Combining Electromagnetic and Piezoelectric Actuators for Control of High Frequency Random Vibration

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1. Introduction

Electromagnetic shakers are commonly used to reproduce the motion of a test part under environmental conditions. These tests can vary greatly in frequency and amplitude depending on the desired environment. To achieve low frequency environments, shakers must be capable of large displacements and hence require large armatures. However, at high frequencies large forces are required to move the armatures and low frequency resonances may be excited, making it difficult to replicate the desired environments. A prior study of electromagnetic shakers done by DeLima et. al. [1], showed large variability between shakers at high frequencies due to higher order modes of the armatures. Furthermore, the shaker resonances and anti-resonances can often hinder the controllability of the system. The resonances require less force and voltage to achieve the desired environment, but rather can make it more challenging for the control system to match the desired environment. On the other hand, anti-resonances are more problematic because they represent frequencies where the voltage input to the shaker causes little motion, hence requiring driver voltage levels above the controller capacity which can cause the test to abort or result in damage to the shaker. A similar method to that suggested by Klenke et. al [2] is examined, utilizing multiple transducers with variable active ranges to yield the best system response, and demonstrates the approach using real actuators.

The work presented in this paper is an expansion of the work done by Singh et. al [3]. In this paper, the use of Multi-Input Multi-Output Active Vibration Control (MIMO AVC) is explored using an electromagnetic shaker in conjunction with piezoelectric actuators to counter the anti-resonances as well as extend the frequency range of the test. The shaker used for this case study is the LDS V830 and is coupled with the CEDRAT PPA40XL piezo actuator. These actuators yield small displacements yet large force amplitudes and are predominantly used for high frequency vibration. Three case studies of the MIMO AVC are examined in this work: a single piezo counteracting a single anti-resonance, dual piezos actuated independently for a single test article, and four piezos mounted below a hard disk drive to seamlessly extend control to higher frequencies. The proposed approach is shown to effectively extend the environment to high frequencies while reducing the amplitude of the control signals needed for each actuator.

2. Case Studies

Prior to conducting test cases with additional piezo actuators, a single piezo was used to characterize a model of the shaker – piezo system [3], which could be used to estimate the strain in the piezo and the voltage required to move various payloads. In addition, a mock test article (a stainless-steel beam) was placed atop the piezo and shaker. The goal of this test was to evaluate the effectiveness of the hybrid shaker – piezo system in comparison to the shaker alone. In summary, a voltage reduction of 86% was observed with the hybrid system for the single piezo. This laid the foundation for testing more complicated systems with two and four piezos. For the following test cases, the system was controlled from 200 – 4500 Hz with a low pass filter placed on the shaker at 2500 Hz. The low pass filter is only used when the piezo and shaker are actuated simultaneously.

2.1 Dual Piezo

The second test case simulates a setup where a test article is connected to the shaker adapter plate using two piezo actuators that can be controlled independently. In Figure 1, the piezos and mounts are shown in red, and the test article is shown in green.

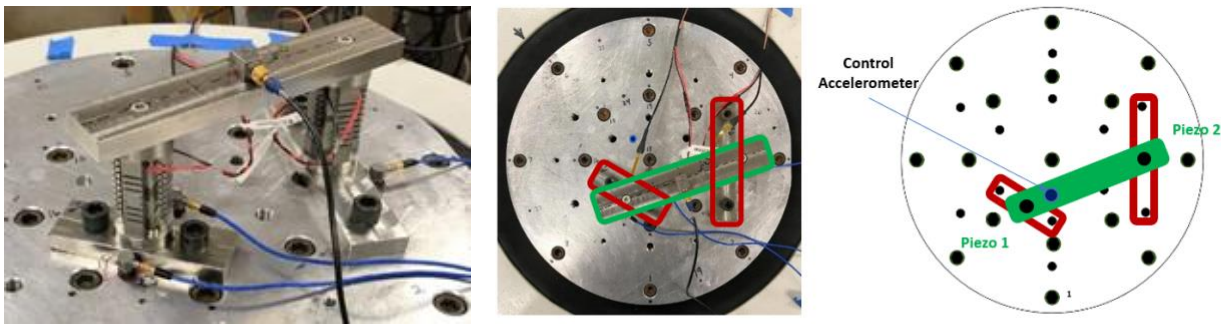

Figure 1: *Dual piezo setup*

Similar to the single piezo case, two tests were run: (1) shaker alone, and (2) shaker drive signal low pass filtered at 2.5 kHz with the piezos run independently. The piezos were placed at locations of expected anti-resonances to test a worst-case control scenario. The resulting drive voltages are presented in Figure 2. The plot on the left displays the shaker voltage PSD when the shaker was run alone, and the plot on the right displays the shaker and piezo voltage PSDs during a MIMO control run.

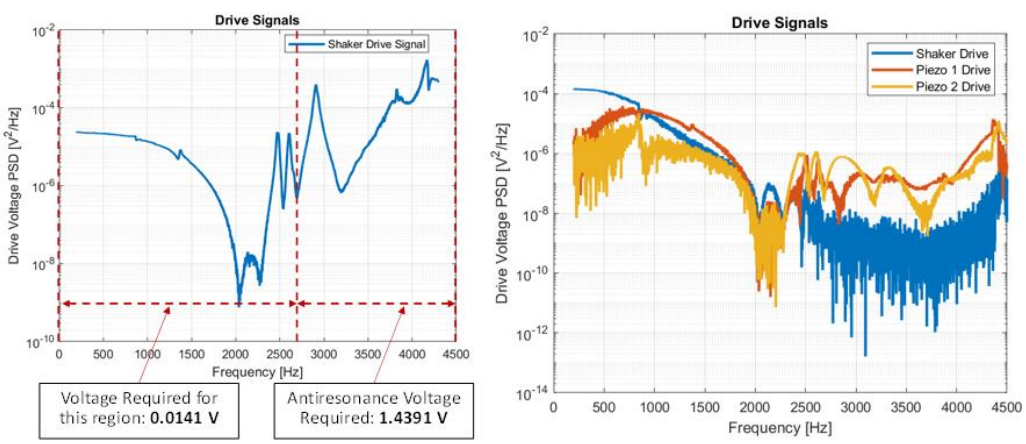

Figure 2: *(Left) Shaker drive showing antiresonance voltages, (Right) MIMO drive for dual piezo case*

As evident in the left figure, the voltage required to maintain a 10m $\left[\frac{g^2}{Hz}\right]$ flat environment increased by 1.42 V due to the antiresonance at 2.9 kHz. However, when the piezos and shaker were actuated independently, the PSD depicts a significantly lower drive voltage for the system. In this case, the shaker drive voltage required decreased to 0.45V with the piezos requiring only 0.14 V and 0.06 V. This significant drop in voltage occurs because the combined system is using each actuator it the regime where it is most effective and allows the system to reach environments with larger amplitudes.

2.2 Four Piezo Hard Drive Test

In contrast to the second test, the final test case uses involves two sets of two piezos actuated in pairs and mounted underneath a commercial Hard Disk Drive (HDD), seeking to replicate the type of configuration that might be used in industry and using a heavier payload (Figure 3). Four accelerometers were placed on the hard drive, with the control accelerometer central to the HDD assembly. The control environment for this system was decreased to a 1m$\left[\frac{g^2}{Hz}\right]$ flat profile as a result of the control difficulties due to the resonances of the test article. Figure 4 below depicts the voltage PSDs for the 0.2 – 4.5 kHz control range for (1) the shaker and (2) the shaker in conjunction with the four piezo actuators.

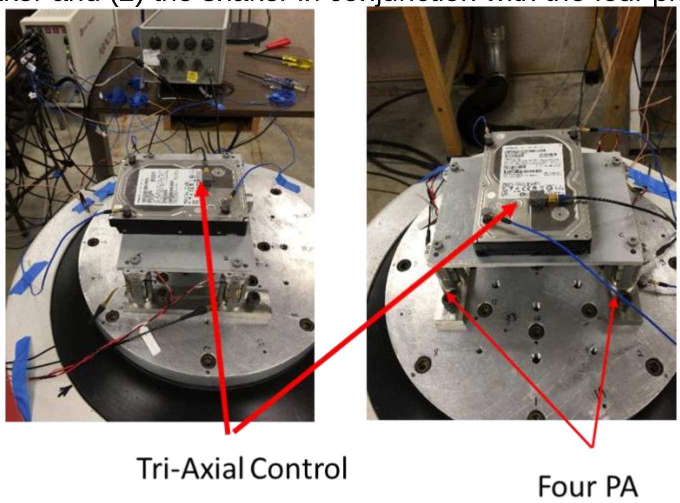

***Figure 3**: MIMO Test set up with one EM shaker and four piezoactuator*

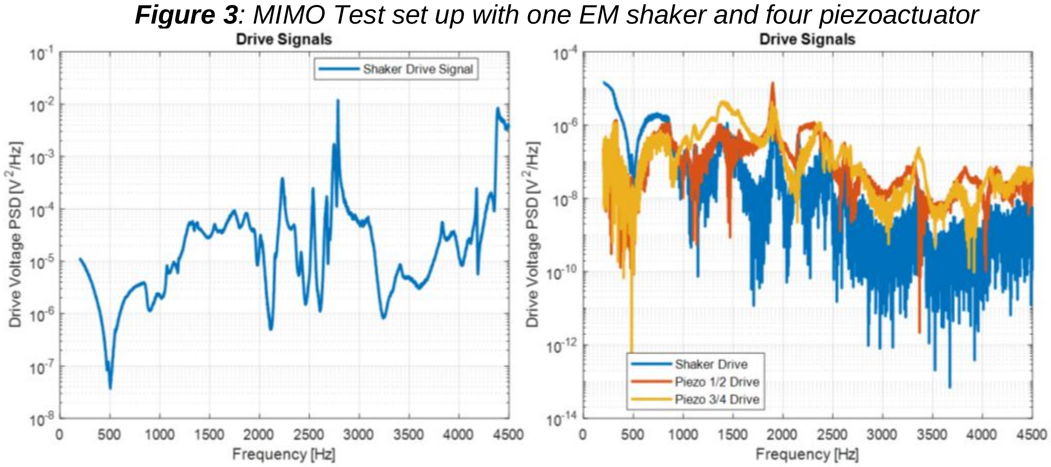

***Figure 4:** (Left) Shaker drive voltage, (Right) MIMO drive signals for the HDD case*

When the shaker was operated with the piezo actuators, the peaks in voltage shown in the left figure were decreased by a factor of 100. The shaker does not show any anti-resonances, although the piezo voltage shows one near 2kHz which may be due to an anti-resonance of the system. In any event, this setup yielded a 95% decrease in the voltage required for the shaker to maintain the desired environment.

3. Conclusion

This work explored the use of piezoelectric actuators in conjunction with an electromagnetic shaker to reproduce a random environment over a large frequency range. The large shaker was limited to low frequency environments through a low pass filter set to 2500 Hz such that the piezos could provide the high frequency environments (2500 – 4500 Hz). The voltages required to maintain an environment for each of the three cases examined in this paper are summarized below in Table 1.

***Table 1:** (Left) Shaker drive voltage, (Right) MIMO drive signals for the HDD case*

Case Study	Control Level $\left[\frac{g^2}{Hz}\right]$	Shaker Only	Shaker + Piezos	Voltage Reduction
Single Piezo	10m	3.19 V	0.44 V	86%
Dual Piezo	10m	1.45 V	0.45 V	81%
HDD Case	1m	0.94 V	0.046 V	95%

As evident, the piezos can actively mitigate the voltage requirement for the shaker while maintaining a simple control profile and extending the allowable test frequency range.

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