On the Cross Axis Responses in SISO and MIMO Random Vibration Control Testing

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Abstract. In random vibration control testing, the nowadays common practice to recreate in the laboratory the multi-directional nature of a real vibration environment is the sequential Single-Input Single-Output (SISO) control testing: the test specimen is sequentially rotated and each axis is individually excited using a single axis shaker. In SISO control configuration, just the drive axis of vibration is feedback controlled and in order to verify the validity of the single axis test, the cross axis responses (the two axes orthogonal to the main axis) should not exceed acceptable thresholds. Significant advances in test hardware and control software, in addition to test facility designed for multi-axial excitation testing, have made possible to perform single axis testing using Multiple-Input Multiple-Output (MIMO) control strategy. The MIMO control configuration allows the simultaneous control of the vibration levels on the main axis and on the two cross axes. This paper presents a part of an test campaign carried out using two different test facilities with the same performance characteristics: a single axis shaker and a three-axial shaker. The aim of the work is to compare the results in term of cross axis responses obtained performing sequential single axis test with SISO and MIMO control strategies.

1. Introduction

Vibration control tests are conducted in the laboratory to simulate with high degree of accuracy the vibration environment that a specimen has to endure during its life cycle. In random control testing, the test specification is typically provided in term of Power Spectral Density (PSD) that needs to be reproduced at a certain control channel location [1]: the control algorithm tunes the input voltages to the shaker in order to excite the test specimen with the required vibration profile. For such tests, the nowadays standard procedure is the single axis control testing where the test specimen is excited in one direction at a time [2] [3]. Therefore, the simplest way to recreate the multi-directional nature of the real vibration environment is to perform a sequential Single-Input Single-Output (SISO) control test [4]: the test specimen is sequentially rotated and each axis is individually excited using a single axis shaker. With the SISO control strategy, only the PSD profile on the drive axis of vibration is feedback controlled, while the vibration levels on the two axes orthogonal to the main axis of vibration (called *cross axes*) can only be measured. Nevertheless, in order to perform a true single axis test, the acceleration levels measured on the cross axes should not exceed acceptance thresholds. In accordance with Standard practice [2], if the amplitude of the measured PSD on one of the cross axis 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 these cases, to overcame the SISO control testing limitations, the use

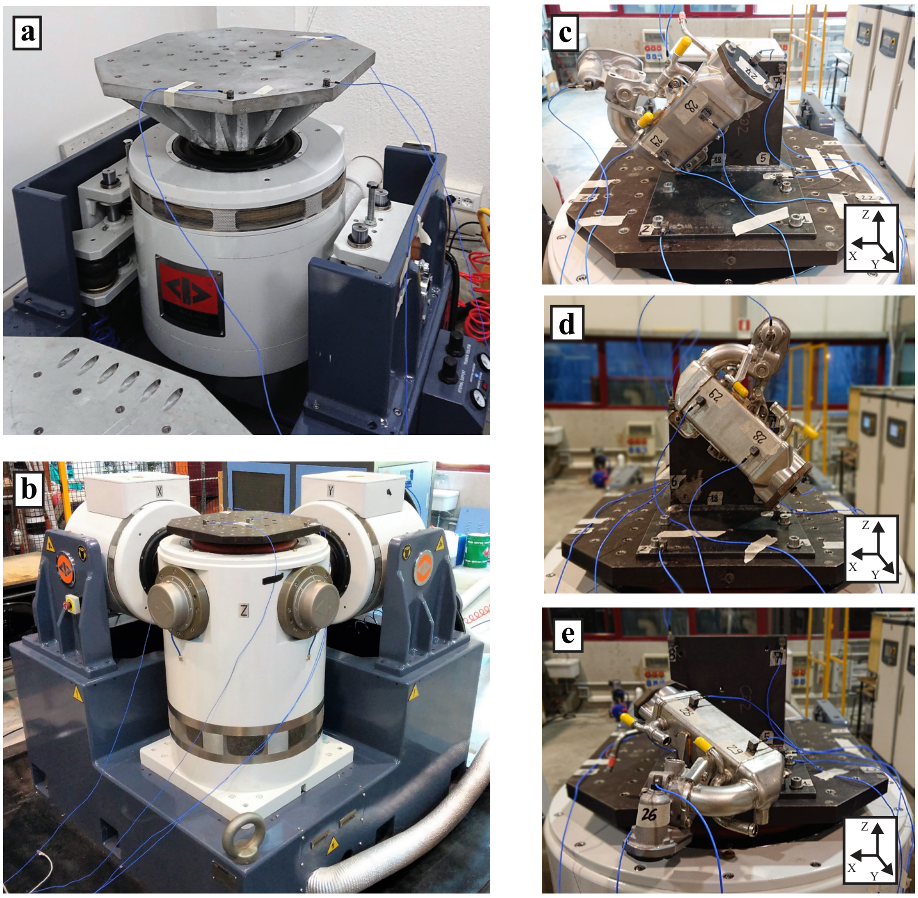

Figure 1. Test facilities: a) Dongling ES-10-240 single axis shaker at G.S.D. Srl of Pisa; b) Dongling 3ES-10-HF-500 three-axial shaker at the University of Ferrara. Sequential single axis testing configurations: c) transversal test configuration; d) longitudinal test configuration; e) vertical test configuration.

of Multiple-Input Multiple-Output (MIMO) control strategy for performing the single axis test could be an effective option [5]. If the test facility has the capability to address multi-axial vibration testing [6] [7], 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 levels to stay below the acceptable thresholds.

2. Sequential Single Axis Test Case

In order to compare and to point out the different capabilities of SISO and MIMO control strategies on performing single axis control test, 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, shown in Figure 1 a), is used in SISO control configuration. The three-axial shaker Dongling 3ES-10-HF-500 at the University of Ferrara, shown in Figure 1 b), is used in MIMO control configuration. Both the vibration test systems are electrodynamic and air cooled shakers of 10 kN rated force. 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 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

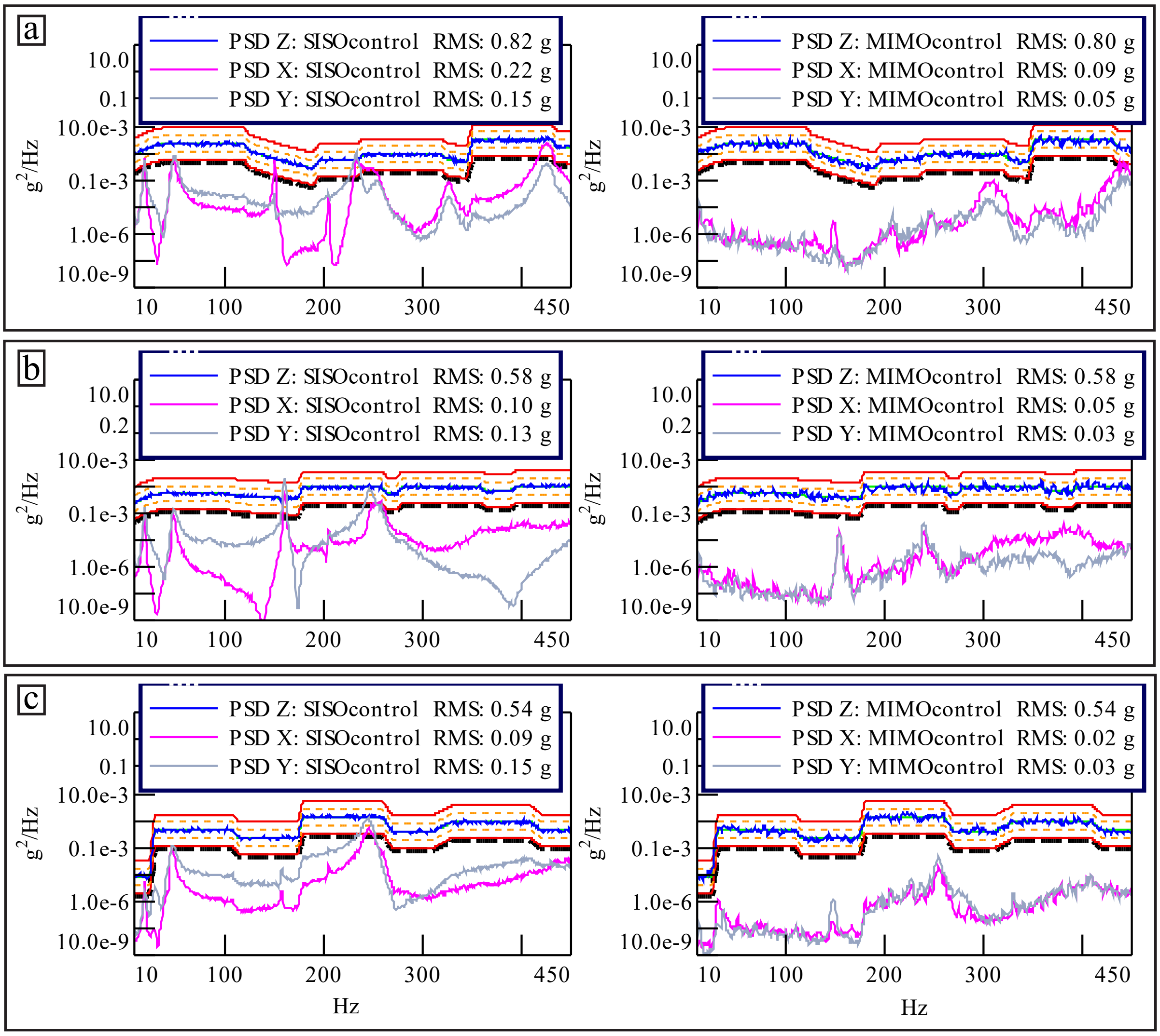

Figure 2. Control point results for the sequential single axis test with SISO (left side) and MIMO (right side) control strategy: a) transversal test configuration; b) longitudinal test configuration; c) vertical test configuration.

configuration and vertical configuration, shown in Figure 1 c), d) and e) respectively. In all the test configurations, for both the SISO and the MIMO control strategy, the Z-axis is the main axis of vibration where the single axis test specification should be replicated. Therefore, the X-axis and the Y-axis correspond to the cross axes of vibration that are feedback controlled only with the MIMO configuration by using the three-axial shaker. 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. The control accelerometer is mounted on the fixture at the head expander mounting point.

Figure 2 shows the control point results for the sequential single axis test performed with SISO (left side) and MIMO (right side) control strategy. For the main axis of vibration (Z-axis), 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), respectively. The magenta and gray curves are the measured PSDs on the cross axes of vibration, X-axis and

Y-axis, respectively. The dashed-black lines represent the acceptable thresholds for the cross axis levels (0.2 times the reference PSDs on the main axis [2]). Figure 2 clearly highlights the limitations of the SISO control strategy on performing a true single axis test. Although the test specification on the main axis of vibration is perfectly replicated, at some frequencies the PSD levels on the cross axes exceed the acceptable threshold (in some cases they even exceed the main axis PSD level). The cross axis responses have been addressed by proving that the cross axis peaks on the control accelerometer are characteristic of the EGR valve resonances and not a product of the test fixture. In accordance with the Standard's rules the SISO sequential single axis test should be considered to be invalid. The MIMO control configuration, even if it introduces a slightly lower control quality on the main axis of vibration (always within the control abort limits), allows the feedback control of the cross axis responses towards low levels. The cross axis peaks are significantly reduced or even eliminated, ensuring to excite the test specimen in the effective single axis testing manner. The comparison of the gRMS values of the cross axis responses (shown in the legends of Figure 2) gives a further remarkable insight of the better behaviour of the MIMO control strategy on globally limiting the cross axis vibrations.

3. Conclusions

This paper tackles the problem of the cross axis responses on performing single axis control test. A sequential single axis control test has been carried out exploiting two different test facilities: a single axis shaker in SISO control configuration (the nowadays common practice) and a three-axial shaker in MIMO control configuration (the more advanced practice). An EGR valve has been used as a test specimen. The control test results clearly point out the different capabilities of the two control strategies. In particular, the SISO control configuration results to be ineffective when the test specimen dynamic is such that cross axis resonances occur at the control point location. At resonance frequencies, the peaks on the cross axes are comparable with the acceleration levels on the main axis of vibration thus compromising the validity of the single axis test. The use of MIMO control strategy totally overcomes these limitations by feedback controlling the cross axis PSDs toward low levels. The promising results shown in this paper are just a small part of an extensive test campaign. A subsequent paper will present deeper analysis on the effects that the high acceleration levels on the cross axes cause on the test specimen. Moreover, the future work will provide a detailed study on how to better exploit the evident potential of MIMO control strategy for definitely avoiding the cross axis response problems in single axis control testing.

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