Siemens Digital Industries Software

Advantages of MIMO control strategies

Providing safe and efficient solutions for environmental vibration testing

Executive summary

Environmental testing is required in a wide range of industries in which the harshness of the conditions may compromise the functionality of a product. Therefore, qualification testing is required to evaluate the survivability of such a product in an operational environment. The need for time-efficient testing procedures, and the guarantee of an accurate replication of the operational environment are two driving factors in the environmental testing community. Beyond effective engineering practices, ultimately, both aspects concern reducing costs in the design-verification production cycle. This could be achieved by exploiting the advantages provided by multiple-input, multiple-output (MIMO) control strategies.

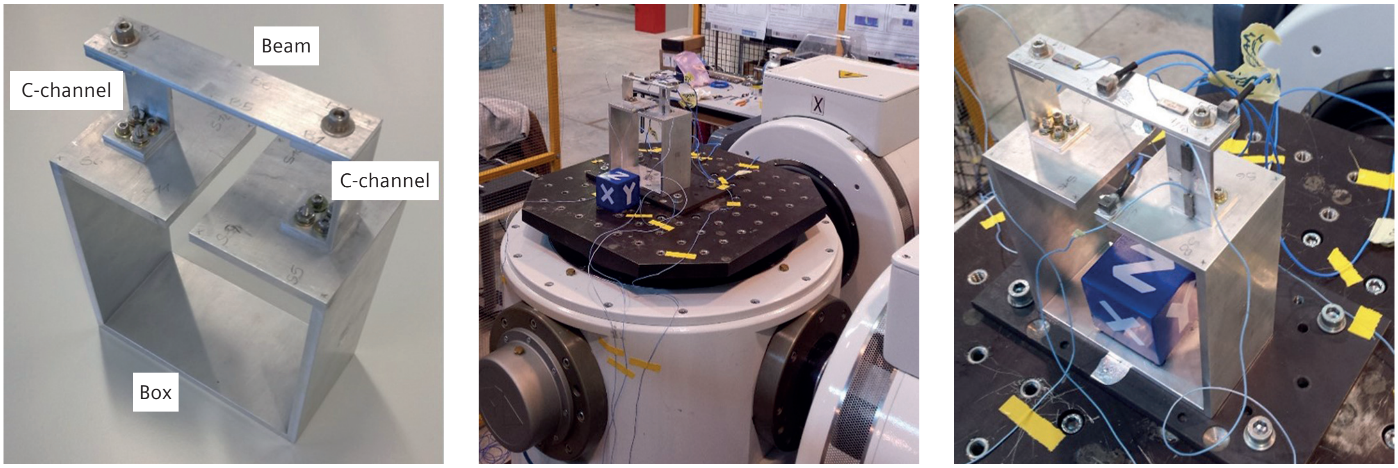
Abstract

Figure 1: Replicating dynamic environments at system and component levels of assembly is required in a wide range of industries.

The environmental testing community is commonly driven by two factors: the need for time-efficient testing procedures, and the guarantee of an accurate replication of the operational environment. The first aspect promotes shorter but representative test procedures for system design, verification and durability analyses. The second one focuses on avoiding over- and under-testing. Over-testing during qualification means the robustness of the design is verified by exposing the product to a harsher environment than it would face in real-life operation. This may lead to overdesign, which can increase the weight or production costs of prototypes, so they comply with unrealistic requirements. Under-testing means the survivability of the product is assessed at lower levels than those in service, which might lead to failure in the field. For safety and design efficiency, an optimal test must subject a product to an accurate replication of the environment experienced during its operational life. This article shows how MIMO control strategies for dynamic environmental testing can provide the required flexibility to design test campaigns that safely comply with these two key drivers – time efficiency and accurate replication of the dynamic input.

Dynamic environmental testing is applied in a wide range of industries and with different objectives: from qualification tests for consumer products [1] to acceptance for space hardware [1-2] and worthiness tests for defense equipment [3]. Among different kinds of dynamic environments, vibration control tests are performed to verify systems, subsystems and components can withstand the vibration environment during their operational life. Naturally, the in-service vibration environment simultaneously excites the structure in multiple axes (degrees-of-freedom) according to the boundary condition of each of the assembly levels.

The simplest, and therefore, most common way to expose a test article to the excitation in multiple axes is using single-input, single-output (SISO) control strategies, with sequential single-axis tests. In this approach, the test article is exposed to a certain vibration level along one of its axes, then rotated sequentially until all three axes (X, Y, Z) have been tested. The capability of this testing approach to replicate any real-life vibration environment has recently been questioned by the academic and industrial community [4-6], as it may lead to (i) incorrectly identifying failure modes [5] and (ii) estimating inaccurate time to failure for the unit being tested [6]. Additional drawbacks of sequential SISO tests are linked to other problems. For example, when the test article is one-of-a-kind, there is the risk of damage during the maneuvers required to change the test setup. When time is a constraint during the design-verification production cycle, another drawback of single-axis testing is the long time needed to physically change the orientation of the test article and instrument it to test each axis.



(a) (b) (c)

Figure 2: BARC structure (a). Test setup with BARC mounted on the three-axis shaker at the University of Ferrara (b). Accelerometers and strain sensors on the unit being tested (c).

The only alternative to overcome the sequential single-axis test limitations is to apply a simultaneous multi-axis excitation test performing MIMO vibration control [5-12]. Although installations for multi-axis vibration excitation have been available for a long time (the first example of a three-directional shaker dates to the 1960s [13]), progressive improvements in computational power have provided the hardware capability to run MIMO vibration tests with closed-loop digital control strategies. The clear advantages of this technology and more readily available equipment has driven the environmental testing community to look deeper into this practice by first exploring its challenges and limitations. Following such experiences and studies, standardized methods are being introduced as test standards and recommended practices (for example, Method 527 of the United States Military Standard 810 G [14] and the on-going working group at IEST DTE-022 [15]).

Today, MIMO environmental testing technology is a proven concept. The remaining challenge for the environmental testing community is the design of optimal control strategies; namely, the best application of such technology for each testing scenario. In this paper, case studies are used to demonstrate the performance of vibration control tests are clearly improved by applying a proper MIMO control strategy, according to the test objective. The case studies make use of a hardware demonstrator: a box assembly with removable component (BARC). In this configuration, the box assembly plays the role of a generic operational mounting, while the removable component represents the unit being tested. Some analogies between the BARC and real-life test scenarios are shown in figure 1. The challenge of replicating the operational boundary conditions during environmental tests can be linked to different industries, such as aerospace, automotive, defense and energy, in which vibration tests need to be conducted during the production cycle at the system and component levels of assembly.

The BARC was designed as part of a collaboration research framework between Kansas City National Security Campus (managed by Honeywell Federal Manufacturing & Technology) and Sandia National Laboratories. In 2016, these organizations introduced the "Boundary Condition Challenge" with the aim of investigating the possibility of improving the in-service environment replication at component level of assembly, and to propose solutions to prove that laboratory tests can lead to damaged mechanisms similar to the ones components suffer while in service [12,16-18].

Figure 2 shows the BARC in a test rig at the University of Ferrara in Italy, where random control and time waveform replication (TWR) tests were conducted with Simcenter Testlab™ software for dynamic environmental testing. The objective of such tests was to control the response at the base of the structure, while also considering the responses produced at the beam of the BARC.

Random control

	Point ID	Base: +X	Base: +Y	Base: +Z
1	Base: +X	0.816 m/s^	0.882	0.98
2	Base: +Y		0.415 m/s^	0.966
3	Base: +Z			1.72 m/s^2

Figure 3: SDM used as a MIMO test reference.

In random control, the objective is to reproduce dynamic base excitations, or test article responses (for example, displacements, velocities or accelerations) with user-defined statistical distribution properties (for instance, Gaussian). The specification for this environmental test is usually a power spectral density (PSD) profile per axis. These profiles are sufficient for SISO but incomplete for MIMO control strategies, since in the latter, a full spectral density matrix (SDM) needs to be defined as a test reference (see figure 3). Different strategies are available to fulfil the matrix when only PSD specifications are available for translational degrees-of-freedom (DOF) [11].

For random control tests, acceleration PSD profiles for +X, +Y and +Z axes can be calculated from time domain operational responses. In this way, test reference profiles can be derived from multiple in-service events to statistically cover a wide range of operational conditions.

SISO versus MIMO random control strategies

Sequential SISO vibration testing requires the testing of one translational DOF at a time. The red curves in figure 4 show the result of the vertical test (+Z), in which the control sensor was located at the base of the BARC. Although the control acceleration in this axis overlaps perfectly with the operational reference profile in green (see +Z:CONTROLS), responses produced in other directions, as well as the monitoring responses at the beam of the BARC, are far from the operational references. This means that SISO control strategy is efficient on the control axis, but it may lead to unwanted responses on other axes as well as at the component level.

A square MIMO control strategy shows higher controllability at the three translational axes simultaneously (see blue curves at +Z:CONTROLS, +Y:CONTROLS, +Z:CONTROLS). Although the monitoring responses at the beam are closer to the operational reference than in the case of the SISO control strategy, the curves are not perfectly matched. This is mainly due to differences between operational and test rig boundary conditions.

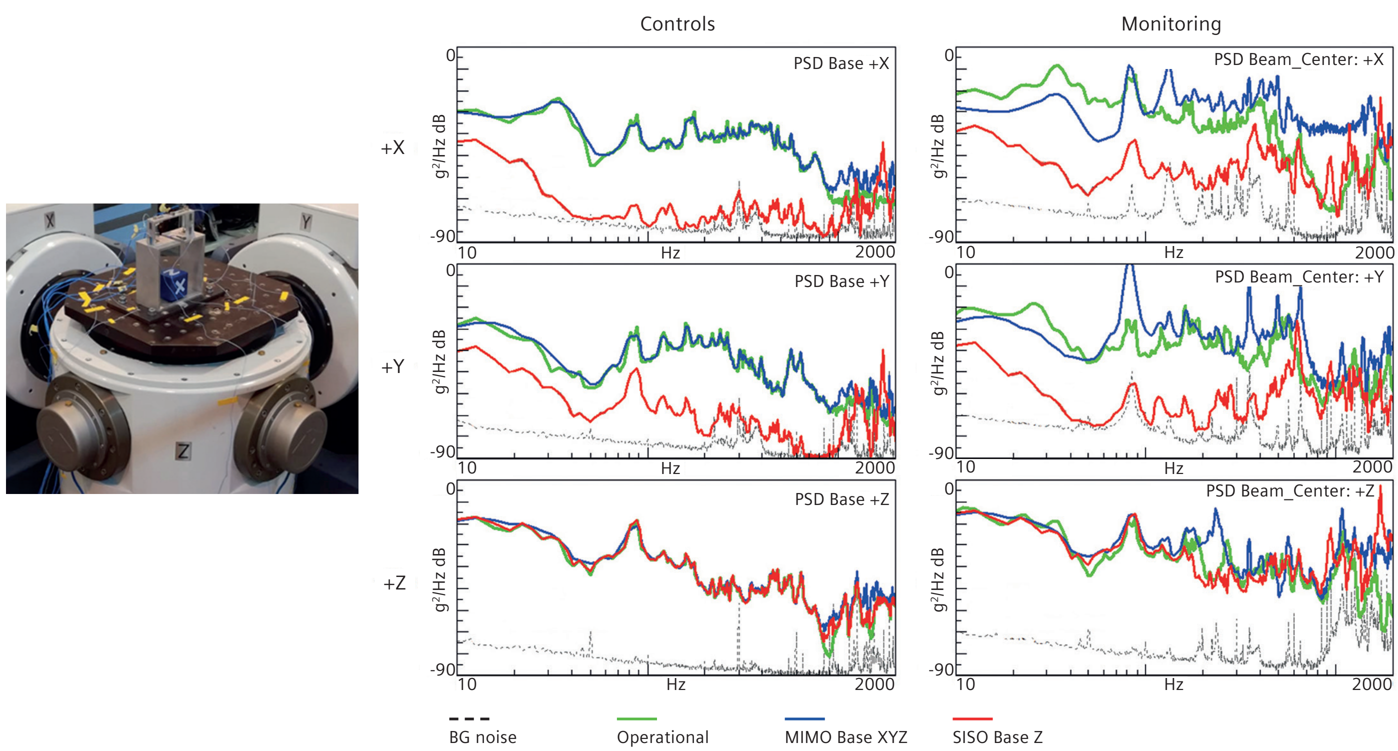


Figure 4: SISO and MIMO random control strategies results at controlled and monitored DOFs.

MIMO square versus MIMO rectangular random control strategies

To compensate for the differences between operational and test rig boundary conditions, the so-called MIMO rectangular control strategy can be applied. This strategy, using a 9x3 rectangular matrix of frequency response functions (FRFs) to represent the system, is meant to control base excitation alongside the dynamics of the box, which is shown in figure 2a. For that reason, the +X, +Y and +Z axes of three accelerometers are controlled, while the system is still driven by three voltage signals. The magenta color in figure 5 represents the improved replication of the operational responses at the beam of the BARC. This is a direct consequence of the modification of the control strategy, something only possible in a MIMO control framework.

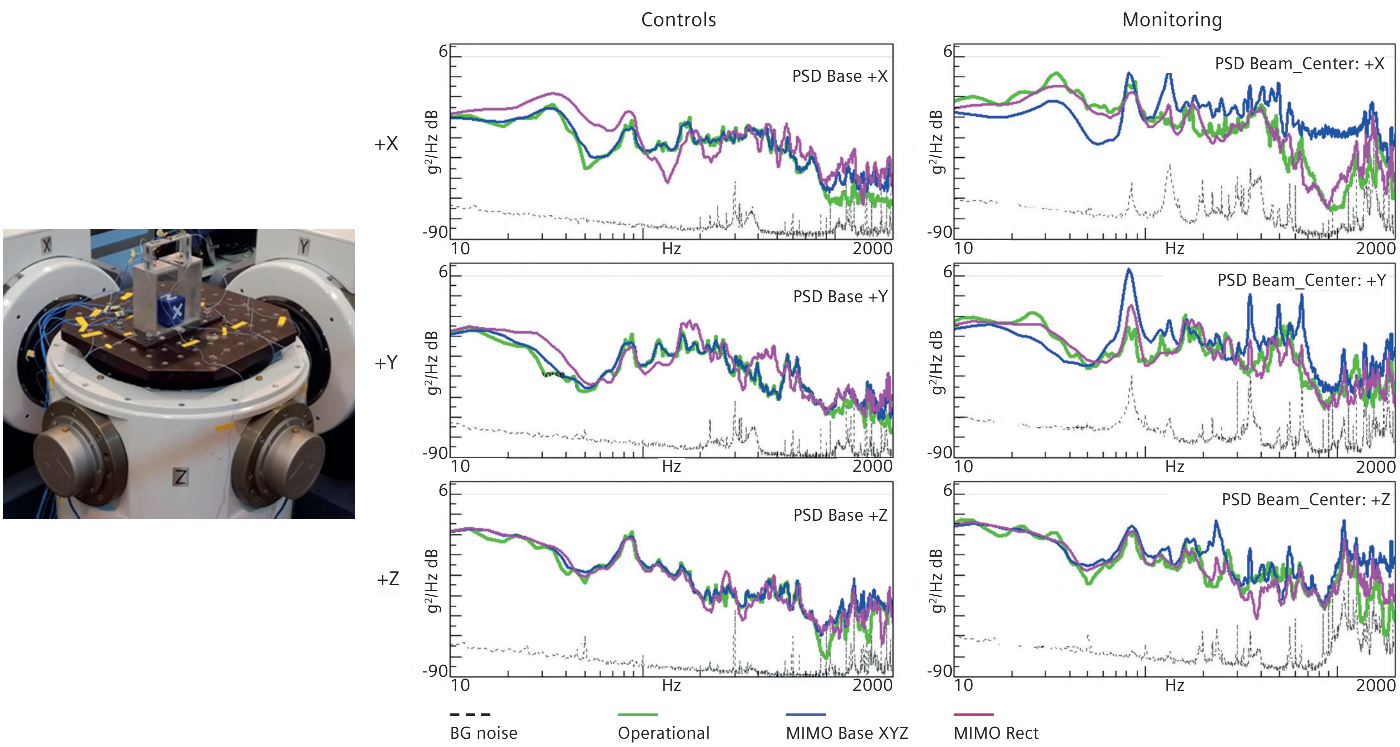


Figure 5: MIMO square and rectangular random control strategies results at controlled and monitored DOFs.

Time waveform replication

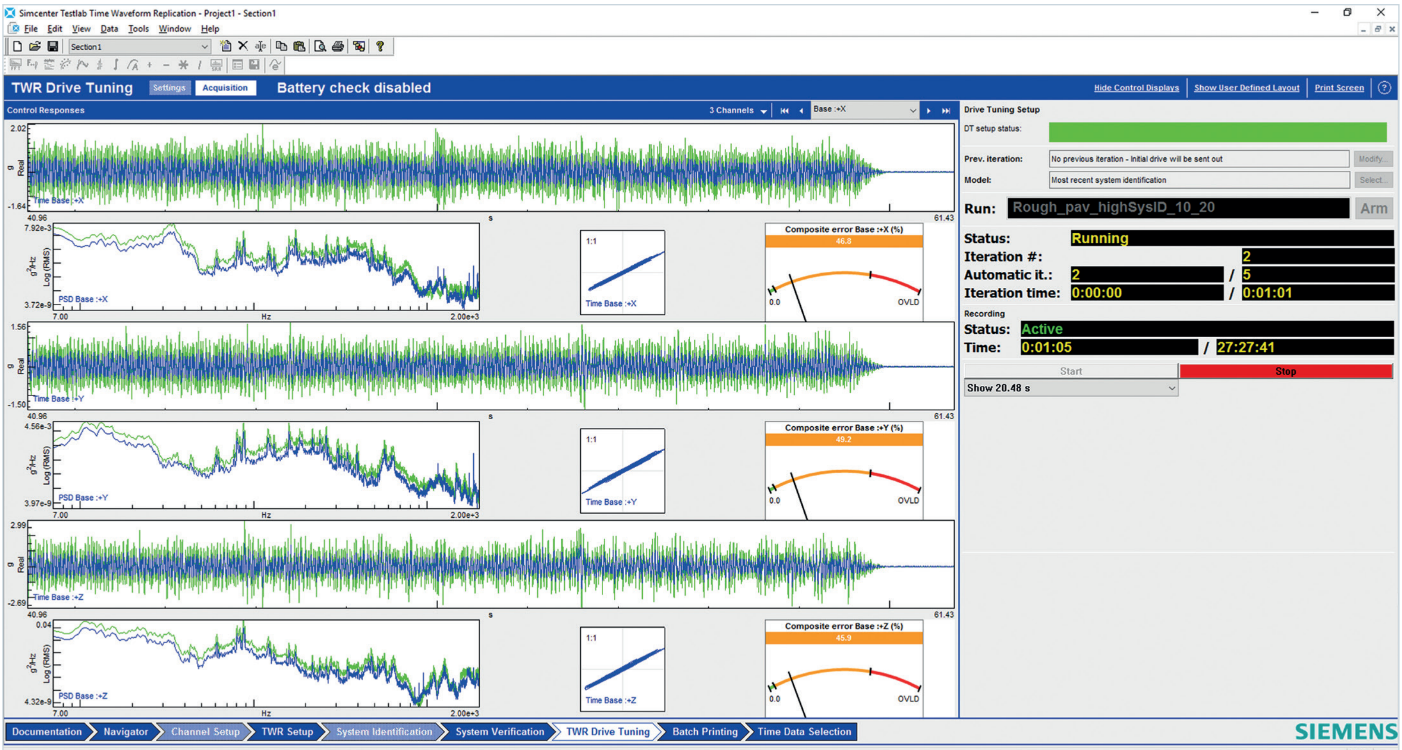


Figure 6: Drive-tuning procedure during TWR test.

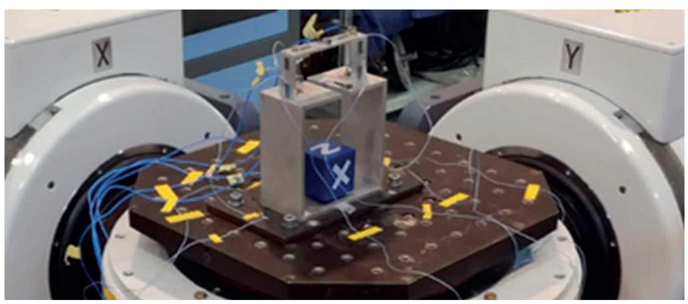
In TWR the objective is to find a set of voltage signals to drive the shakers system to accurately reproduce the time domain responses at the control sensors (for example, displacements, velocities and accelerations). In this environmental test there is no assumption regarding the statistical distribution of the amplitude of the targeted responses.

Figure 6 shows the TWR drive-tuning process, which iteratively modifies the time waveform of the voltage signals until the target responses are replicated at the control sensors.

MIMO square versus MIMO rectangular TWR control strategies

The results on the top of figure 7 correspond to a MIMO square TWR control strategy in which three drives are tuned to replicate responses at the base of the BARC for +X, +Y and +Z axes. The blue curves on the left present the results after the tuning of the drives is finished. Here, the responses at the control sensors are perfectly matched after five tuning iterations. However, such drives lead to significant over-testing at the beam of the BARC, as shown on the right.

Again, the differences between operational and test rig boundary conditions are playing an important role in the reproduction of operational responses for all the components of the BARC. Shown at the bottom of figure 7 are the results of a MIMO rectangular TWR control strategy. In this approach the control responses do not perfectly match the targets anymore; however, the monitoring responses are much closer to the operational data. This is proof the MIMO rectangular TWR control strategy leads to dynamic behavior of the beam, which is much closer to the operational data than in the MIMO square approach.



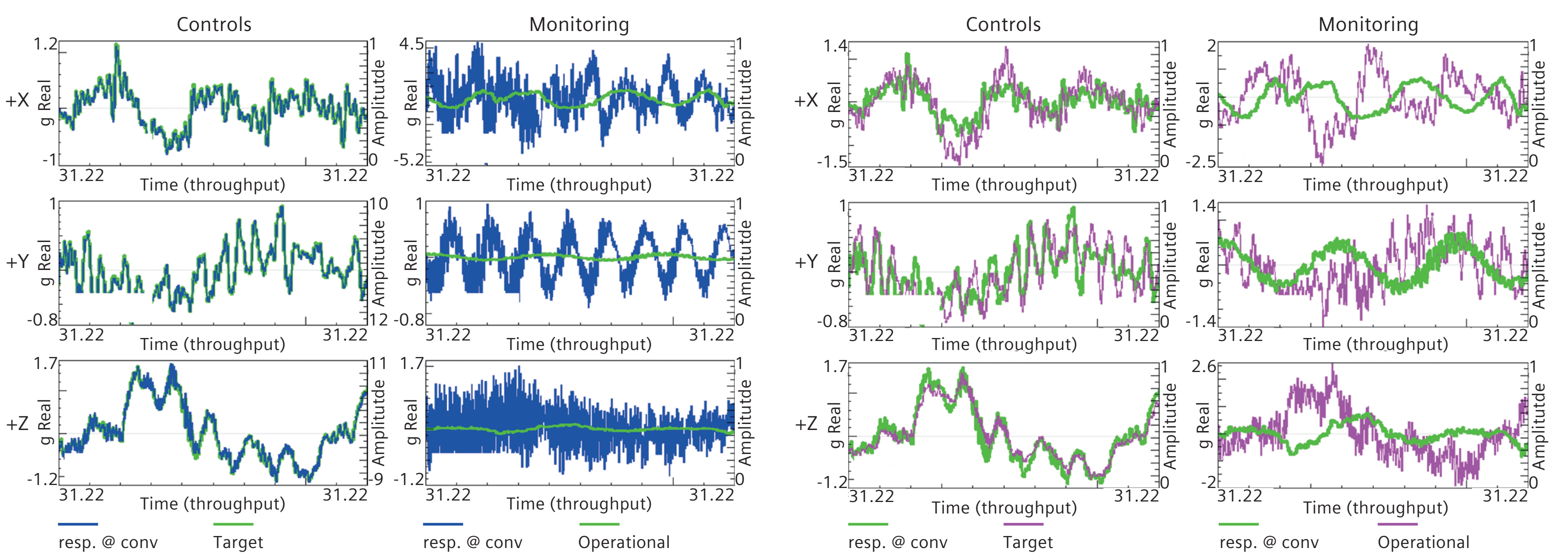


Figure 7: TWR results for MIMO square and rectangular control strategies.

Conclusion

This paper shows how MIMO control strategies could potentially change the way vibration tests are conducted. This paper not only highlights the time efficiency of this approach, but also shows that proper control strategies can lead to vibration responses that are more representative of operating conditions.

Control strategies must be designed according to the environmental test objective. To gain flexibility and reduce testing time, MIMO random control and TWR technologies can be implemented, avoiding over- and under-testing and ensuring that data is optimally acquired for prototype design and/or verification purposes.

Further research efforts need to be dedicated by the environmental engineering community to standardize testing methods and the design of MIMO test specifications.

References

1. C. Myron Fuller, H. Himelblau, T. D. Scharton, "Assessment of space vehicle aeroacoustic-vibration prediction, design, and testing," Technical Report, NASA Langley Research Center (1970).
2. P. K. Aggarwal, "Dynamic (vibration) testing: design certification of aerospace systems," Technical Report, NASA Marshall Space Flight Center (2010).
3. United States Department of Defense, Mil-Std 810 G, Met. 514.6: Vibrations (2008).
4. M. Mršnik, J. Slavič, M. Boltežar, "Multi-axial vibration fatigue - a theoretical and experimental comparison," Mechanical Systems and Signal Processing. 76–77 (2016).
5. M. Ernst, E. Habtour, D. Abhijit, M. Polhand, M. Robeson, M. Paulus, "Comparison of electronic component durability under uniaxial and multiaxial random vibrations," J. Electron. Packag. 137 (2015) 165–180.
6. D. Gregory, F. Bitsie, D.O. Smallwood, "Comparison of the response of a simple structure to single axis and multiple axis random vibration inputs," in proceedings of the 79th Shock and Vibration Symposium, (2008).
7. M. Appolloni, R.B. Dacal, A. Cozzani, R. Knockaert, B. Thoen, "Multi-Degrees-Of-Freedom vibration platform with MIMO controller for future spacecraft testing: an application case for virtual shaker testing," in proceedings. of the 29th Aerospace Testing Seminar, (2015).
8. P.M. Daborn, P.R. Ind, D.J. Ewins, "Enhanced ground-based vibration testing for aerodynamic environments," Mechanical Systems and Signal Processing. 49 (2014) 165–180
9. C. Roberts, D.J. Ewins, "Multi-axis vibration testing of an aerodynamically excited structure," J. Vib. Control 1 (2016).
10. U. Musella, G. D'Elia, A. Carrella, B. Peeters, E. Muchi, F. Marulo, P. Guillaume, "A minimum drives automatic target definition procedure for multi-axis random control testing," Mechanical Systems and Signal Processing 107 (2018), 452-68.
11. U. Musella, M. Alvarez Blanco, B. Peeters, "Improved vibration control strategies allowing the replication of operational dynamic environments at component level testing," in proceedings of the 89th Shock and Vibration Symposium (2018).
12. F. Edgington, "A three directional vibration system, Dynamic Environments test branch," White Sands Missile Range (1960).
13. United States Department of Defense, Mil-Std 810 G, Met. 527: Multi-Exciter tests (2014).
14. Institute of Environmental Sciences and Technology, DTE-022 Multi-Shaker test and control (2014).
15. J. Harvie, D. E. Soine, R. J. Jones Jr, T. J. Skousen, T. F. Schoenherr, Mike Starr, "Boundary conditions in environmental testing round robin," in proceedings of the Institute for Environmental Sciences and Technology, (2018).
16. D. E. Soine, R. J. Jones Jr, J. Harvie, T. J. Skousen, T. F. Schoenherr, "Designing hardware for the boundary condition round robin challenge," in proceedings of the XXXV International Modal Analysis Conference, 2017.
17. W. Larsen, J. R. Blough, J. P. DeClerck, C. D. VanKarsen, "Initial modal results and operating data acquisition of shock/vibration fixture," in proceedings of the XXXV International Modal Analysis Conference, 2017.

Acknowledgements

Siemens Digital Industries Software NV gratefully acknowledges the MechLav Research Group of the University of Ferrara for providing access to their three-axis shaker, as well as engineer Giacomo D'Elia for assisting the test campaign. Thank you also to Sandia National Laboratories and Honeywell for initiating the Boundary Condition Challenge and providing the BARC.

Siemens Digital Industries Software

Headquarters
Granite Park One
5800 Granite Parkway
Suite 600
Plano, TX 75024
USA
+1 972 987 3000

Americas
Granite Park One
5800 Granite Parkway
Suite 600
Plano, TX 75024
USA
+1 314 264 8499

Europe
Stephenson House
Sir William Siemens Square
Frimley, Camberley
Surrey, GU16 8QD
+44 (0) 1276 413200

Asia-Pacific
Unit 901-902, 9/F
Tower B
Manulife Financial Centre
223-231 Wai Yip Street
Kwun Tong, Kowloon
Hong Kong
+852 2230 3333

About Siemens Digital Industries Software

Siemens Digital Industries Software is driving transformation to enable a digital enterprise where engineering, manufacturing and electronics design meet tomorrow. Our solutions help companies of all sizes create and leverage digital twins that provide organizations with new insights, opportunities and levels of automation to drive innovation. For more information on Siemens Digital Industries Software products and services, visit siemens.com/software or follow us on LinkedIn, Twitter, Facebook and Instagram. Siemens Digital Industries Software – Where today meets tomorrow.

siemens.com/software

76740-C5 3/19 Y