Chapter 4
Smart Dynamic Testing of Aero Engine Externals: Challenges and Directions

Simon Euler, Ibrahim Sever, and Bernd Beirow

Abstract Aero engines are complex systems with stringent safety and performance requirements. These requirements apply to all engine parts, including a large number of control units, pipes, pumps, brackets etc. that sit outside gas path of a jet engine and are collectively referred to as externals. As with other parts in engines, manufacturers must demonstrate compliance with safety standards to regulatory authorities for the externals too. The said compliance evidence is mainly generated through rigorous qualification tests which are often based on specifications such as RTCA DO-160. However, such standardized tests may not accurately reflect real-world operating conditions, leading to over- or under-testing and potential in-service failures. Smart Dynamic Testing (SDT) is an evolving research domain aimed at addressing these limitations, encompassing Impedance-Matched Multi-Axis Testing (IMMAT), field environment characterization, control specification, test integration, and optimization. Among these, IMMAT has emerged as a promising methodology in experimental structural dynamics, aiming to replicate the in-field dynamic environment of the Unit Under Test (UUT) within a controlled laboratory setting. By replacing sequentially performed multiple single-axis tests with a single multi-axis test, IMMAT offers significant advantages in terms of cost and time savings, potentially eliminating the need for full-scale field trials. Despite its potential, IMMAT remains an open and complex research area, presenting several challenges. One key issue lies in the accurate definition of the target function, often hindered by incomplete sensor data from field measurements or the reliance on unvalidated numerical models. These limitations complicate the formulation of the Cross-Power Spectral Density (CPSD) matrix, which is essential for laboratory test replication. Furthermore, the placement of actuators (shakers) and control sensors is frequently based on engineering intuition, as systematic methodologies for their optimal configuration, and for the design of impedance-matched test fixtures, are currently lacking or underdeveloped. This paper exposes the challenges around SDT and provides an overview of the current methodologies and research areas approaching the underlying problems.

Introduction

The aerospace industry is a sector that depends heavily on the safety and reliability of its technical products. Aircraft manufacturers, engine producers, and component suppliers share the responsibility of demonstrating the functionality of their products under all operational conditions and throughout the product's lifecycle. This is achieved by providing evidence of functionality, mechanical integrity, and airworthiness to regulatory authorities, primarily through a combination of simulations and physical testing. The ultimate objective is to obtain product certification.

One critical area in which product robustness must be demonstrated is the field of aerodynamic and structure-borne vibration, which is the primary focus of this article.

For aero-engine manufacturers, components located outside the gas path – such as control units, pipes, pumps, and brackets (collectively referred to as externals) – are typically qualified through laboratory-based vibration testing. Depending on the application, this testing is carried out in accordance with standards such as RTCA DO-160G [1] for civil aviation or

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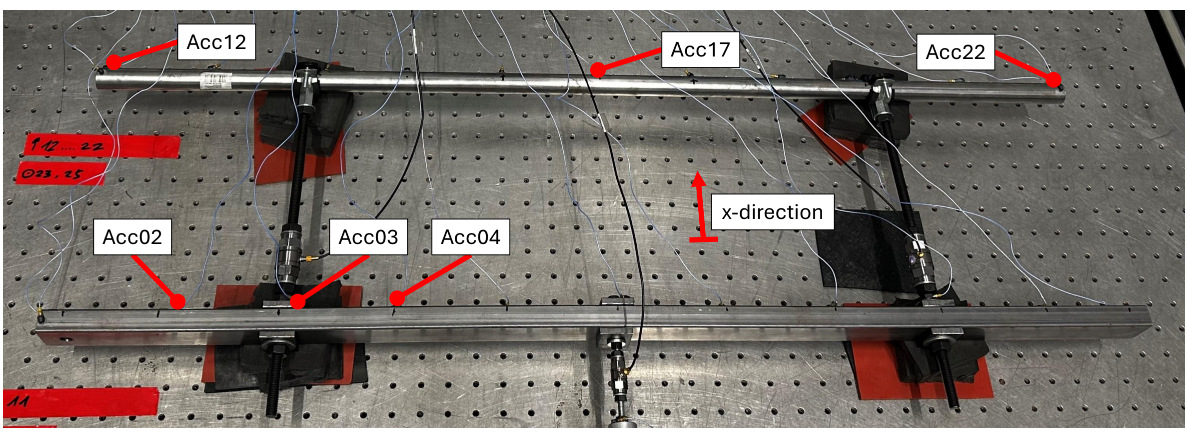
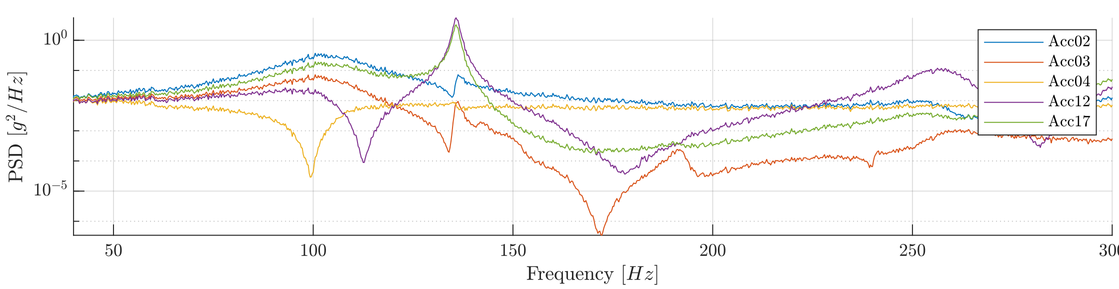
MIL-STD-810H [2] for defence applications. Although MIL-STD-810H permits multi-axis testing (see Method 527), most vibration testing continues to rely on traditional uniaxial methods developed in the 1960s and 1970s. These methods simulate a multi-directional vibration environment by sequentially applying excitation along the x-, y-, and z-axes using standardized test profiles and procedures [5, 6]. A typical vibration testing application in aero-engine development involves replicating a failure mode observed either on a development engine or in the operational fleet. Accurate replication in the lab requires environmental measurements from the system. However, due to the limited number of sensors installed on an engine, these measurements often do not coincide precisely with the failure location. As a result, the acceleration data used for base excitation is typically estimated from the closest available sensor.

Vibration Testing of Aero Engine Components

For this study, a simplified test setup was developed to represent a system environment. The setup consists of a pipe (e.g., a fuel line, representing the Unit Under Test – UUT) mounted on a steel beam (representing the Next-Level Assembly – NLA), and excited by a constant random drive signal form a $1kN$ shaker. The experimental setup is illustrated in figure 1a. Acceleration and force sensors were placed in-plane with the structure, aligned along the x-axis as shown in the figure. The measured power spectral density (PSD) spectra from selected sensors are presented in figure 1b. Notably, sensors $Acc12$ and $Acc17$ exhibit a peak at approximately $135Hz$. At this frequency, the PSD value at the coupling point between the beam and the vertical connection – measured by $Acc03$ – is approximately $0.008g^2/Hz$.



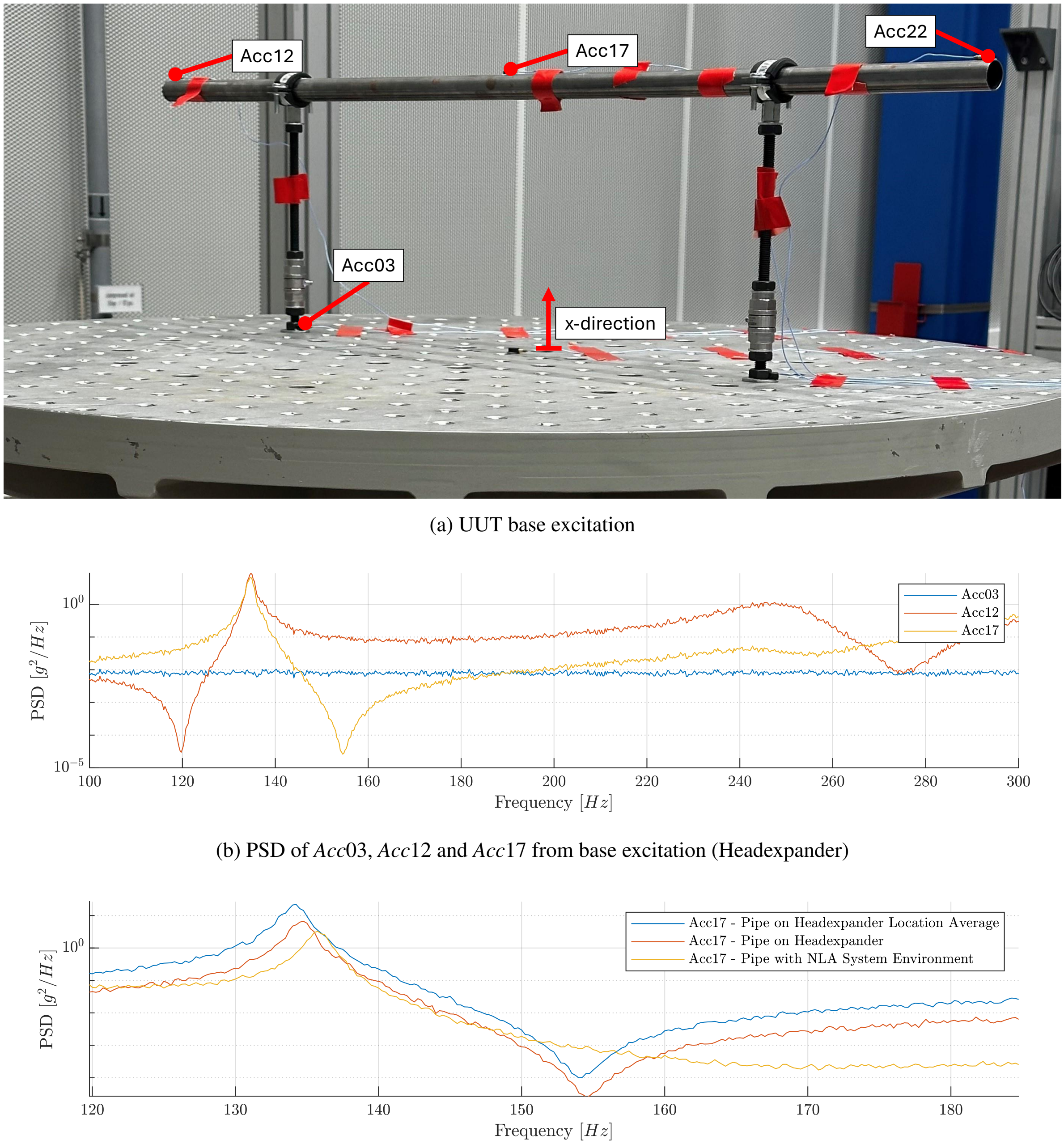
(a) UUT in System Environment



(b) PSD of selected sensors from system environment (with NLA)

Fig. 1 Simplified experimental set-up for pipe testing

A typical objective in a laboratory vibration test is to reproduce this peak excitation on the UUT through base excitation – commonly for high cycle fatigue (HCF) or qualification testing – using a defined acceleration input. The set-up for the laboratory configuration is shown in figure 2a. To investigate the influence of differences in mechanical impedance between the field and laboratory systems, an initial test was performed by directly applying the same PSD value ($0.008g^2/Hz$) measured by $Acc03$ in the system environment. This excitation was applied across a frequency range from $100Hz$ to $300Hz$. The resulting PSD spectra are shown in figure 2b.



(a) UUT base excitation

(b) PSD of $Acc03$, $Acc12$ and $Acc17$ from base excitation (Headexpander)

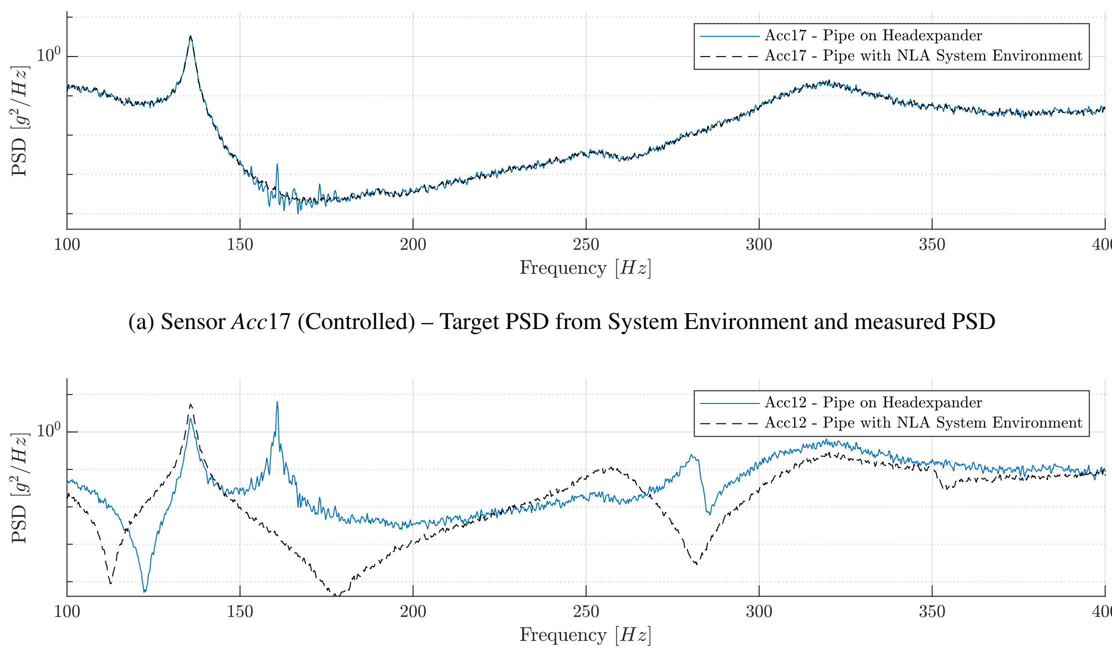
(c) $Acc17$ of system environment and base excitation

Fig. 2 Simplified experimental set-up for pipe testing

Often, the test engineer does not have access to measurements taken directly at the component interface. In such cases, nearby sensor data is typically used to estimate the base acceleration. For instance, if data from sensor $Acc03$ (located at the interface) is unavailable, one might use the PSD values from nearest sensors – such as $Acc02$ and $Acc04$ – and compute their average to define the base excitation. Based on this approach, the second test with the laboratory set-up was done with a base excitation of $0.0258 g^2/Hz$.

The resulting PSD spectra for sensor $Acc17$ of the different set-ups are shown in figure 2c. When compared to the system environment data, it becomes evident that even when using the exact interface acceleration, the Unit Under Test (UUT) experienced an over-test of approximately twice the amplitude due to differences in the mechanical coupling impedance between the field and lab set-ups. When instead using the average of neighbouring sensors, the over-test increased by a factor of six. This result highlights a key issue: base-controlled vibration tests can lead to significant over- or under-testing depending on the mechanical impedance mismatch between the laboratory setup and the actual system environment. To address this, it becomes reasonable to consider response-controlled testing as an alternative.[1]

The first response-controlled test was carried out using the laboratory setup on the head expander (figure 2a), with the PSD of sensor $Acc17$ from the system environment serving as the reference. Figure 3a compares the controlled response at $Acc17$ to the target PSD from the system environment. The results show a good match at the control point. However, examining the uncontrolled response at $Acc12$ reveals that the component was under-tested at $135Hz$ and over-tested around $160Hz$, relative to the field data (figure 3b). This highlights a fundamental challenge: controlling a single response point is often insufficient to accurately reproduce the entire system dynamic.



(a) Sensor $Acc17$ (Controlled) – Target PSD from System Environment and measured PSD

(b) Sensor $Acc12$ (Not Controlled) – Target PSD from System Environment and measured PSD

Fig. 3 Response-controlled at $Acc17$ on headexpander

To better replicate the dynamic environment, a rudimentary Multi-Exciter Single-Axis (MESA) setup was build by placing the UUT on two shakers (figure 4). The reference Cross-Power Spectral Density (CPSD) matrix for this random test was formulated using the PSD and phase data from the system environment (similar to the approach from Daborn et al. [5]). A coherence value of 1.0 was assumed across the frequency range.[2] The obtained PSD for the control points $Acc17$ and $Acc12$ can be found in figure 5a and figure 5b. It can be seen, that there are still control issues around a certain bandwidth of the anti-resonances, but in general showing a significant improvement in the response of the now controlled position $Acc12$.

Nevertheless, even by adding an additional control point to the UUT, the majority of the component is still uncontrolled during the test. For example, sensor $Acc22$ – located at the far right of the UUT – remains uncontrolled across all tests. Comparing its response from the test on the headexpander (figure 6a) and the dual shaker setup (figure 6b) shows that the response does not only differ significantly from the system environment, but switching to dual control can sometimes worsen the correlation. These results demonstrate a critical point: simply adding more exciters or control points may not be sufficient. There is a growing need for impedance-matched fixtures or a higher number of control points to better replicate the system environment dynamics.

The test series presented in this section underscores the uncertainties introduced by standard base-controlled vibration testing, which often lead to over- or under-testing. In practice, such uncertainties are typically addressed by applying conservative safety factors or broad acceleration envelopes, which can result in severe over-testing.[3] Response-controlled testing

[1] It is worth mentioning, that at least the RTCA DO-160 does not intend to carry out response-controlled testing.

[2] The MIL-STD-810H Method 527.2 Annex D recommends to use a coherence between 0.95 to 0.98 in the CPSD formulation, if not available from field measurements, to account for the always present noise in the measurement. This will be considered in future measurements.

[3] Daborn et al. [5] showed, that using ”enveloping” over-tests the UUT by magnitudes.

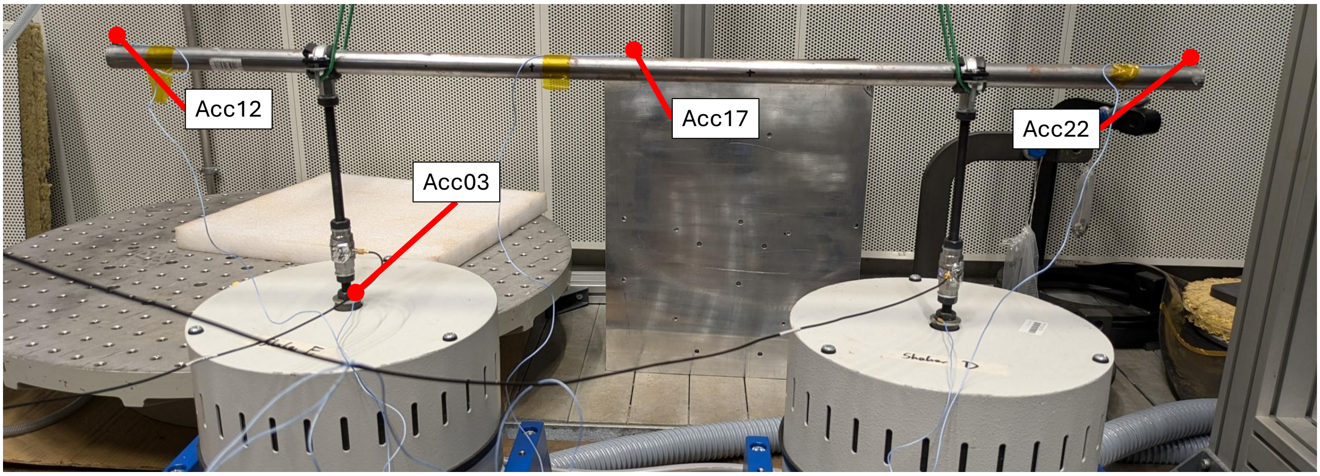
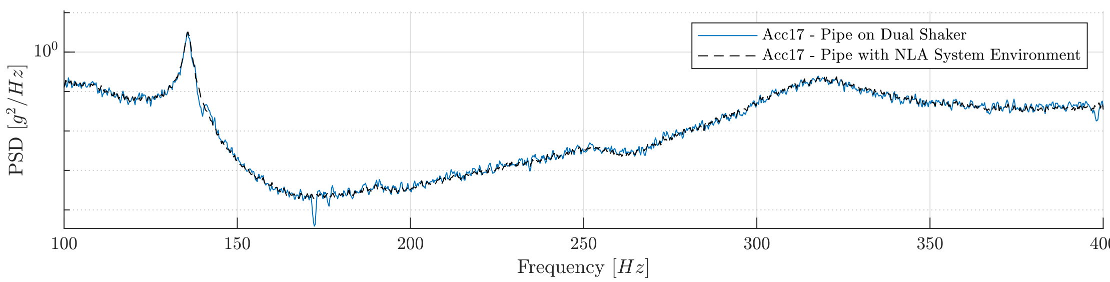
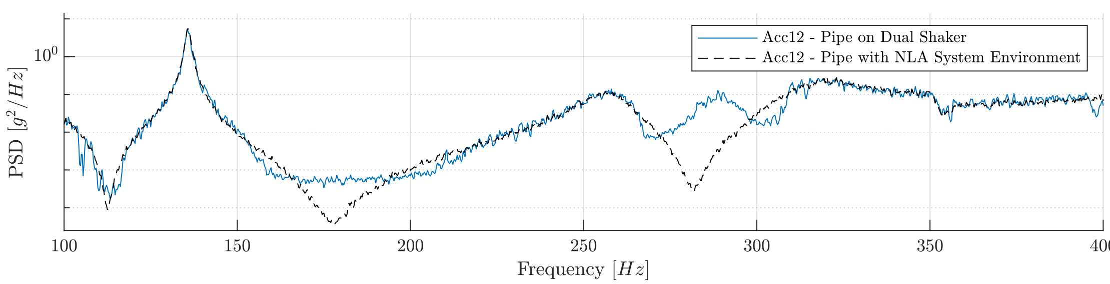


Fig. 4 UUT on Dual Shaker Set-Up



(a) Sensor $Acc17$ (Controlled) – Target PSD from System Environment and measured PSD



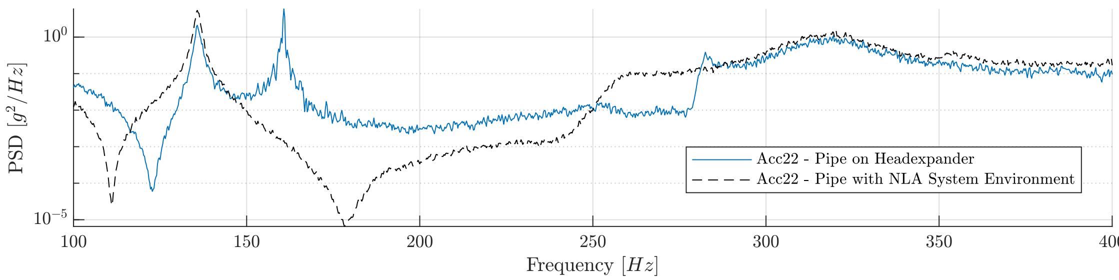
(b) Sensor $Acc12$ (Controlled) – Target PSD from System Environment and measured PSD

Fig. 5 Response-controlled at $Acc12$ and $Acc17$ on dual shaker

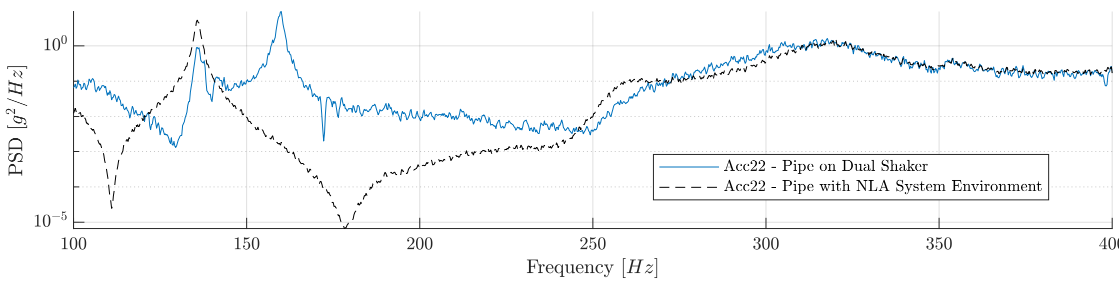
offers a more targeted approach, particularly when transitioning from single- to multi-exciter setups. However, even with increased control points, unmeasured positions may still exhibit significant deviations from their reference responses, as demonstrated in the final experiment.

Smart Dynamic Testing

Smart dynamic testing is an emerging research area aimed at addressing the limitations outlined in section . It provides the foundation for advanced techniques such as Impedance-Matched Multi-Axis Testing (IMMAT). Additional challenges not captured by the test series – such as field environment characterization, reference signal formulation, fixture design, and sensor/exciter placement – must also be considered.



(a) Sensor *Acc*22 (Not Controlled) – Target PSD from System Environment and measured PSD



(b) Sensor *Acc*22 (Not Controlled) – Target PSD from System Environment and measured PSD

Fig. 6 *Acc*22 of response-controlled at headexpander on dual shaker test

The overarching goal is to enable accurate replication of the system environment in the laboratory, without requiring the full physical system, by virtually planning and optimizing the IMMAT approach in advance. Several key developments are summarized below.[4]

Field Characterization and Test Specifications

Daborn et al. [5] presented a method to replicate the system dynamics of a free-flying missile in a multiple-input multiple-output (MIMO) vibration test. They also showed, that a MIMO test is operating with lower force levels compared to traditional vibration testing, indicating an inherent problem with traditional test set-ups. The authors pointed out, that there is need for research in the area of test specification, as cross spectra many not always be available from direct measurements.

Mayes [8] introduced a method combining Modal Craig-Bampton (MCB) substructuring with a Transmission Simulator (TS) to decompose the system into the elastic response of the fixture/NLA and the fixed-base motion of the component. This technique enables quantification of mechanical impedance mismatches between lab and field environments and supports the selection of appropriate control parameters. Schultz and Nelson [13] proposed strategies to address differences between field and lab setups using spatial and frequency averaging, as well as frequency axis warping.

Shaker and Sensor Placement

Rohe et al. [9] developed a shaker placement method for IMMAT and highlighted the dependency of results on control strategy. Their method used the frequency response matrix obtained from modal impact tests to predict responses across different exciter combinations.

Beale and Schultz [3] developed and demonstrated [4] a sensor selection method for multi-exciter test, based on an error metric that quantifies the difference between the reference CPSD and the predicted response of a preselected set of sensors. To apply this method, one needs the frequency response functions of the laboratory system to calculate the laboratory response. Mayes et al. [7] presented a shaker placement strategy that uses substructured models and amplifier constraints to ensure target responses are met without exceeding operational limits.

[4]This is not meant to be a full literature review and only shows exemplary work in the areas.

Impedance-Matched Multi-Axis Testing

As early as the 1960's Klein and Piersol [6] pointed out, that an impedance-mismatch leads to a severe difference between the laboratory test and the coupling impedance in field. Scharton [10] showed, that using multimodal fixture to replicate the mounting point impedance, leading to a significant improvement of the structural response and developed a design guidelines for multimodal fixtures, including dimensions, measured point impedance, modal density and damping of the fixture. These fixtures enabled smaller shakers to achieve target vibration levels and provided a more triaxial excitation environment.

Schoenherr et al. [11] used an objective function that is based on matching the frequency response matrix of the laboratory and field configuration. Due to the amount of local minima the solution did not convert towards the global minium. Latest research of Schoenherr et al. [12] shows, that using an optimization approach with an objective function, based on the modal projection error is converging best towards an impedance-matched design, but also mentions, that the gradient based algorithm is struggling to follow the decreasing slope in the solution space. Tuman et al. [15] proposed the Transmission Simulator IMMAT (TS-IMMAT) approach, wherein only the control points on an impedance-matched fixture are excited. Although promising, challenges remain – e.g., reproducing radial responses in rocket vibration environments.

Conclusion and Planned work

This paper highlights the key differences between standard base-controlled vibration testing – such as that used for component qualification – and more advanced Multi-Exciter Single-Axis (MESA) configurations. The tests showed that coupling impedance plays a crucial role in determining the actual dynamic loading experienced by the UUT. While transitioning from base-controlled to response-controlled testing can reduce over-testing, the limited number of control points in conventional setups restricts test accuracy. Even MESA configurations only partially address this issue. Future work will focus on:

- Topology optimization for the design of impedance-matched fixtures, that replicates the field dynamics over a predefined frequency range.
- Incorporation of real aero-engine structures, including larger components and higher response magnitudes.

These efforts aim to move closer toward accurate, efficient, and reliable dynamic testing that truly reflects the operational environment, enabling better qualification of aerospace components.

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