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Comparison of SISO and MIMO control strategies for performing sequential single axis random vibration control test

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Abstract

In random vibration control testing, the nowadays common practice to replicate in the laboratory the operational vibration environment is the sequential Single-Input Single-Output (SISO) vibration control testing: the test specimen is sequentially rotated and three orthogonal axes are individually excited exploiting a single axis shaker. With SISO control strategy, just the drive axis of vibration is feedback controlled. In order to verify the validity of the single axis control test, the vibration levels on the two axes orthogonal to the main axis of vibration should not exceed acceptable thresholds. Significant advances in test hardware and control software, in addition to test facility designed for multi-axial excitation, have made possible to perform vibration testing using Multi-Input Multi-Output (MIMO) control strategy. Besides the feedback control of the main axis, the MIMO control configuration allows the simultaneous control along the two cross axes, thus improving the quality of the single axis test.

This work presents a test campaign carried out using two different test facilities with the same performance characteristics: a single axis shaker and a 3-DoF shaker table. The objective of the research is to critically compare the results obtained by performing sequential single axis vibration test with SISO and MIMO control strategies. Moreover, the work provides a detailed study followed by practical examples on how to better exploit the evident potential of MIMO control strategy for definitely avoiding cross axis vibration control problems.

Keywords

Single Axis Vibration Testing, MIMO Control, SISO Control, Random Vibration, Cross Axis Vibrations.

Introduction

Random vibration control tests are conducted in the laboratory to simulate with high degree of accuracy the vibration environment that a specimen has to withstand during its life cycle (Lalanne 2014). For decades, single axis shakers have been the only available excitation systems. Therefore, in order to recreate in the laboratory the multi-directional nature of a real vibration environment, the sequential single axis random vibration control testing has been established as a standard method (United States Department of Defence 2008; Ministere de la Defense - Delegation Generale pour l'armement 1986; International Organization for Standardization 2012). In such tests, the test specimen is sequentially rotated along three orthogonal axes and excited in one direction at a time by exploiting a single axis shaker. The Single-Input Single-Output (SISO) control strategy is the simplest technique for carrying out these types of tests (Bendat and Piersol 2011): the control algorithm tunes the input voltages to the shaker (Single-Input) in order to excite the specimen with the required Power Spectral Density (PSD) profile (Single-Output).

However, the methodologies for performing random vibration control tests are constantly evolving thank to the enormous advances in control technologies. Over recent years, the avant-garde test facilities have the capability to address simultaneous multi-axial vibration testing by exploiting Multi-Input Multi-Output (MIMO) control techniques (Smallwood and Paez 1993; Underwood et al. 2017; Zheng et al. 2019). Several publications show the advantages in replicating the in-service conditions by exciting the test specimen in more directions simultaneously (Whiteman and Berman 2001; Daborn et al. 2014; Mršnik et al. 2016; Roberts and Ewins 2018; Musella et al. 2019).

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Even if the benefits of the MIMO control strategy are widely accepted by the research community, most of the current industrial practice is strongly relying on SISO control that still remains the nowadays standard technique for vibration control testing.

This research wants to highlight one of the potential limitation of SISO control strategy to perform single axis random vibration testing. With the SISO control strategy, only the PSD profile on the drive axis of vibration is feedback controlled, while the vibration levels along the two axes orthogonal to the main axis (called *cross axes* or *off axes*) can only be measured. Nevertheless, the presence of uncontrollable cross axis vibrations could compromise the validity of the single axis test. In some cases, the coupling between the excitation system and the test specimen can cause cross axis excitations that alter the dynamic behaviour of the test specimen by inducing different stress state and unexpected failure modes. In accordance with Standard practice (United States Department of Defence 2008), if the amplitude of the cross axis PSD is more than 0.2 times the amplitude of the required PSD on the drive axis of vibration, the single axis test should be deemed to be invalid. In order to overcame the SISO control limitations, the use of more advanced MIMO control strategies could be an effective option. The MIMO control configuration guarantees to accurately replicate the required PSD profile on the main axis of vibration and to simultaneously control the cross axis vibration levels below the acceptable thresholds.

The final objective of this research is thus to point out and to critically analyse the different capabilities of SISO and MIMO control strategies for performing single axis vibration control tests. In order to compare the two control techniques, a test campaign has been carried out using two different test facilities with the same performance characteristics: a single axis shaker and a 3-DoF (Degrees of Freedom) shaker table. The details of the test equipments and the discussion of the test results are provided in the test case section. Moreover, the following section offers a detailed overview and practical examples about the definition of the MIMO control target to be used in single axis vibration testing.

Defining the MIMO control target

Theoretical background and practical examples

The definition of the control target is the first step for carrying out any random vibration control test. In SISO control configuration, this procedure results to be easy and direct. The control target is just the PSD profile that needs to be reproduced at the single output location. Typical synthesized PSD profiles are provided by the Standards according to the specific specimen to be tested (United States Department of Defence 2008; Ministere de la Defense - Delegation Generale pour l'armement 1986; International Organization for Standardization 2012). Otherwise, the test specifications could come directly from field measured data and the required PSD profile is defined by following Mission Synthesis procedures based on fatigue damage spectrum equivalence (Lalanne 2014).

Nevertheless, the control target definition could be more challenging in case of MIMO control configuration. When multiple outputs need to be controlled simultaneously, besides the vibration levels for each control output, the cross-correlation between each pair of the outputs has to be defined (Peeters and Debille 2002; Underwood 2002). The MIMO control target is thus a full Spectral Density Matrix (SDM) in the frequency band of interest. The diagonal terms of the reference SDM are the reference PSDs and the off-diagonal terms are the reference CSDs (Cross Spectral Densities) (United States Department of Defence 2014).

The reference CSDs can be defined starting from the respective reference PSDs and by specifying coherence and phase profiles as functions of frequency. For instance, the reference CSD between the *i*-th and the *j*-th control output can be computed as (Bendat and Piersol 2011)

$$\begin{aligned} CSD_{ij}(f) &= \left|CSD_{ij}(f)\right| e^{\mathrm{i}\phi_{ij}(f)} = \\ &= \sqrt{\gamma_{ij}^2(f)\, PSD_i(f)\, PSD_j(f)}\; e^{\mathrm{i}\phi_{ij}(f)} \end{aligned} \tag{1}$$

where γ_{ij}^2 and ϕ_{ij} are the coherence and the phase angle between the two reference outputs, respectively.

For the generation of the MIMO control target, the definition of the reference CSDs is important as much as the definition of the reference PSDs. Setting different profiles of phase and coherence for the reference CSDs means to change the way of combining the test specifications along the control output directions. As a consequence, the test specimen could be excited in completely different manners even imposing the same reference PSD.

Figure 1 gives a practical example for a two-inputs two-outputs control case. The same flat PSD profile (0.56 g_{RMS} in the frequency range [10-1000] Hz) is considered as test specification along the two control directions X and Y. The figure shows three different ways of combining the two reference PSDs: the values of coherence and phase of reference $\mathrm{CSD}_{\mathrm{XY}}$ are represented in the top of the figure; the bivariate histogram plots of the recorded acceleration signals along X and Y are depicted in the bottom of the figure, with the color bar that shows the relative number

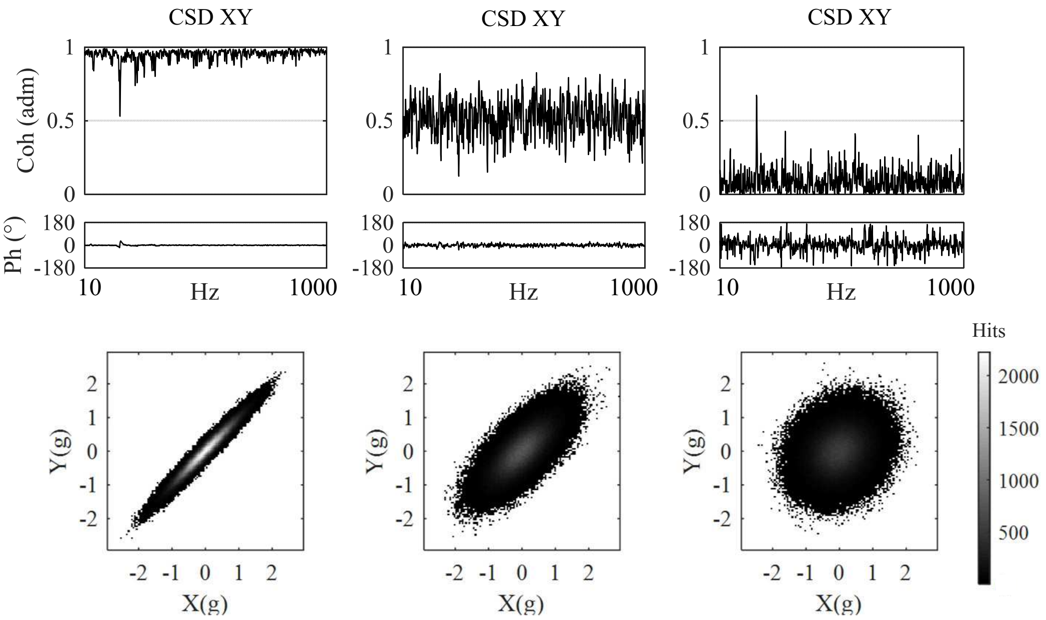

Figure 1. Coherence role for two (in phase) control outputs: $\gamma^2_{XY} = 0.98$ (left), $\gamma^2_{XY} = 0.5$ (middle) and $\gamma^2_{XY} = 0.98$ (right).

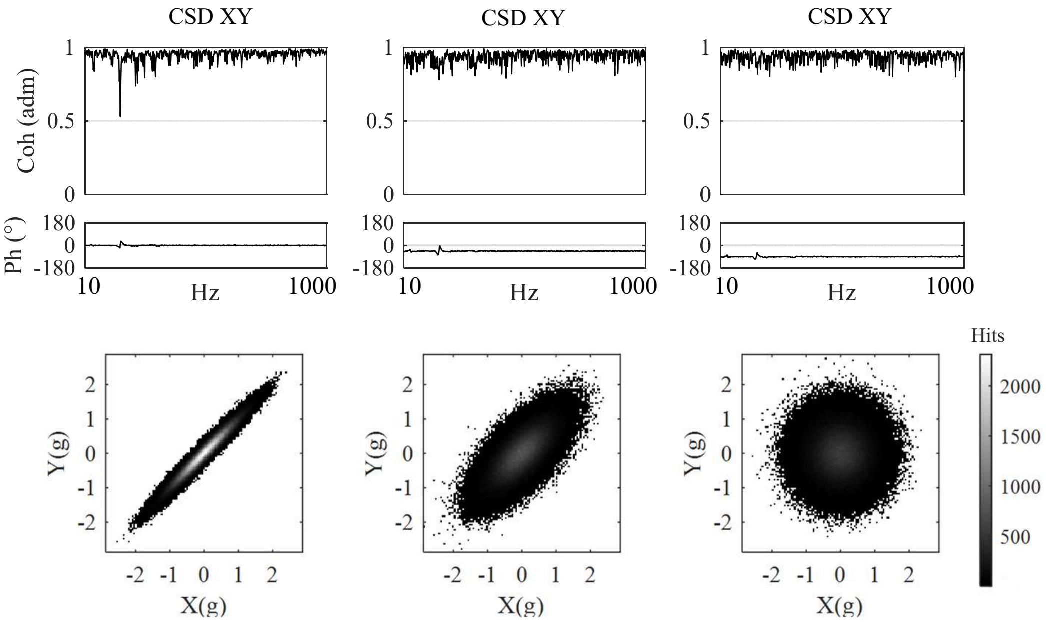

Figure 2. Phase role for two (fully coherent) control outputs: $\phi^2_{XY} = 0^o$ (left), $\phi^2_{XY} = 45^o$ (middle) and $\phi^2_{XY} = 90^o$ (right).

Table 1. Breakpoints of the reference PSDs used in the main axis of vibration for the three sequential test configurations (Transversal, Longitudinal and Vertical)

PSD$_{TRANS}$ $(0.817\ g_{RMS})$															
Hz	10	40	120	125	190	195	235	240	320	325	345	350	430	435	450
$\frac{g^2}{Hz}$ (e^{-3})	0.88	2.2	2.2	1.2	0.27	0.56	0.56	0.87	0.87	0.56	0.46	3.0	3.0	1.8	1.6
PSD$_{LONG}$ $(0.577\ g_{RMS})$															
Hz	10	35	105	110	175	180	260	265	275	280	360	365	390	395	450
$\frac{g^2}{Hz}$ (e^{-3})	0.23	0.56	0.56	0.49	0.35	0.97	0.97	0.56	0.56	0.97	0.97	0.70	0.70	1.1	1.1
PSD$_{VERT}$ $(0.535\ g_{RMS})$															
Hz	10	25	30	110	115	175	180	260	270	310	330	410	420	450	
$\frac{g^2}{Hz}$ (e^{-3})	0.008	0.008	0.43	0.43	0.22	0.22	1.4	1.4	0.37	0.37	0.88	0.88	0.43	0.43	

Table 2. Values gRMS of the recorded control signals during sequential single axis vibration test; Combination I) single axis shaker - SISO control, Combination II) 3-DoF shaker table - SISO control and Combination III) 3-DoF shaker table - MIMO control.

		Combination I	Combination II	Combination III
Trans. Conf.	X (cross)	0.225 g_{RMS}	0.281 g_{RMS}	0.122 g_{RMS}
	Y(cross)	0.156 g_{RMS}	0.153 g_{RMS}	0.068 g_{RMS}
	Z (main)	0.818 g_{RMS}	0.823 g_{RMS}	0.804 g_{RMS}
Long. Conf.	X (cross)	0.104 g_{RMS}	0.113 g_{RMS}	0.059 g_{RMS}
	Y (cross)	0.137 g_{RMS}	0.150 g_{RMS}	0.037 g_{RMS}
	Z (main)	0.580 g_{RMS}	0.580 g_{RMS}	0.590 g_{RMS}
Vert. Conf.	X (cross)	0.096 g_{RMS}	0.102 g_{RMS}	0.030 g_{RMS}
	Y (cross)	0.156 g_{RMS}	0.166 g_{RMS}	0.037 g_{RMS}
	Z (main)	0.540 g_{RMS}	0.535 g_{RMS}	0.547 g_{RMS}

Figure 3. Three DoF shaker table at the University of Ferrara: Dongling 3ES-10-HF-500.

of hits. In particular, the figure highlights the effects of the coherence variation from high coherence ($\gamma^2_{XY} = 0.98$) to low coherence ($\gamma^2_{XY} = 0.05$) for in phase control outputs ($\phi_{XY} = 0^o$). It can be noted that, in case of fully coherent (in phase) control outputs, the data distribution is perfectly oriented toward the bisector of the two control directions. This combination is practically identical to a single output test 45^o inclined. Moreover, the more the coherence is low, the more the phase value loses in relevance: the data dispersion increases around the bisector until reaching a circle data distribution (uncorrelated control outputs). However, Fig. 2 shows that it can be possible to obtain similar results by keeping fully coherent control outputs ($\gamma^2_{XY} = 0.98$) and playing with the phase values. The data distribution moves from an elliptical to a circular shape by simply setting 45^o and 90^o out of phase fully coherent control outputs.

The previously described examples underline how the choice of the phase and coherence profiles could be decisive in order to properly combine the test specifications and to correctly excite the test specimen. Due to the key role for any successful MIMO control test, the definition of the MIMO control target is still being investigated in numerous publications (Smallwood 2010; Underwood et al. 2011; Martin and Schneider 2017; Musella et al. 2017, 2018).

Experimental approach for single axis random vibration testing

This paragraph describes how to define the MIMO control target for performing a true single axis vibration test. The MIMO control strategy is used in order to feedback control the main axis of vibration and to simultaneously force the cross axis levels below the acceptable thresholds. Therefore, a three-outputs control configuration is at least required, i.e. one control output for each of the three orthogonal directions. Typically, the only available test specification corresponds to the PSD profile that needs to be replicated on the main axis of vibration. In order to complete the control target, the user has to specify the PSD profiles of the two cross axes and to define the coherence and phase values for combining the three reference PSDs.

Following the previously described examples of Fig. 1 and Fig.2, a straight line movement is generated by in phase and fully coherent control outputs. Therefore, in order to perform a true single axis vibration test, it is necessary to set zero phase and high coherence for all the reference CSDs and to rescale down the reference cross axis PSDs as

$$PSD_{Cross}(f) = \beta * PSD_{Main}(f) \qquad (2)$$

where β is the scale factor that guarantees a data distribution perfectly oriented along the main axis of vibration.

The following test case explains the effects of imposing different values of β for the definition of the cross axis reference PSDs. The test objective is to perform a single axis vibration test by simultaneously control the three orthogonal direction (X, Y and Z) of a three axial accelerometer. The control accelerometer is fixed on the bare head expander of

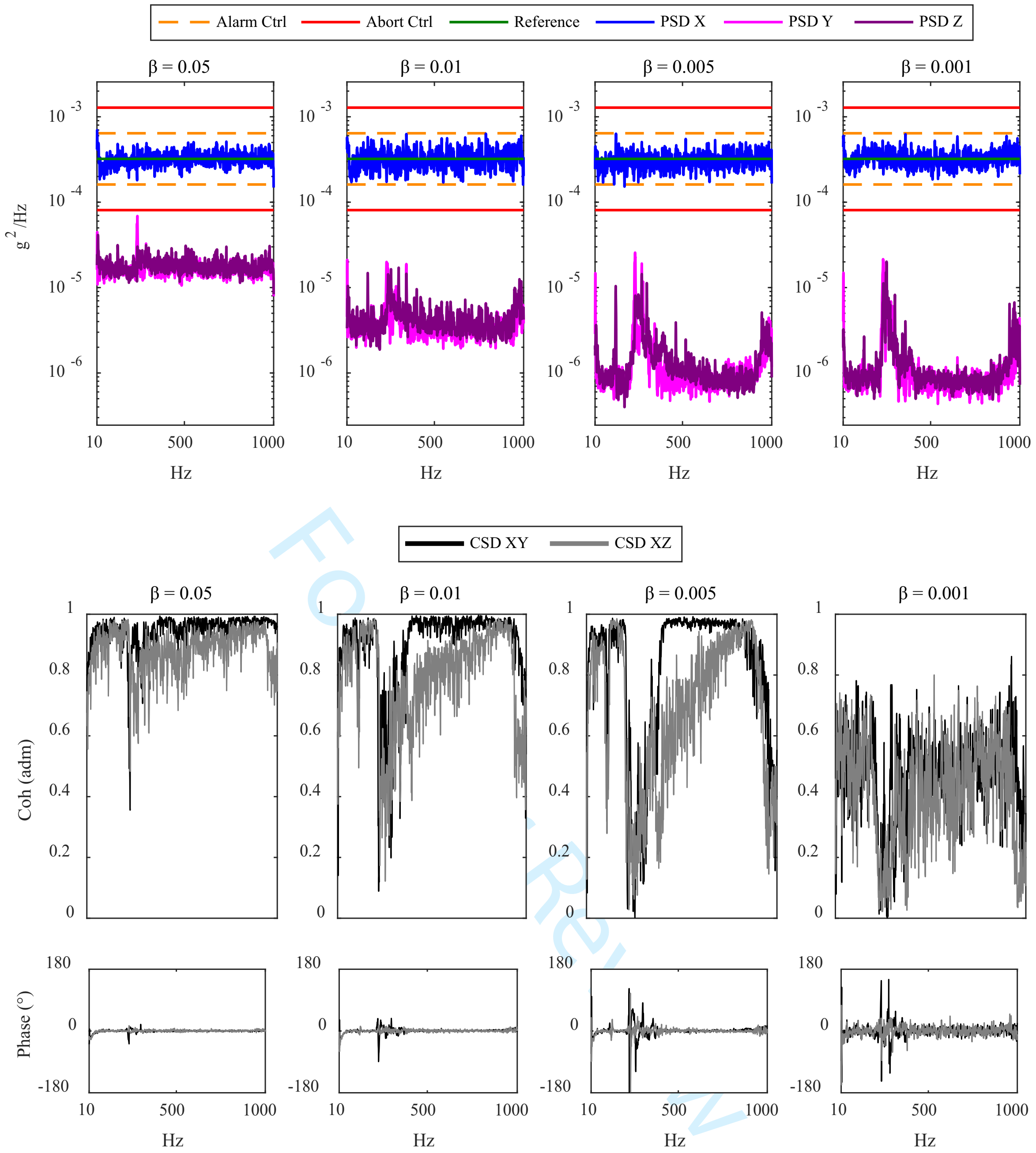

Figure 4. Effects of the scale factor β used for defining the cross axis reference PSDs: measured PSDs in the three control outputs (top); coherence and phase values of the two measured CSDs (bottom).

the 3 DoF (Degree of Freedom) shaker table shown in Fig. 3 (technical details of the shaker are provided in following section). A flat PSD profile of 0.56 g_{RMS} in the frequency range [10-1000] Hz is the test specification along the main axis of vibration (axis X). Directions Y and Z correspond to cross axes.

Figure 4 shows the control results obtained with four different scale factors β. In particular, the PSDs measured along axes X, Y and Z are depicted in the top of the figure, i.e. the blue, magenta and purple curves respectively. For the main axis of vibration, the dashed-orange lines and the red lines are the alarm and abort control limits fixed at $\pm 3dB$ and $\pm 6dB$ from the reference (green line). The bottom of the figure shows instead the coherence and the phase values deriving from the combination of the three control outputs. Figure 4 emphasizes some remarkable results. Clearly, there is a physical control limit below which the cross axis PSDs cannot be further lowered, even imposing lower scale factors. Moreover, the lower the scale factor β, the higher the deviation from the in phase and fully coherent outputs scenario. This means that, going beyond the physical control limit by setting too low scale factors does not lead to any gain in terms of cross axis PSD reduction, rather it worsens the quality of the single axis vibration test. The bivariate

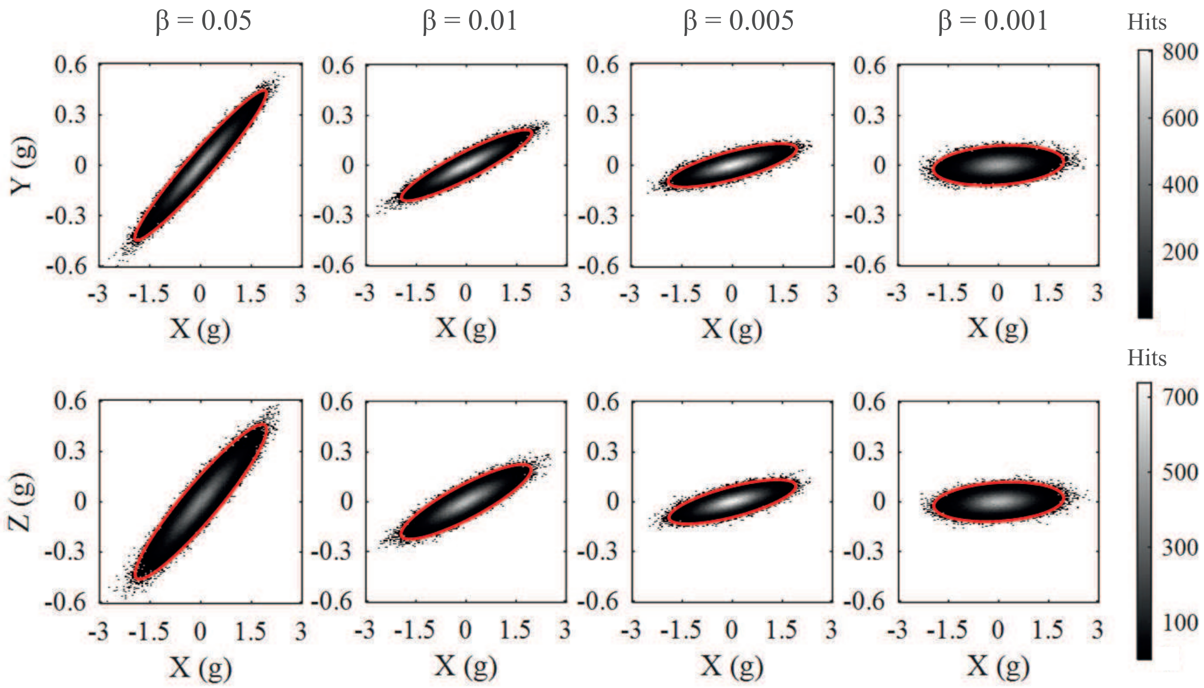

Figure 5. Effects of the scale factor β used for defining the cross axis reference PSDs: bivariate histogram plots between the measured acceleration signals along main axis X and cross axis Y (top); main axis X and cross axis Z (bottom).

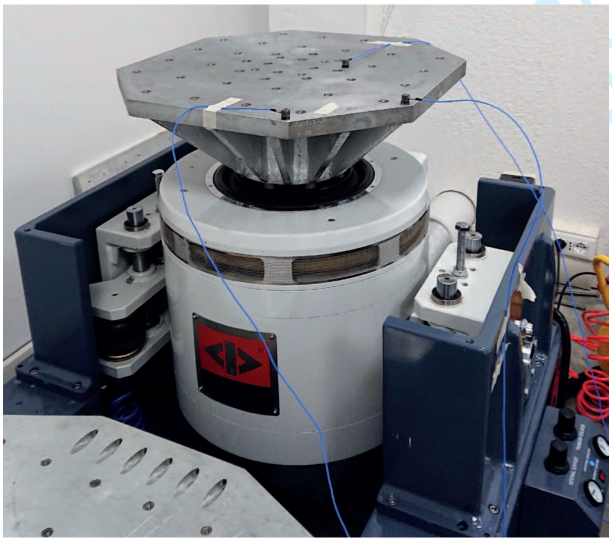

Figure 6. Single axis shaker at G.S.D. Srl of Pisa: Dongling ES-10-240.

histogram plots between the acceleration signals, shown in Fig. 5, confirm the previous results. The color bar shows the relative number of hits and the red line is the 3σ confidence ellipse, the region that contains the 99.7% of all samples. The case of $\beta = 0.001$ has the same cross axis acceleration levels with respect to the case of $\beta = 0.05$, but a more spread data distribution due to lower coherence values between the control outputs.

Unfortunately, the a priori knowledge of the best scale factor β to be used for defining the cross axis reference PSDs is practically impossible. It strongly depends on the specific interactions between excitation system and test specimen, combined with the controller capabilities to perform the actual test. The proper scale factor can significantly vary from case to case. Therefore, some preliminary tests could be useful in order to tune the control parameters and to properly define the MIMO control target.

Test case: sequential single axis random vibration control

Experimental setup

In order to compare and to point out the different capabilities of SISO and MIMO control strategies, the same series of tests has been carried out using two different test facilities: the single axis shaker Dongling ES-10-240 at G.S.D. srl of Pisa and the 3-DoF shaker table Dongling 3ES-10-HF-500 at the University of Ferrara, shown in Fig. 6 and Fig. 3 respectively. Both the vibration test systems are electrodynamic and air cooled shakers of 10 kN rated force. If the single axis shaker is a well known and widely used technology, the three-axial shaker table at the University of Ferrara is a more advanced vibration test system. This avant-garde actuation system adopts an hydraulic orthogonal decoupling bearings unit for connecting three independent shakers. The patented technology allows the simultaneous excitation in three orthogonal directions.

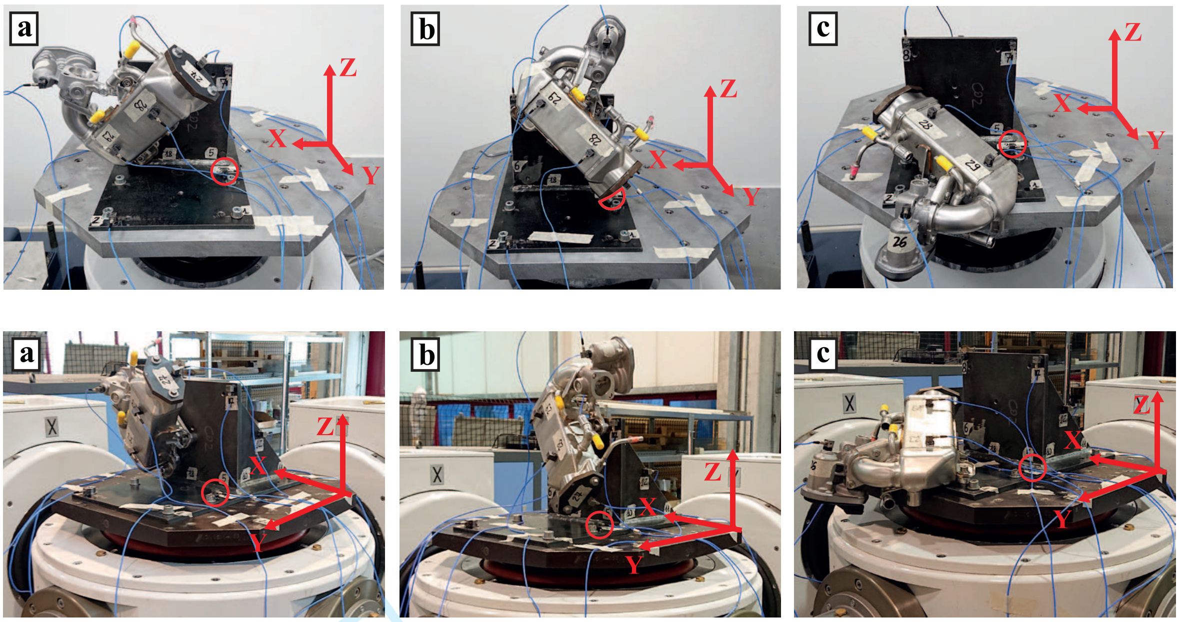

Figure 7. Test configurations for sequential single axis vibration test with the single axis shaker (top) and with the 3-DoF shaker (bottom): a) transversal test configuration; b) longitudinal test configuration; c) vertical test configuration. The red circle highlights the control accelerometer location.

The same sequential single axis vibration test has been carried out in three different combinations of excitation system and vibration control technology:

Combination I) single axis shaker with SISO control strategy

Combination II) 3-DoF shaker table with SISO control strategy

Combination III) 3-DoF shaker table with MIMO control strategy

It is worth to notice that for Combination II), the 3-DoF shaker table can be used as single-input excitation system by shutting down the power supply of two shakers.

The test specimen is an Exhaust Gas Recirculation (EGR) valve, an automotive component used to reduce the emissions in internal combustion engines. The sequential single axis vibration test is performed by exploiting a specifically designed fixture that allows the sequential rotation of the EGR valve in three test configurations: transversal configuration, longitudinal configuration and vertical configuration, shown in Fig. 7 a), b) and c) respectively. For all the test configurations, axis Z is the main axis of vibration where the single axis test specification should be replicated. Therefore, axes X and Y correspond to the cross axes of vibration that are feedback controlled only with MIMO control configuration by using the 3-DoF shaker table, i.e. Combination III). The three-axial control accelerometer is mounted on the fixture at the head expander mounting point (highlighted with a red circle in Fig. 7). Additional 13 three-axial accelerometers are mounted on the system as measurement points: 4 on the EGR valve and 9 on the fixture.

The single axis test specifications come from field measured data after being averaged, smoothed and enveloped for representing the operational vibration environment of the EGR valve. Table 1 summarizes the breakpoints of the reference PSDs to be replicated in the main axis of vibration for the three sequential test configurations.

The Siemens SCADAS Mobile SCM202V (V8 input and DAC4 output modules) is used as data acquisition system and Simcenter Testlab as vibration control software.

Test results

Figure 8 shows the control point results for the sequential single axis vibration test carried out in the three previosly described control test combinations (Combinations I, II and III). For the main axis of vibration (axis Z), the blue curves are the measured PSDs, the dashed-orange lines and the red lines are the alarm and abort control limits fixed at $\pm 3dB$ and $\pm 6dB$ from the references (green lines). The purple and magenta curves are the measured PSDs along cross axes X and Y, respectively. The dashed-black lines represent the acceptable thresholds for the cross axis vibration levels (0.2 times the reference PSDs on the main axis of vibration (United States Department of Defence 2008)). Figure 8 clearly highlights the limitations of SISO control strategy to perform a true single axis vibration test. In both Combinations I and II, although the test

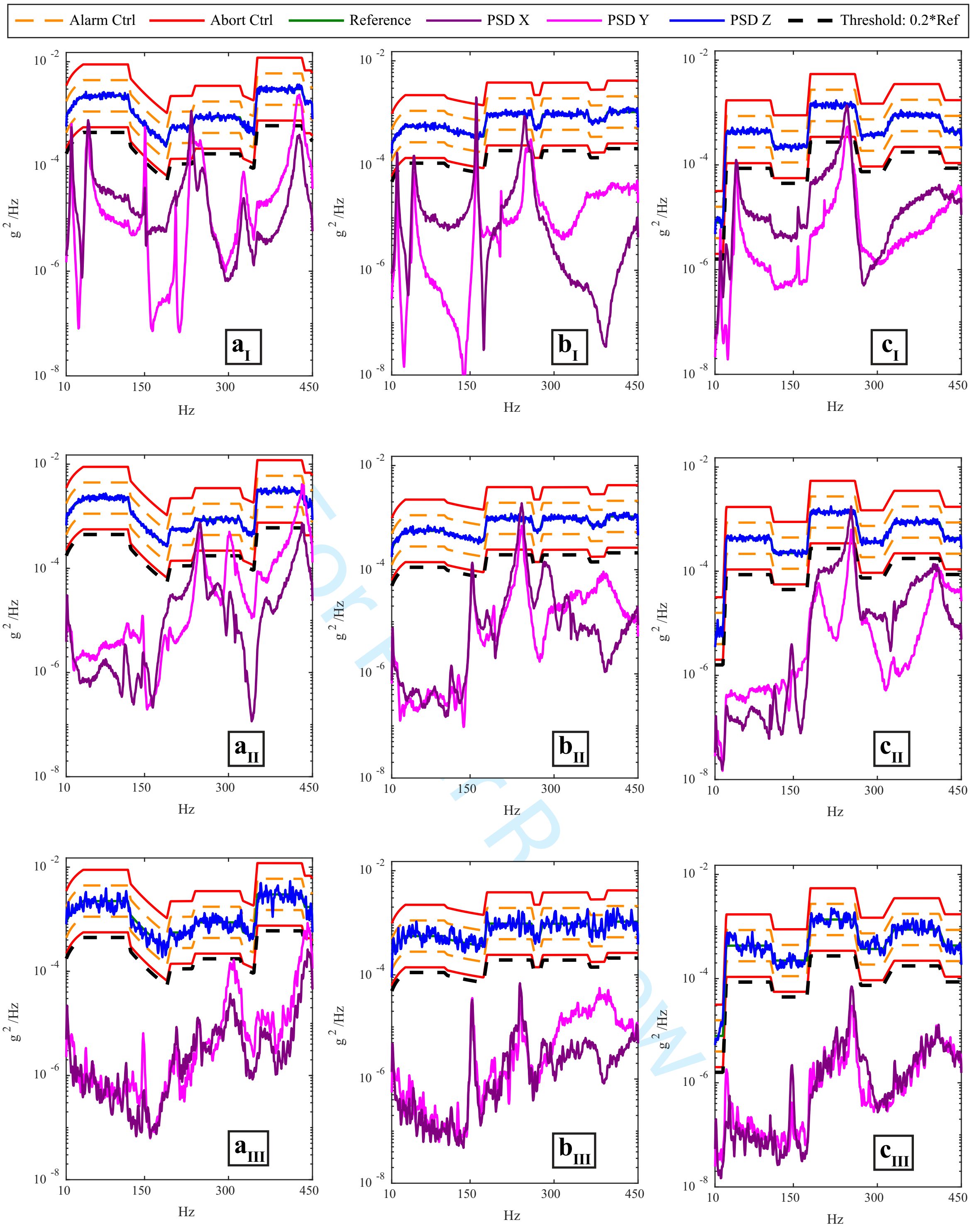

Figure 8. Control point results for sequential single axis vibration test: a) transversal test configuration; b) longitudinal test configuration; c) vertical test configuration. Subscript: I) single axis shaker - SISO control, II) 3-DoF shaker table - SISO control and III) 3-DoF shaker table - MIMO control.

specification along the main axis of vibration is perfectly replicated, at some frequencies the cross axis PSDs exceed the acceptable threshold (in some cases they even exceed the main axis PSD). In accordance with the Standard's rules, both sequential single axis tests carried out with SISO control strategy must be considered invalid. The MIMO control configuration instead, even if introduces a slightly lower control quality in the main axis of vibration (always within the control abort limits), keeps the feedback control of the cross axis responses towards low levels. The cross axis peaks are significantly reduced or even eliminated.

The three-dimensional scatter plots deriving from the control point acceleration signals, shown in Fig. 9, give a further remarkable insight of the better behaviour of

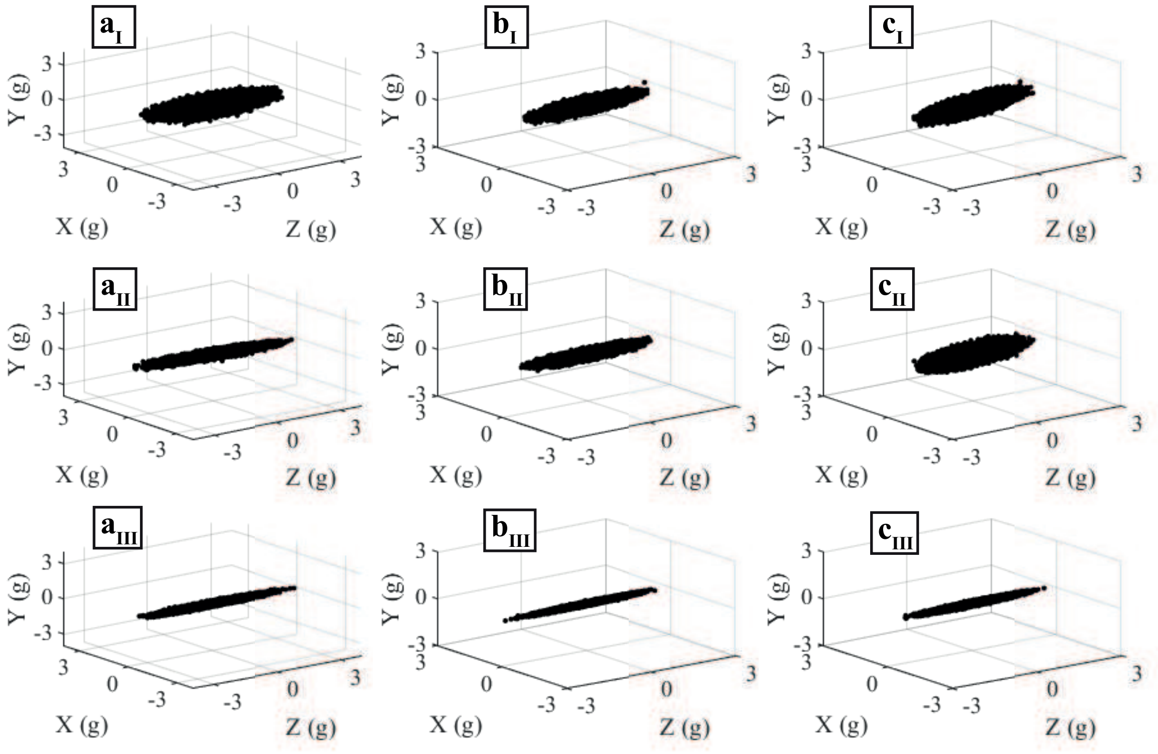

Figure 9. Three-dimensional scatter plots between the control point acceleration signals: a) transversal test configuration; b) longitudinal test configuration; c) vertical test configuration. Subscript: I) single axis shaker - SISO control, II) 3-DoF shaker table - SISO control and III) 3-DoF shaker table - MIMO control.

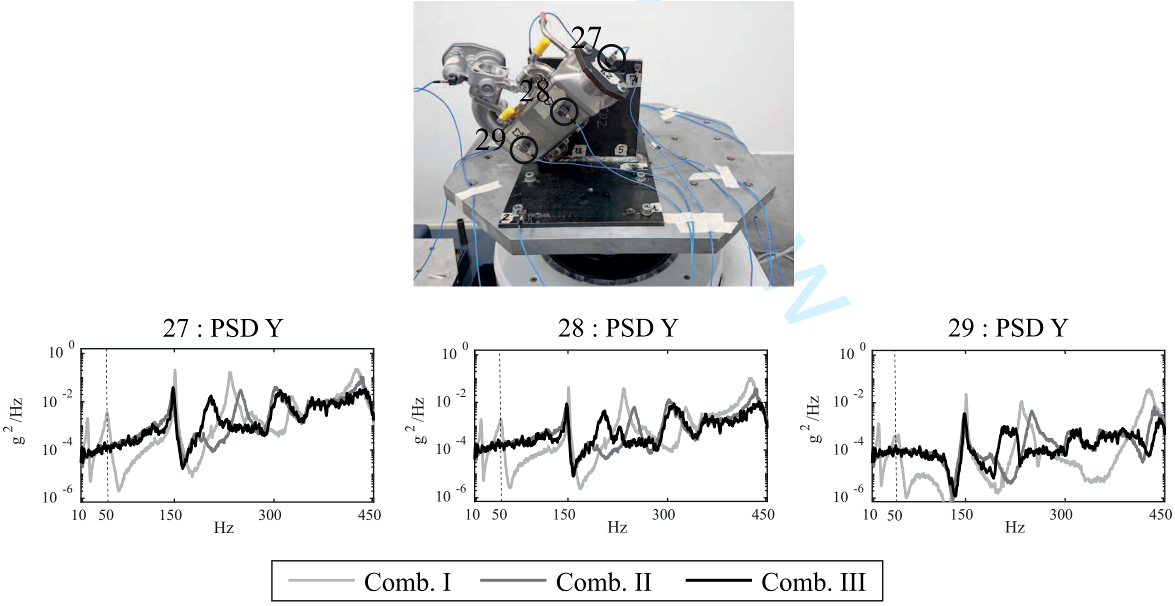

Figure 10. Measurement point results for single axis vibration test in transversal configuration: Comb. I) single axis shaker - SISO control, Comb. II) 3-DoF shaker table - SISO control and Comb. III) 3-DoF shaker table - MIMO control.

the MIMO control strategy on globally limiting the cross axis vibrations. Combination III offers a high straight line distribution of the data along the main axis of vibration, thus ensuring to excite the test specimen in the effective single axis testing manner. Moreover, Tab. 2 provides the gRMS values of all recorded control signals. The values confirm the previous results, i.e. Combination III guarantees at least one-half lower cross axis values with respect to other test combinations.

The evident different capability of SISO and MIMO control strategies to perform true single axis vibration test, inevitably implies some differences on the dynamics

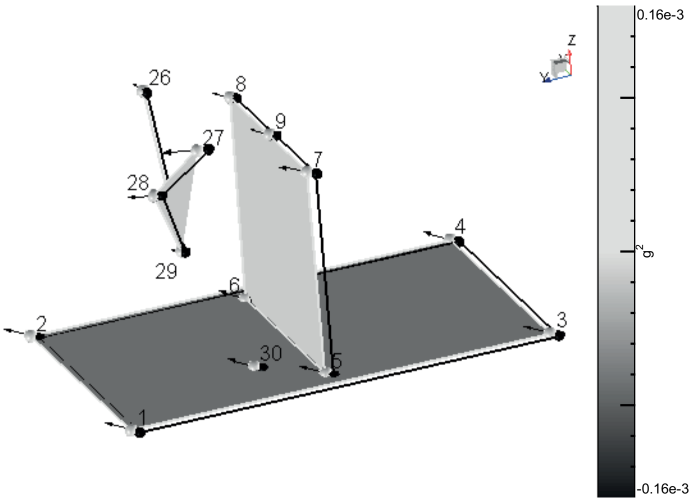

Figure 11. Operational Deflection Shape analysis at 49 Hz for single axis vibration test in transversal configuration with Combination I.

behaviour of the test specimen during the various control tests. Figure 10 shows the effects that uncontrolled cross axis vibrations cause on the EGR valve. For sake of brevity, the results of transversal configuration are taken as demonstrative example, but similar results can be obtained for the other test configurations. The three plots correspond to three measurement points fixed on the EGR valve, i.e. points 27, 28 and 29 (highlighted with black circles in the top of the figure). The light-gray, gray and black curves are the measured PSDs for Combinations I, II and III respectively. It can be noted that the frequencies where the PSD profiles of Combinations I and II (SISO cases) do not match the profile of Combination III (MIMO case), are the same frequencies where uncontrollable cross axis peaks occur at control point (Fig. 8). For these critical frequencies, an Operational Deflection Shape (ODS) analysis has been done in order to provide additional insight about the nature of the mismatched peaks. An example is given in Fig. 11 for the peak at 49 Hz. The analysis highlights a rigid deflection shape mode of the entire system (EGR valve and fixture). Therefore, the recorded peak in the measurement points cannot be considered a characteristics of the EGR valve resonance, but it is a consequence of the SISO control configuration that excites the test specimen along a cross axis.

Conclusions

This work tackles the problem of high level cross axis responses during single axis vibration control test. Two different excitation systems, i.e. a single axis shaker and a 3-DoF shaker table, have been used in combination with two different control strategies: the SISO control technique (nowadays common practice) and the MIMO control technique (more advanced practice). An EGR valve has been used as the test specimen for the sequential single axis random vibration control test. The control test results clearly point out different capabilities of the two control strategies. In particular, SISO control configuration results to be ineffective when the system dynamics is such that cross axis vibrations occur at the control point location. In some cases, the cross axis peaks are comparable with the acceleration levels on the main axis of vibration thus compromising the validity of the single axis vibration test. The use of MIMO control strategy totally overcomes these limitations by feedback controlling the cross axis vibrations towards low levels. Moreover, the work has shown the key role of the MIMO control target definition. A proper definition of the reference SDM can improve the potential of MIMO control strategy in order to definitely avoid the cross axis vibration problems. Finally, the analysis on the measurement points has verified that uncontrollable cross axis excitations can alter the dynamic behaviour of the test specimen. As a consequence, a different stress state and unexpected failure modes could occur: further research will aim to assess the influence of these phenomena on the fatigue life of the test specimen.

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Declaration of conflicting interests

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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