KU Leuven
Department of Mechanical Engineering
LMSD (Mecha(tro)nic System Dynamics)
Celestijnenlaan 300 - box 2420
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Proceedings of

ISMA2024

International Conference on

Noise and Vibration Engineering

USD2024

International Conference on

Uncertainty in Structural Dynamics

9 to 11 September, 2024
Editors: W. Desmet, B. Pluymers, D. Moens, J. del Fresno Zarza.

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A novel MIMO random control strategy for efficient response replication at the component level

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Abstract

The CSD terms in MIMO testing can significantly impact the structure's response intensity, potentially deviating from real operating conditions. This paper introduces a novel methodology, named Minimum PSD Method (MPM), that aims to replicate a random vibration environment at the component level with minimal excitation. The approach pre-defines the phase and correlation of the reference SDM that maximize the response of the Unit Under Test (UUT). Then, the reference SDM is completed with the minimum PSD values ensuring that the structure's response in the laboratory aligns with the target vibration environment. This manuscript provides the mathematical implementation of the MPM. In addition, the MPM is studied in an experimental campaign comprising two test cases: one conducted on an aluminium cantilevered beam, the other on an Exhaust Gas Recirculation (EGR) assembly.

1 Introduction

Random vibration control tests are used to assure that a system can withstand the required operational conditions. Historically, random vibration tests have been carried out using single-axis excitation systems. However, single-axis excitations are not able to replicate operational environments, which are in general multi-axial [1, 2, 3, 4]. In the past decade, particular focus has been given to multi-axis testing as a tool to overcome the limitations of single-axis testing procedures. In fact, multi-axis executations allow to closely match the operational environment that the test is supposed to mimic [5, 6, 7, 8, 9]. In multi-axis random control test the control target is a reference Spectral Density Matrix (SDM) comprising of Power Spectral Densities (PSDs), on the diagonal, and Cross Spectral Densities (CSDs), out of the diagonal [10]. The PSDs data provide the energy of each control channel, the CSDs define the degree of correlation and the phase between each pair of control channels. Typically, only the PSDs are provided, because of the lack of assessed multi-axis testing procedures and the impracticality of combining the CSDs from different operational conditions. However, the CSDs of the reference SDM play a key role in the outcome of the test. In fact, completing the reference SDM with different CSDs may significantly alter both the drive required to conduct the test [11] and the response of the Unit Under Test (UUT) [12, 13]. This aspect of multi-axis random control tests has been intensively studied over the past years. In particular, many drive minimization techniques have been formalized. These techniques exploit the CSDs of the reference SDM to minimize the total energy required to conduct the test. However, completing the reference SDM with the only objective of minimizing the shakers drives may alter the UUT response, causing under or over-testing of the UUT. In this scenario, this paper proposes a novel target generation technique, namely the *Minimum PSDs Method (MPM)*. The objective of the *MPM* is to minimize the drive required to conduct the test while preserving the response of the UUT. In particular, the *MPM* predefines the CSDs of the reference SDM and finds the minimum excitation PSDs that generate the target response on the UUT. Therefore, the MPM offers a MIMO random target generation technique that enables the redesign of MIMO random tests, effectively lowering the overall energy demand from the shakers while dealing the same damage to the tested article.

2 Fatigue analysis under multi-axis excitation in the frequecy domain

Fatigue analysis of random loading is usually performed in the frequency domain. For a linear time-invariant system, the relationship between acceleration input and stress output can be written in terms of SDMs [14]:

$$S_{\sigma\sigma} = F_{\sigma a} S_{yy} F_{\sigma a}^{H} \tag{1}$$

where $S_{\sigma\sigma}$ is the stress tensor, $F_{\sigma a}$ is the transfer function between acceleration inputs and stress outputs and the superscript ^{H} indicates the transpose complex conjugate. The stress tensor $S_{\sigma\sigma}$ represents a multi-axis stress state, in order to compute the fatigue damage the multi-axial stress must be converted in to an equivalent uni-axial stress PSD. A possible solution is to determine the *Von Mises PSD* as follows [15]:

$$S_{VM} = trace\left(Q S_{\sigma\sigma}\right) \tag{2}$$

where maatrix Q is given by

$$Q = \begin{bmatrix} 1 & -0.5 & -0.5 & 0 & 0 & 0 \\ -0.5 & 1 & -0.5 & 0 & 0 & 0 \\ -0.5 & -0.5 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 3 & 0 & 0 \\ 0 & 0 & 0 & 0 & 3 & 0 \\ 0 & 0 & 0 & 0 & 0 & 3 \end{bmatrix} \tag{3}$$

Once the uni-axial stress PSD is obtained the fatigue damgae can be comupted. In general, the instantaneous fatigue damage caused by the stress PSD can be expressed as:

$$D = \frac{n_0^+}{C} \int_0^\infty \sigma^k p_a(\sigma) d\sigma \tag{4}$$

where k and C are the slope and constant of the S-N curve approximated according to Basquin's law, n_0^+ is the mean number of zero up-crossings, σ is the stress amplitude and $p_a\left(\sigma\right)$ is the stress amplitude probability distribution of the stress PSD. A close form solution to Equation (4) can be obtained only in the case of narrow-band stress PSD. However, in real environments the stress PSD is in general wide-band, in these cases an approximation of $p_a\left(\sigma\right)$ is needed. One of the most accredited solution is the one proposed by Dirlik which provides good results for both narrow and wide-band PSDs [16]. In particular, by using the Dirlik probability distribution Equation (4) becomes:

$$\begin{gathered} D = \frac{n_p^+ m_0^{k/2}\left[G_1 Q^k \Gamma\left(1+k\right) + 2^{k/2}\Gamma\left(1+\frac{k}{2}\right)\left(G_2|R|^k + G_3\right)\right]}{C} \\ G_1 = \frac{2\left(x_m - \alpha_2^2\right)}{1+\alpha_2^2}; \quad G_2 = \frac{1-\alpha_2 - G_1 + G_1^2}{1-R}; \quad G_3 = 1 - G_1 - G_2 \\ R = \frac{\alpha_2 - x_m - G_1^2}{1-\alpha_2-G_1+G_1^2}; \quad Q = \frac{1.25\left(\alpha_2 - G_3 - G_2 R\right)}{G_1}; \quad x_m = \frac{m_1}{m_0}\sqrt{\frac{m_2}{m_4}} \end{gathered} \tag{5}$$

where n_p^+ is the mean number of peaks, α_2 is the bandwidth parameter, x_m is the normalized mean frequency, Γ is the gamma function and m_0, m_1, m_2, and m_4 are the zeroth, first, second and fourth statistical moments of the stress PSD.

3 The proposed methodology

In this section the theroetical aspects of the proposed methodology are discussed. The general idea of the method is to find the minimum PSDs of the reference SDM that allows to replicate a set of response PSDs on the UUT. The minimum PSDs can be obtained by defining the phase and coherence of the reference

SDM that maximize the response of the UUT. This condition can be obtained by using the Extreme Dynamic Response Method (EDRM) [12]. In fact, the EDRM aims to maximize the trace P of the response of the UUT. In particular, the maximum trace can be obtained with the following condition:

$$P\ is\ maximum \Leftrightarrow \begin{cases} \gamma_{jk}^{2} = 1 \\ \phi_{jk} = \xi_{jk} \end{cases} \quad \forall j,k = 1:l, j \neq k \tag{6}$$

Once the EDRM is used to retrive the phase and coherence of the reference SDM, the l reference PSDs can be obtained by solving the following set of equations:

$$\begin{cases} S_{xx,11} = \Sigma_{j=1}^{l} S_{yy,jj}^{ref} G_{jj}^{1} + 2\Sigma_{j=1}^{l-1} \Sigma_{k=j+1}^{l} \sqrt{\gamma_{jk}^{2} S_{yy,jj}^{ref} S_{yy,kk}^{ref}} G_{jk}^{1} cos\left(\phi_{jk} - \alpha_{jk}\right) \\ \dots \\ S_{xx,mm} = \Sigma_{j=1}^{l} S_{yy,jj}^{ref} G_{jj}^{m} + 2\Sigma_{j=1}^{l-1} \Sigma_{k=j+1}^{l} \sqrt{\gamma_{jk}^{2} S_{yy,jj}^{ref} S_{yy,kk}^{ref}} G_{jk}^{m} cos\left(\phi_{jk} - \alpha_{jk}\right) \end{cases} \tag{7}$$

where $G^{m} = F(:,m)^{H} F(m,:))$ and α_{jk} is the phase angle of $G(i,j)$. In Equation (7) matrix G^{m} can be retrieved during the system identification phase of the MIMO random test, the coherences γ_{jk} and phases ϕ_{jk} are determined using Equation(6), $S_{xx,mm}$ are the target response PSDs on the UUT, and the only unknown terms are the reference PSDs $S_{yy,jj}^{ref}$. The solution of Equation (7) allows to find the minimum reference PSDs that determine the UUT target response. As a consequence, the MPM guarantee the reduction of the drives required to conduct the test while maintaining the response on the UUT constant. The conclusion of this Section is devoted to the discussion of the potential application of the *MPM*. The critical aspect of the *MPM* is the response PSDs of the UUT to be replicated, which are required to calculate the excitation PSDs. There are various ways to obtain the response PSDs. The first application involves replicating operational measurements in a laboratory setting. In this scenario, the MPM may enable the replication of operational PSDs on a shaker table while simultaneously reducing the energy required to conduct the test. The second application of the *MPM* considers scenarios where operational measurements are not available. When operational measurements are not available, test specifications are typically derived from Standards. However, Standards often provide only the PSD profiles to be used as excitation during testing. In multi-axis testing, Standards suggest to assume low coherence between the control channels, determining an uncorrelated multi-axis excitation [17]. In this instance, the resulting diagonal reference SDM can be utilized to calculate the response of the UUT. Subsequently, the MPM can be applied to obtain a test that requires less energy to perform while still delivering the same damaging effect as the Standard profiles.

4 Experimental verification

The experimental activity of this work is divided in two test cases, showcasing the applicability and potential of the proposed procedure. The first test case is carried out on a specifically designed specimen, consisting of an cantilever aluminum beam. The main objective of this test case is to demonstrate the ability of the *MPM* to mimic the fatigue damage of a target vibration environment using the least amount of energy possible. The second test case is carried out on an automotive ERG valve assembly, comprising the EGR valve and the intake manifold. This activity allows to test the *MPM* with a real component exhibiting complex dynamic behaviour and focus more on the resulting vibration at different location with respect to the target one. In both test cases, the target vibration environment is obtained from a test conducted with flat uncorrelated PSDs as excitation. Furthermore, the responses and the drive PSDs obtained with the target vibration environment and the MPM are compared to those obtained by conducting a test with the same specifications as the target vibration environment but correlated using the *Minimum Drives Method (MDM)*, which is a state of the art drive reduction technique. The tests are conducted using the three-axial electrodynamic shaker available at the University of Ferrara. The data acquisition hardware and vibration control software used are the SCADAS Mobile SCM202V (V8 input and DAC4 output modules) and MIMO Random of Simcenter Testlab, respectively.

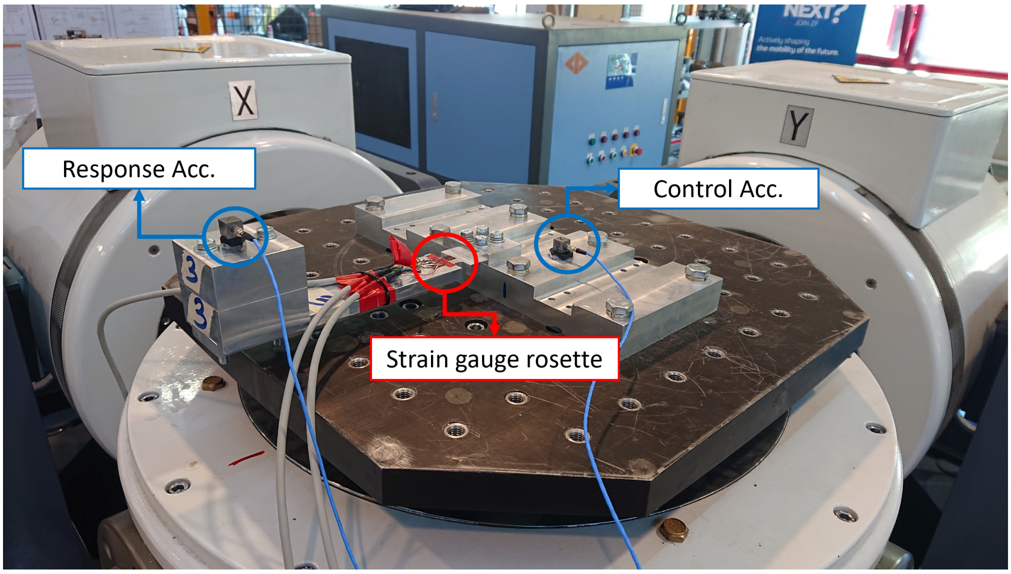

Figure 1: Specimen mounted on the shaker table and sensors used.

4.1 Test case A : aluminum cantilever beam

The specimen chosen for this test case is a cantilever aluminum beam with rectangular section and U-shaped notches near the fixed end. A lumped mass of 0.47 kg is placed on the free-end of the beam, to tune its natural frequencies in a convenient frequency range. Figure 1 shows the specimen mounted on the shaker table and the sensors used during the tests. The control accelerometer is placed near the fixed end of the specimen and the response accelerometer is placed on the lumped mass. The response accelerometer is the location where the vibration environment is measured to obtain the PSDs to be replicated using the *MPM*. Additionally, a strain gauge rosette is bonded near the notches, allowing to study the fatigue damage inflicted to the specimen. The test specification used to generate the target vibration environment consists of flat profile of 3 gRMS in the frequency range $[20 - 800]\ Hz$ replicated simultaneously on each direction the *Control* accelerometer.

Figure 2 depicts the comparison of the response PSDs measured on the lumped mass of the specimen. The three subplots on the left show the acceleration PSDs along the three orthogonal direction measured by the *response* accelerometer. These include the target PSD (solid line), the PSD obtained using the *MPM* (dashed lines) and the those obtained in the test performed using the *MDM* (dotted-dashed line). On the right side of Figure 2, the bar plot reports the difference in acceleration RMS value measured by the *Response* accelerometer with respect to the *target* measurement, expressed in decibels (dB). In particular, the bar plot shows the difference with respect to the *target* measurement of the RMS value of each axis and of their sum, which is representative of the overall similarity between the target and the measured response.

The *Response RMS* bar plot illustrates that the *MPM* achieved a deviation from the response RMS of the target measurement of $-0.03dB$ along the X direction, $+0.03dB$ along the Y direction and $+0.16dB$ along the Z direction. Moreover, the sum of the PSDs measured by the *response* accelerometer has an RMS difference of $0.03dB$ from the target. On the other hand, the *MDM* always achieved a greater deviation from the target. In particular $+0.64dB$ along the X direction, $+0.57dB$ along the Y direction , $-0.28dB$ along the Z direction and a total difference of $0.54dB$. In fact, changing the correlation of the reference SDM can significantly affect the response intensity on the UUT. Therefore, not adjusting the reference PSDs may cause significant deviation from the target vibration environment. These results highlight how the *MPM* is capable of replicating the target vibration environment. Moreover, it should be noted that test conducted using the *MDM* resulted in a higher deviation from the target. Furthermore, Figure 3 presents the comparison between the drives required to conduct each test. The plots on the left show the drive PSDs, the bar plot on the right illustrates the difference in voltage RMS value in dB with respect to the drives required by *target* measurement. The *MPM* consitently achieved a higher reduction than the *MDM*. In particular, the *MPM*

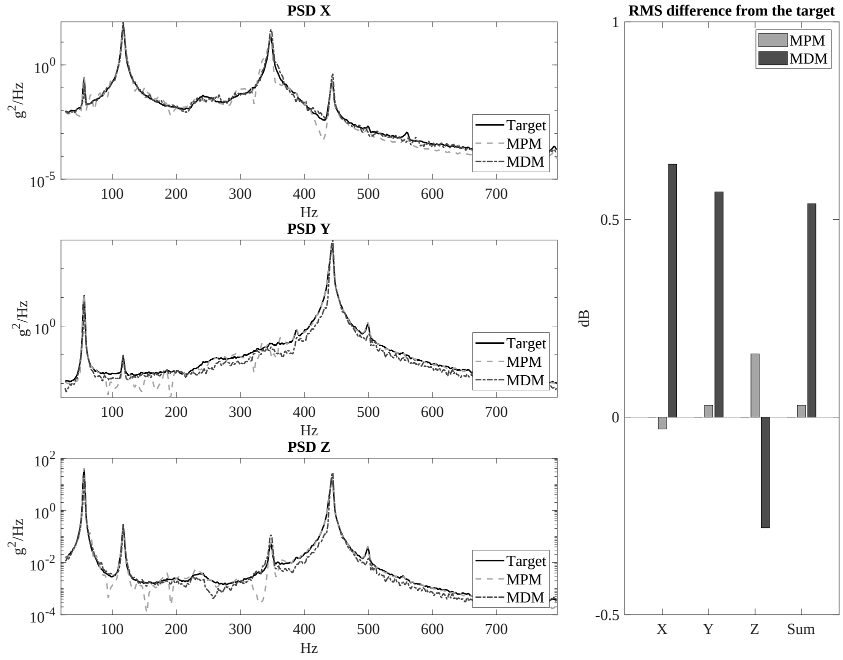

Figure 2: Comparison of the response accelerometer of the *target measurement*, the *MPM* and the *MDM* (dB reference: X: 18.1 g, Y: 58.62 g, Z:14.28 g, Sum: 63.08 g).

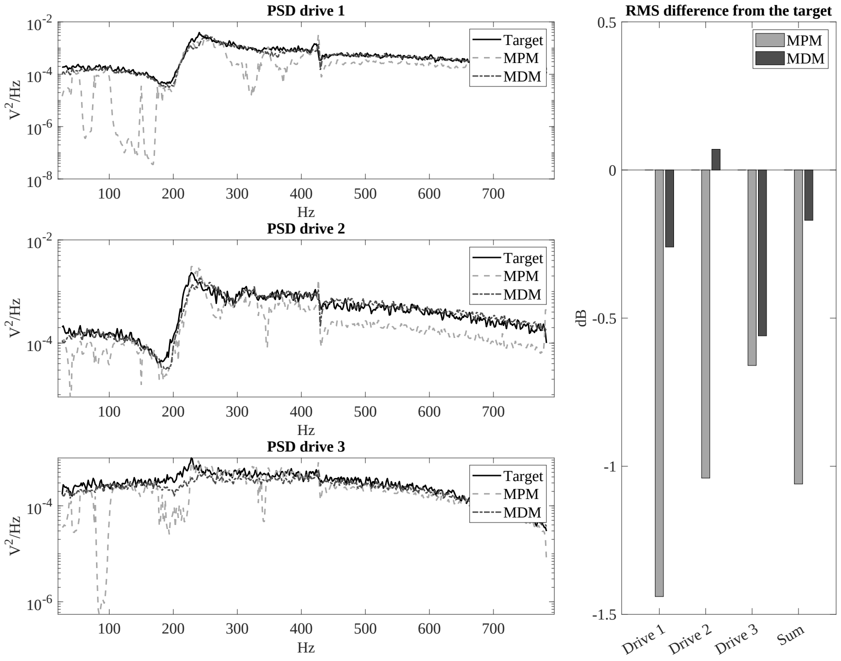

Figure 3: Comparison of the drives required by the *target measurement*, the *MPM* and the *MDM* (dB reference: drive 1: 0.67 V, drive 2: 0.61 V, drive 3: 0.49 V, Sum: 1.02 V).

achieved a reduction of $1.44dB$, $1.04dB$ and $0.66dB$ for drive 1, 2 and 3, respectively, while the *MDM* reduced the only drive 1 and 3 by $0.26dB$ and $0.56dB$, with drive 3 increased by $0.07dB$. Moreover, the total reduction of the drives achieved by the *MPM* was $1.06dB$, while the *MDM* reduced the total voltage required by $0.16dB$. It should also be noticed that the *MPM* achieved an higher reduction of the drives while preserving the response of the target measurement, while the *MDM* obtained a lower reduction of the drives and an higher deviation from the target PSDs. The last comparison involves the analysis of the fatigue damage inflicted to the specimen by each test.

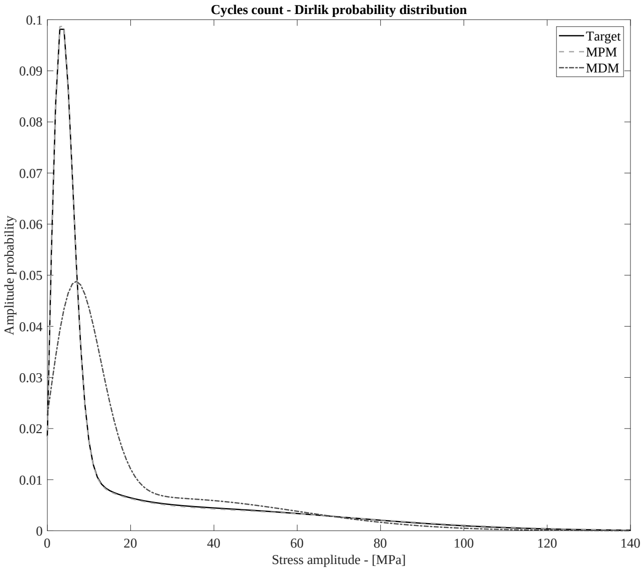

Figure 4: Amplitude probability distribution (Dirlik) of the Von Mises stress PSD of each test

Figure 4 shows the amplitude probability distribution calculated from the Von Mises stress PSD obtained during the *target measurement* (solid line), the one obtained with the *MPM* (dashed line) and the one obtained with the *MDM* (dotted-dashed line). It can be noticed that the dashed line (*MPM*) almost perfectly overlaps the *target* line, indicating that the *MPM* is equivalent to the target vibration environment by means of damaging cycles experienced by the specimen. On the contrary, the *MDM* determined a completely different amplitude probability distribution, yielding a different damage inflicted to the component.

4.2 Test case B : EGR assembly

The second experiment is carried out on a EGR assembly of a automotive engine. The assembly consists of the intake manifold and the EGR valve, which is mounted on the manifold using two brackets. In this case, a total of four accelerometers are employed: the *Control* accelerometer, mounted on the shaker table, and three measurement accelerometers placed on the EGR valve, in position 7, 20 and 27. All the accelerometers are ICP triaxial accelerometers, model 356B21 from PCB. Figure 5 shows the EGR assembly mounted on the shaker table and the measured locations. The test specification used to generate the *target* measurement are flat PSDs of 3 gRMS in the $[20 - 900]\,Hz$ frequency bandwidth replicated simultaneously on each direction the *Control* accelerometer. The PSDs measured at position 27 are the target responses for the *MPM*. The purpose of this experiment is to study the capabilities of the *MPM* on a real component with complex dynamic behaviour. Particular focus is given to the quality of the replication of the target measurement in positions far from the target location. he results of the test performed on the EGR are illustrated in Figure 6 and Figure 7. Once again the *MPM* achieved both a better representation of the target vibration environment and greater drive reduction compared to the test performed with the *MDM*.

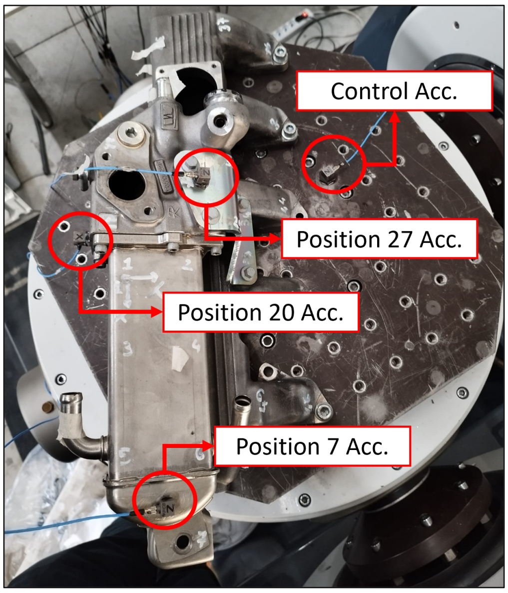

Figure 5: EGR assembly mounted on the shaker table.

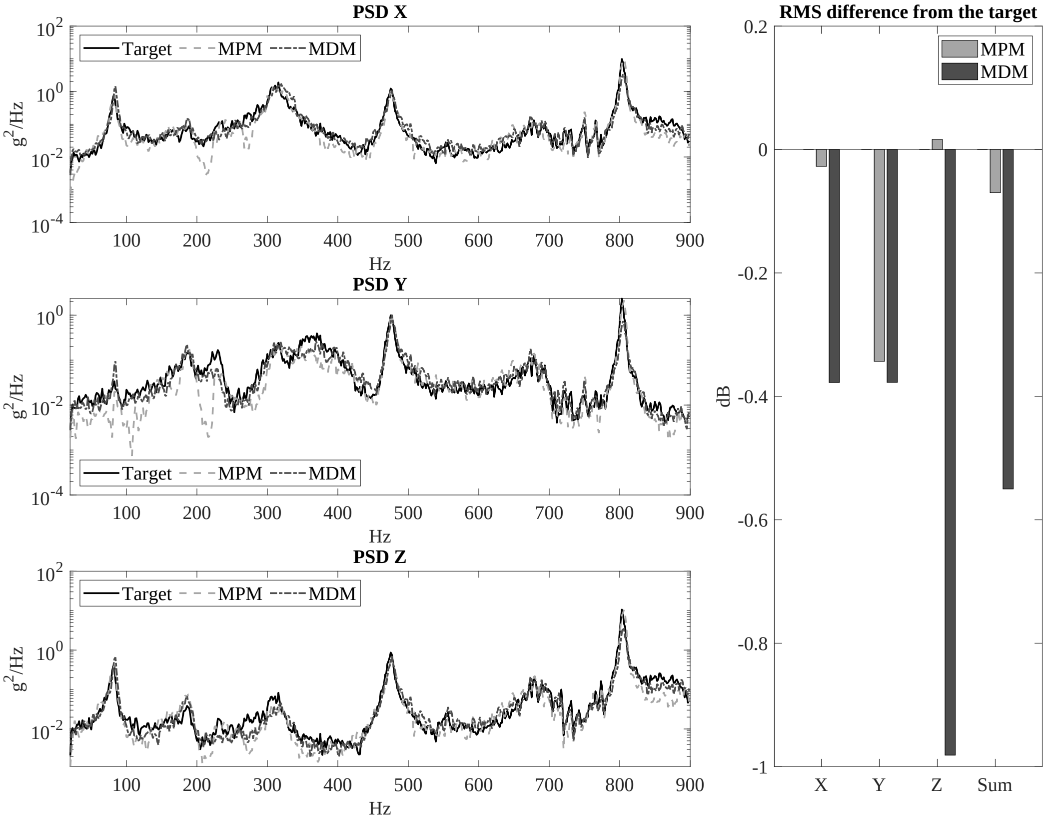

Figure 6: Comparison of the responses measured in position 27 during the test performed with the *target measurement*, the *MPM* and the *MDM* (dB reference: X: 12.73 g, Y: 8.29 g, Z:10.68 g, Sum: 18.57 g).

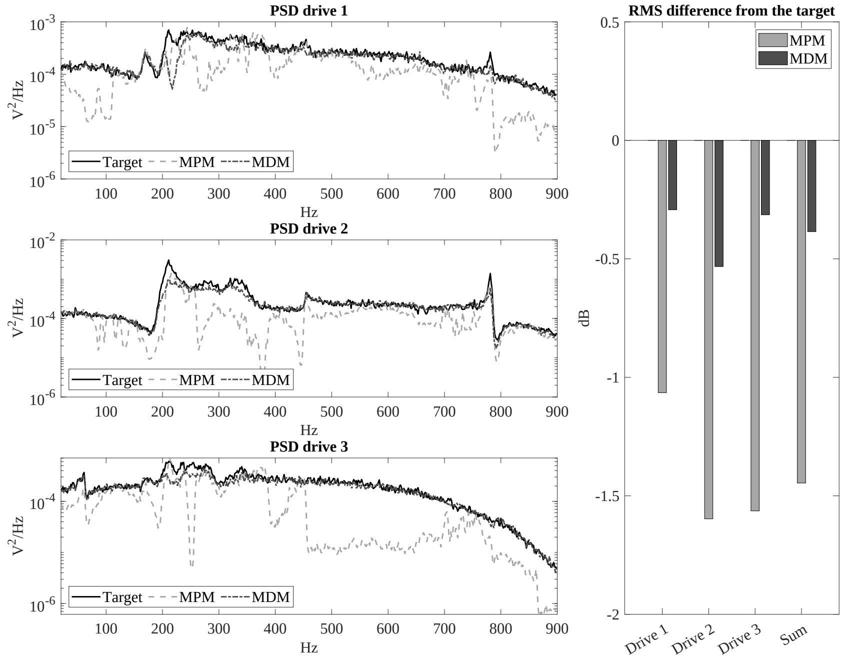

Figure 7: Comparison of the drives required by the *target measurement*, the *MPM* and the *MDM* (dB reference: drive 1: 0.46 V, drive 2:0.52 V, drive 3: 0.43 V, Sum: 0.81 V).

Finally, the other measured locations are observed. For the sake of brevity, the trace of the response is shown for the other measured locations. Figure 8 shows the trace of the SDM (left) and the difference , in dB, in acceleration RMS from the target measurement (right) measured in position 7 (top) and 20 (bottom).

The results show that the *MPM* was able to correctly replicate the response at both the observed locations on the EGR valve. In particular, the total response RMS deviation determined by the *MPM* is $0.03dB$ for position 7 and $0.12dB$ for position 20. This final result demonstrate the *MPM* ability to consistently reduce the drives required to conduct the test while maintaining the same response caused by the target vibration environment all across the UUT.

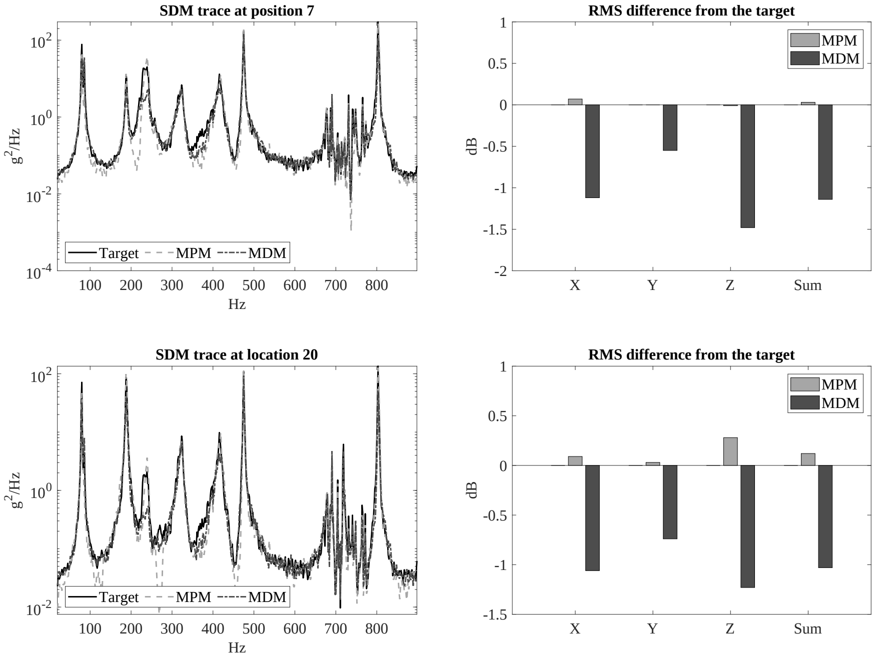

Figure 8: Comparison of the response SDM trace measured in position 7 and 20 during the test performed with the *target measurement*, the *MPM* and the *MDM* (dB reference position 7: X: 37.16 g, Y: 17.11 g, Z: 26.61 g, Sum: 48.81 g; dB reference position 20: X: 32.53 g, Y: 17.50 g, Z: 17.94 g, Sum: 41.07 g).

5 Conclusions

This manuscript proposes a novel methodology to define the target for a MIMO random control test, the *Minimum PSDs Method*. The method provides the minimum excitation PSDs that allow to replicate the response of the UUT caused by a different set of excitations, minimizing the voltage required by the shakers to conduct the test and preserving the damage inflicted to the UUT. The effectiveness of the *MPM* has been verified through two separate test cases. In both test cases the *MPM* has been compared to the *MDM*, a state of the art solution for drive power reduction in MIMO random tests. In both test cases the proposed methodology has provided better results by means of drive reduction, response replication and fatigue damage inflicted to the UUT.

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