Fig. 37.9. It should be noted that harmonics, beginning at 307 Hz, can clearly be seen in the spectral density curves in Fig. 37.9. These harmonics are from the wind tunnel fan and excite the missile via the roof of the wind tunnel. They have been included in this case study to simulate the vibration that a missile might experience from its parent structure, e.g. the vibration induced by the engine through the aircraft wing.

The two electrodynamic shakers were rigidly connected to the missile via fixtures. This fixturing arrangement is typical of current practice and significantly alters the dynamics of the missile by stiffening and mass loading the local region, preventing it from bending freely and restricting cross-axis excitation. The shakers provided random excitation to the missile for 50 seconds with the test being controlled and recorded using the Leuven Measurement Systems (LMS) MIMO Random Control software and the Supervisory Control and Data Acquisition System (SCADAS) hardware.

The control curves from the twin-shaker test are shown in Fig. 37.10 and indicate good agreement between the test specification and the vibration test. This demonstrates that at the two control positions the vibration test is providing a good simulation of the aerodynamic environment from the wind tunnel. In addition, there is good agreement between the CSD from the wind tunnel and that of the twin-shaker test and of particular importance is the relative phase between the two control positions. The twin-shaker vibration test was able to go some way to replicating the harmonics of the wind tunnel fan, but it could not achieve the amplitude of the peaks.

As with the wind tunnel measurements, all thirteen accelerometers were used to measure the vibration in the twin-shaker test. Of these, two were control accelerometers used to control the vibration test with the remaining eleven being uncontrolled response measurements. The PSDs from the twin-shaker test are shown in the appendices (Fig. 37.13), with only twelve of the thirteen shown for convenience. The plots show that the vibration at the uncontrolled positions is a relatively poor simulation of the complete aerodynamic environment. In particular, there is evidence of considerable overtesting, undertesting and cross-axis overtesting (Fig. 37.13). Similar results were observed for the CSDs from the twin-shaker test (Fig. 37.14). There were

Fig. 37.9 Test specification used in the twin-shaker vibration test



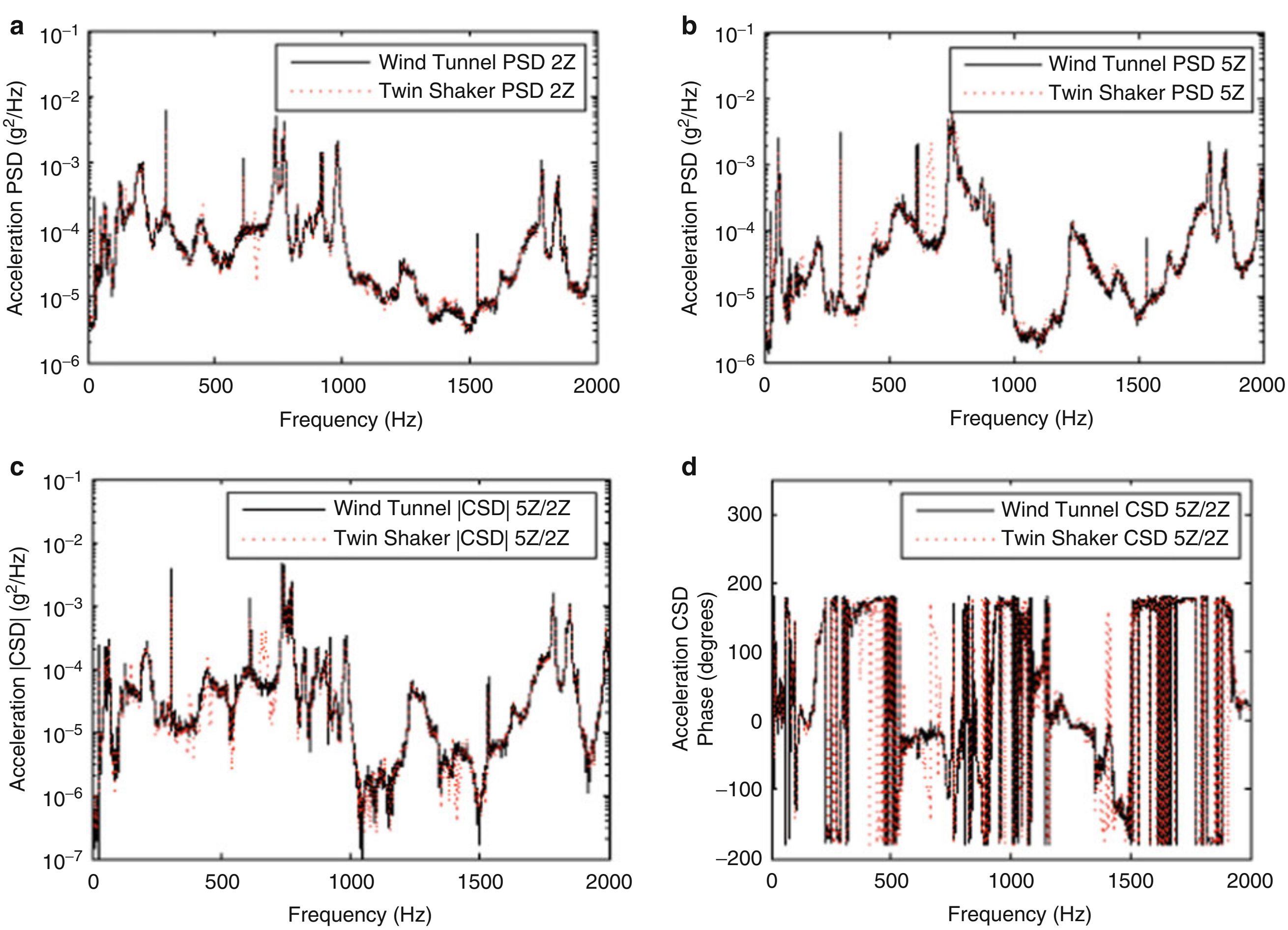


Fig. 37.10 MIMO random control curves from twin-shaker test. (**a**) PSD 2Z. (**b**) PSD 5Z. (**c**) |CSD| 5Z/2Z. (**d**) Phase (CSD) 5Z/2Z

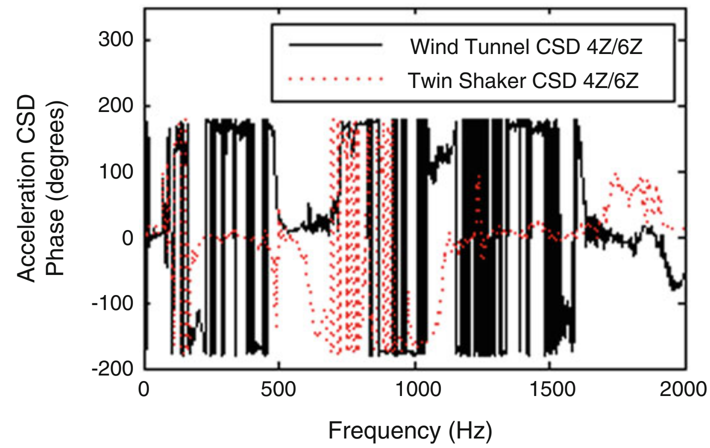


Fig. 37.11 Example of phase plot from twin-shaker test

many CSDs from the twin-shaker test; it is not necessary to present them all in this paper and the plots in Fig. 37.14 are representative of the full data set. A noteworthy result is the phase of the CSDs and a representative curve is shown in Fig. 37.11. These plots show that the twin-shaker test was poor at replicating the relative phase between some of the locations when compared to the original aerodynamic environment. This has significant consequences as it means that the operating deflection shapes in the laboratory test, and the associated stress patterns are very different to the aerodynamic environments it is attempting to replicate.

37.6 Impedance Matched Multi-Axis Test (IMMAT)

A new approach to vibration testing has been developed and can offer significant enhancements over traditional vibration testing methods. This new approach is called Impedance Matched Multi-Axis Testing (IMMAT) and has the following critical characteristics:

(i) The local impedance from the parent structure is included in the vibration test.
(ii) The structure is excited in all axes simultaneously.
(iii) The attachment of the exciters has minimal influence on the dynamics of the structure.
(iv) The vibration test is controlled at many response locations using MIMO control.

The IMMAT approach was applied to the missile and is shown in Fig. 37.12. The local impedance from the wind tunnel environment was simulated by including the launcher rail and a section of wood with the same thickness as the wooden ceiling of the wind tunnel. The missile was excited in three orthogonal axes simultaneously using electrodynamic shakers attached via flexible drive rods. The vibration response of the IMMAT was controlled at the thirteen accelerometers using the Leuven Measurement Systems (LMS) MIMO Random Control software and the Supervisory Control and Data Acquisition System (SCADAS) hardware.

The test specification consisted of **all** of the PSD and CSD measurements from the wind tunnel environment and was comprised of thirteen PSDs and 78 CSDs. This resulted in a test specification with approximately 60,000 breakpoints; a breakpoint is a frequency/amplitude data point, a set of which defines the outline of the test specification and typically consists of only tens of breakpoints in traditional vibration tests.

The PSDs from the IMMAT are shown in the appendices (Fig. 37.15), with only twelve of the thirteen shown for convenience. A representative selection of |CSD| plots and CSD phase plots are displayed in the appendices (Figs. 37.16 and 37.17). The plots demonstrate that the IMMAT was able to accurately simulate the wind tunnel environment, including the wind tunnel fan harmonics.

37.7 Discussion and Conclusions

A case study has been presented which demonstrates some of the limitations with the conventional twin-shaker, single-axis, vibration test for underwing missiles, in particular, the poor simulation of the aerodynamic environment at uncontrolled locations during the vibration test. This was apparent in the severity of the overtest at some locations and for portions of the

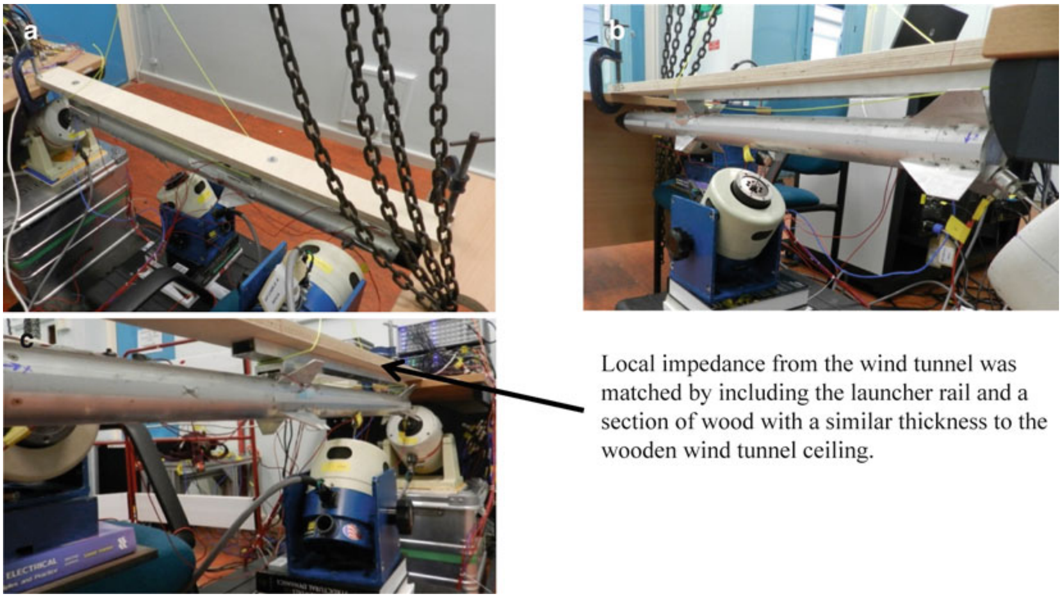


Fig. 37.12 Impedance Matched Multi-Axis Test for dummy missile. (**a**) IMMAT—view from above test setup. (**b**) IMMAT—view from tail of the missile. (**c**) IMMAT—view from below test setup

frequency bandwidth. Of more concern was the observed undertest at some uncontrolled locations. In addition, the evidence of this may not be discovered during typical qualification programs as often only the control locations are considered. Furthermore, there was evidence of cross-axis overtesting which means that any subsequent testing in orthogonal axes would subject the structure to unrealistically high stresses at the relevant frequencies. Other limitations of the twin-shaker test include the need to carry out three orthogonal tests sequentially to adequately excite all directions. In addition the fixture arrangement is likely to significantly alter the dynamics of the structure in terms of natural frequencies, modeshapes and damping. The twin-shaker test is a significant improvement compared to traditional large shaker, single-axis tests which are still commonplace today for many qualification programs on a variety of structures. The limitations described above could be considerably exaggerated for vibration tests that involve these large shaker systems.

The new Impedance Matched Multi-Axis Testing (IMMAT) technique potentially offers considerable improvements. IMMAT includes enhancements such as matching the local impedance of the parent structure and controlling the response of the structure at many locations using Multi-Input-Multi-Output control and has been successfully demonstrated in this paper.

A noteworthy improvement of IMMAT over current methods includes the excitation of all axes simultaneously with a considerable reduction in test time and the elimination of problems such as cross-axis excitation. Another major benefit of the IMMAT approach is the simulation of the original aerodynamic environment, including the power spectral densities, the cross spectral densities and the relative phase between locations. This ensures that the operating deflection shape of the structure in the IMMAT is very similar to the aerodynamic environment, leading to similar stress patterns. Finally, test houses could make substantial long-term cost savings by replacing some of their large shaker systems with a few smaller shaker systems for random vibration tests.

A.1 Appendix 1: Twin-Shaker Vibration Test Results

See Figs. 37.13 and 37.14.

A.2 Appendix 2: IMMAT Results

See Figs. 37.15, 37.16, and 37.17.

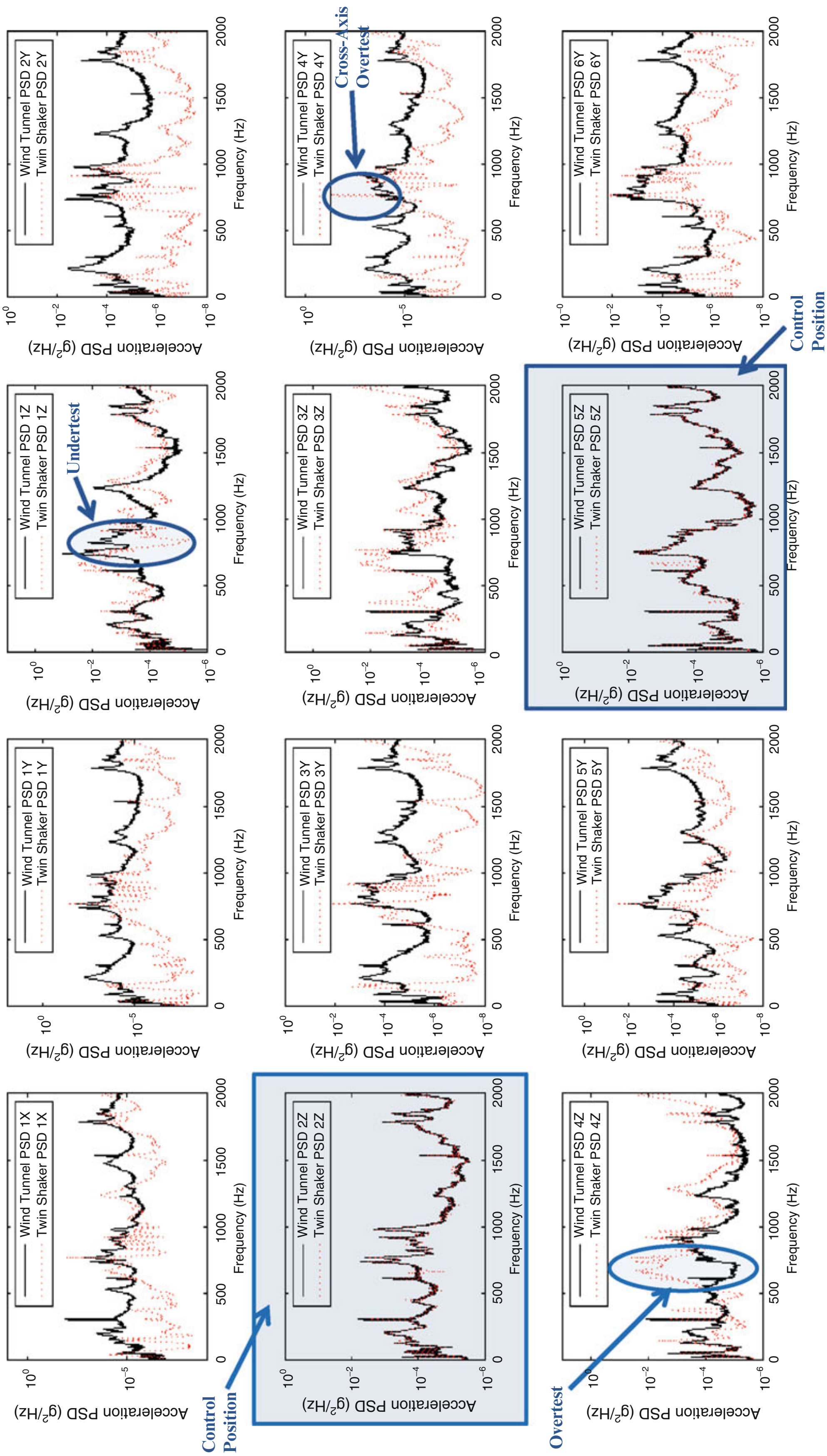


Fig. 37.13 PSD response plots from twin-shaker test (Z-axis excitation)

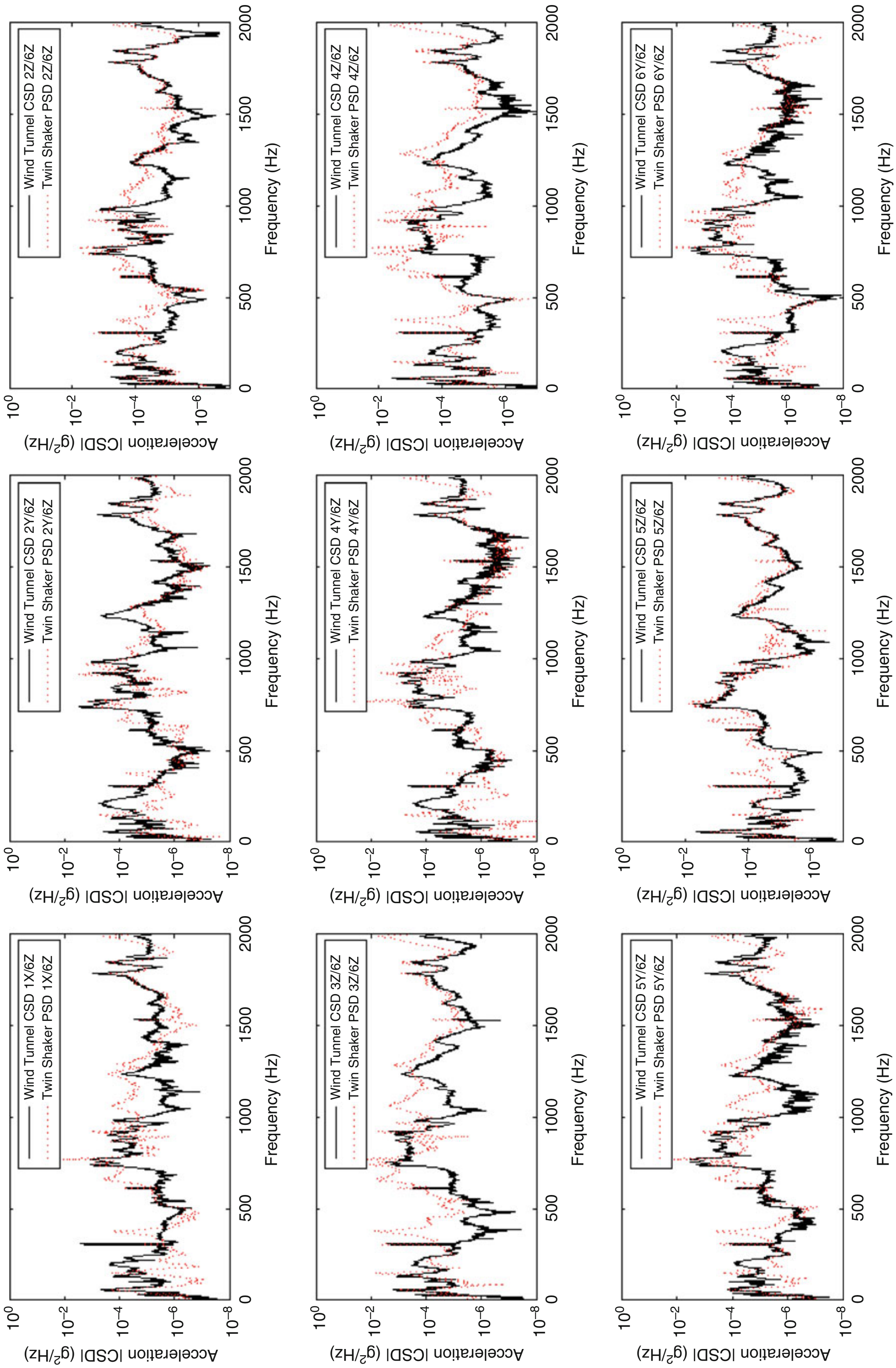


Fig. 37.14 |CSD| response plots from twin-shaker vibration test (Z-axis excitation)

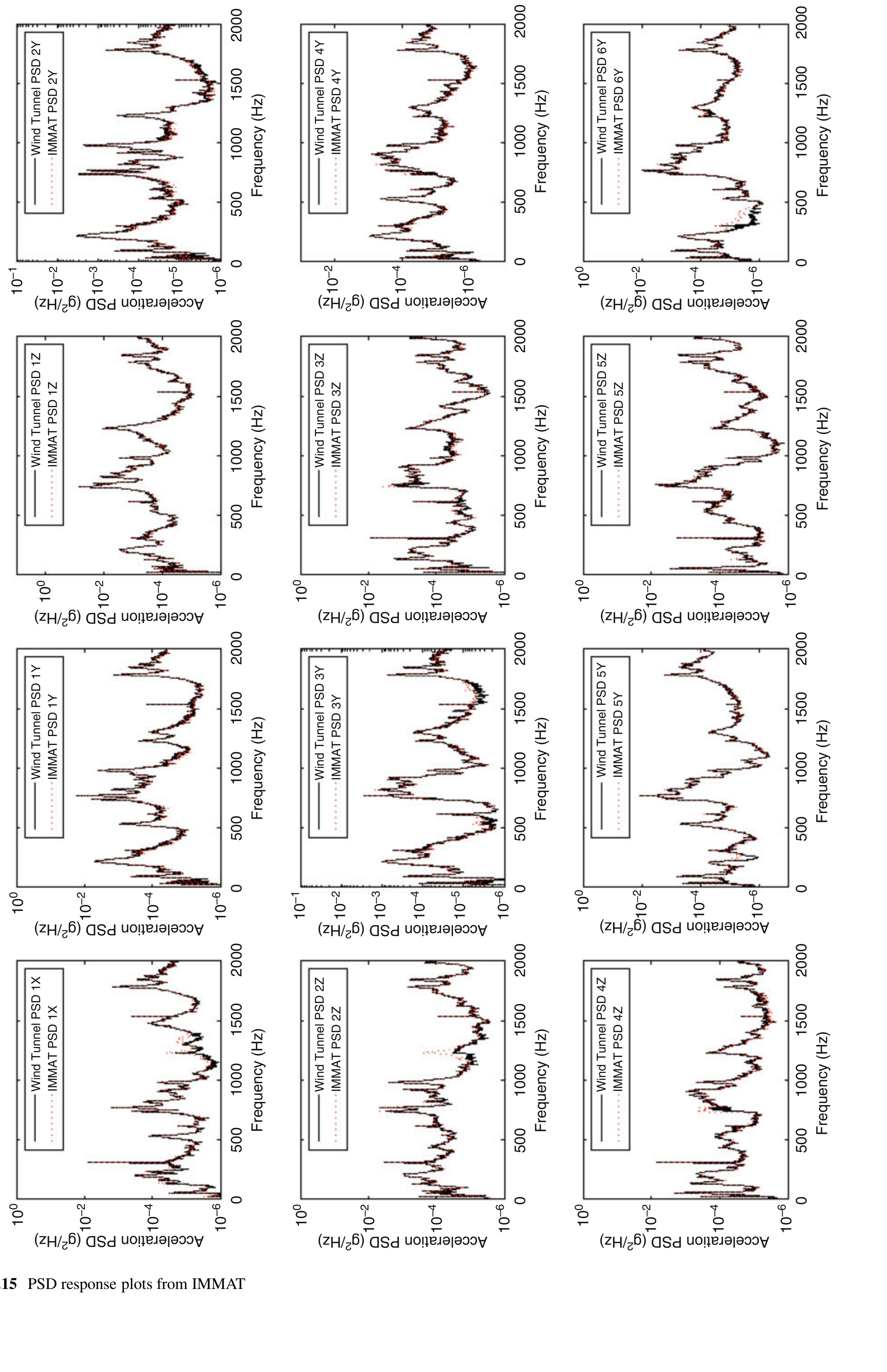


Fig. 37.15 PSD response plots from IMMAT

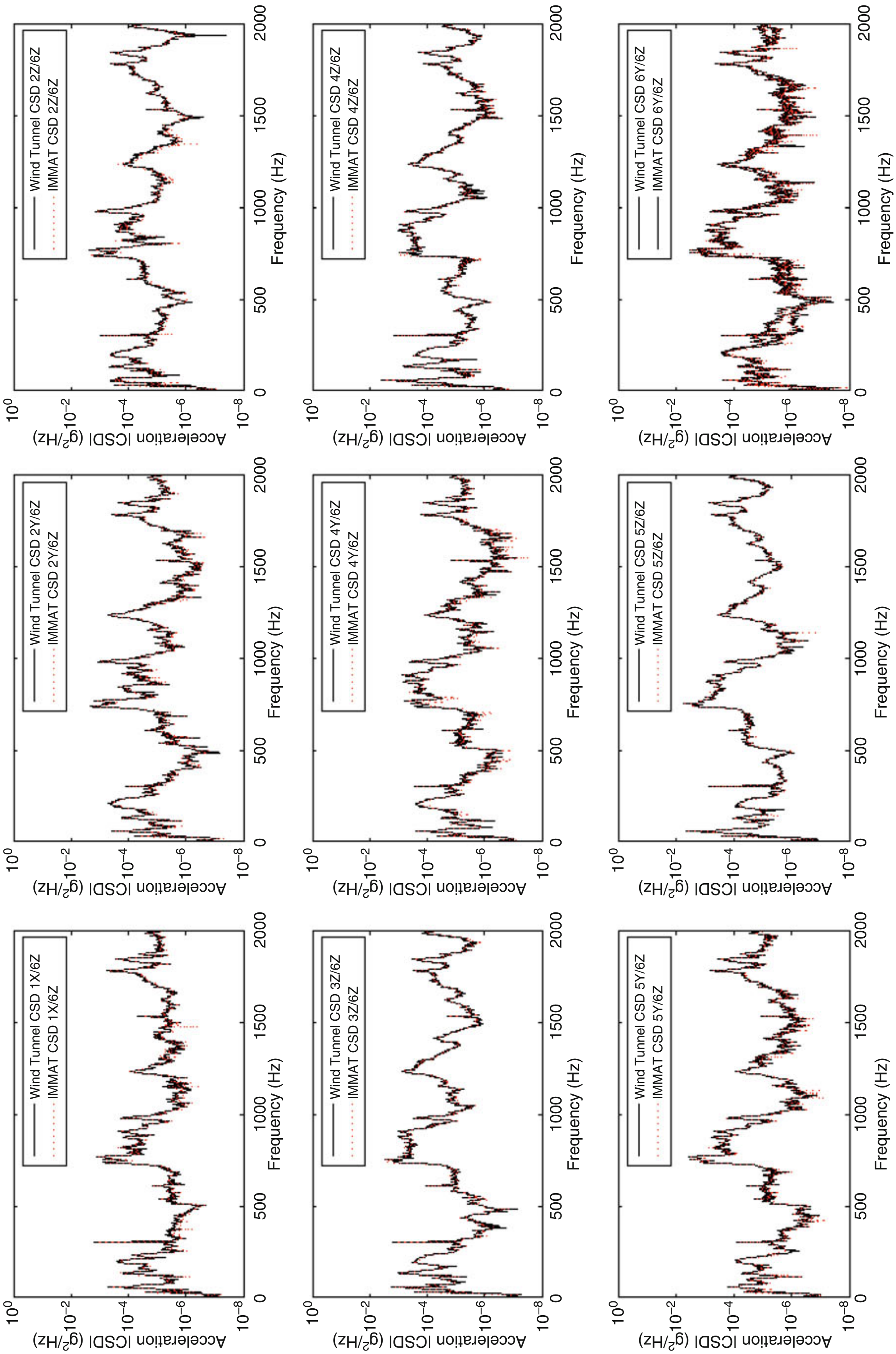


Fig. 37.16 |CSD| response plots from IMMAT

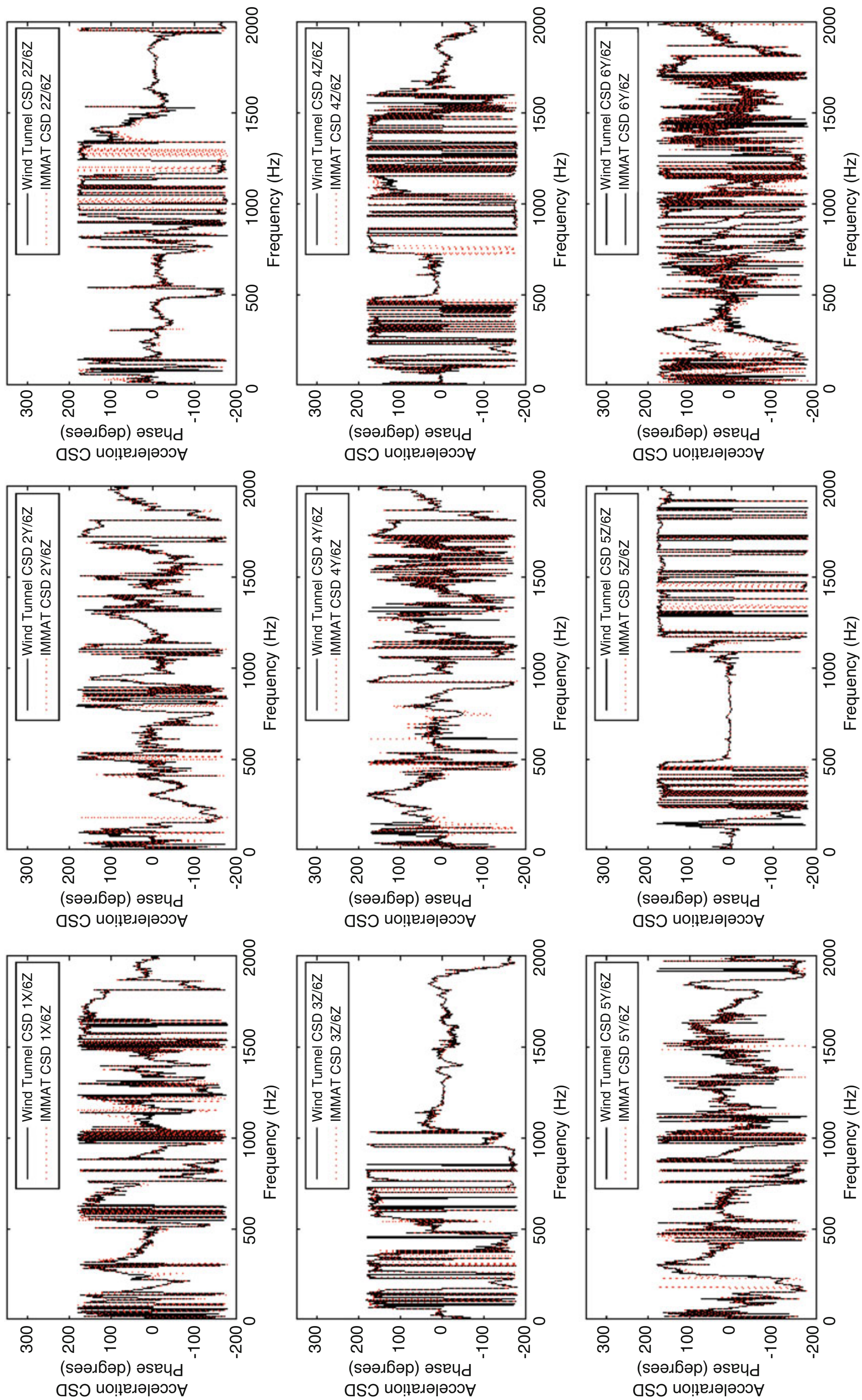


Fig. 37.17 CSD phase plots from IMMAT

References

1. Kroeger RC, Hasslacher GJ III (1965) Relationship of measured vibration data to specification criteria. Acoust Soc Am 37(1):43–53
2. Piersol AG (1966) The development of vibration test specifications for flight vehicle components. J Sound Vibr 4(1):88–115
3. Piersol AG (1974) Criteria for the optimal selection of aerospace component vibration test levels. In: Proceedings of institute of environmental sciences, pp. 88–94
4. Scharton TD (1997) Force limited vibration testing. NASA Reference Publication RP-1403, Pasadena, CA
5. Osterholt DJ, Napolitano KL (2007) Six degree of freedom vibration testing. In: Proceedings of IMAC XXV, Orlando, FL
6. Smallwood DO, Gregory DL (2008) Evaluation of a 6-DOF electrodynamic shaker system. In: Proceedings of the 79th shock and vibration symposium, Orlando, FL
7. Salter JP (1964) Taming the general-purpose vibration test. Environ Eng 33(2–4):211–217
8. Witte AF, Sandia National Laboratories, Albuquerque (1970) Realistic vibration tests. Instrum Technol. 45–48
9. Soucy Y, Cote A (2002) Reduction of overtesting during vibration tests of space hardware. Can Aeronaut Space J 48(1):77–86
10. Scharton TD (1995) Vibration-test force limits derived from frequency-shift method. J Spacecraft Rockets 32:312–316
11. Daborn PM (2013) Replicating aerodynamic excitation in the laboratory. In: Proceedings of IMAC XXXI, Garden Grove, CA
12. French RM, Handy R, Cooper HL (2006) A comparison of simultaneous and sequential single-axis durability testing. Exp Techniques 30(5):32–37
13. Whiteman WE, Berman M (2005) Inedaquacies in uniaxial stress screen vibration testing. J IEST 44(4):20–23