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DESIGN OF A TRIPOD VIBRATION ACTUATOR FOR ACTIVE REDUCTION METHODS

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ABSTRACT

Every active noise and vibration reduction system needs actuators capable of controlling the considered vibroacoustic system. Structural actuators are commonly utilized for this purpose. Inertial actuators are particularly convenient to use due to their simple audio-type amplifiers and relatively low cost. However, due to the fact that they are relying on inertia in order to generate force, they are rather inefficient for lowest frequencies. In this paper a novel concept is investigated, which adds a tripod structure to the seismic mass, allowing controlled structure displacement even for a constant voltage. Advantages and drawbacks of such a design are investigated numerically and experimentally.

Keywords: *mathematical modelling, actuation, experimental measurements*

1. INTRODUCTION

Vibration and noise control are vital aspects of many engineering applications, ranging from industrial machinery in manufacturing facilities to everyday household appliances. Effectively managing vibrations, and the noise they generate, has long been a focus of research aimed at enhancing both performance and acoustic comfort.

The most practical strategy for noise reduction is to address it directly at the source. While passive vibration and sound-absorbing materials are commonly used for this purpose, they come with significant limitations—particularly at low frequencies, where their effectiveness drops considerably. Achieving sufficient attenuation at these frequencies often requires barriers that are impractically thick or heavy. These constraints have driven growing interest in active control systems, which can effectively target low-frequency noise and serve as a valuable complement to passive solutions in areas where they fall short [1]. In recent years, various solutions have been developed [2], in which actuators are used to control the vibrations of thin barriers, thereby reducing both noise transmission and acoustic radiation. Numerous applications use thin panels and shells as sound barriers to reduce the spread of acoustic noise [3, 4]. Such an approach can be applied to many different types of structures, including aircraft fuselage [5, 6]. To improve the effectiveness of these barriers, active control systems with inertial actuators can are used. When applied to individual panels or entire device casings, active structural acoustic control (ASAC) systems exhibit superior performance [7]. However, to ensure efficient operation of an active system, the actuators must be efficiently controlling vibrations.

This paper introduces the design and preliminary analysis of a novel tripod-supported electromagnetic actuator intended to improve the effectiveness of vibration control, especially in the case of thin metal plates. Conventional electromagnetic inertial actuators often face challenges due to their single-point actuation, which can result in poor force transmission when placed on vibrational nodal lines. The proposed tripod structure overcomes this limitation by distributing the actuation force across multiple contact points, increasing the system's adaptability to various vibrational modes and enabling the use of a single actuator where traditionally multiple actuators might be required for successful vibration control.

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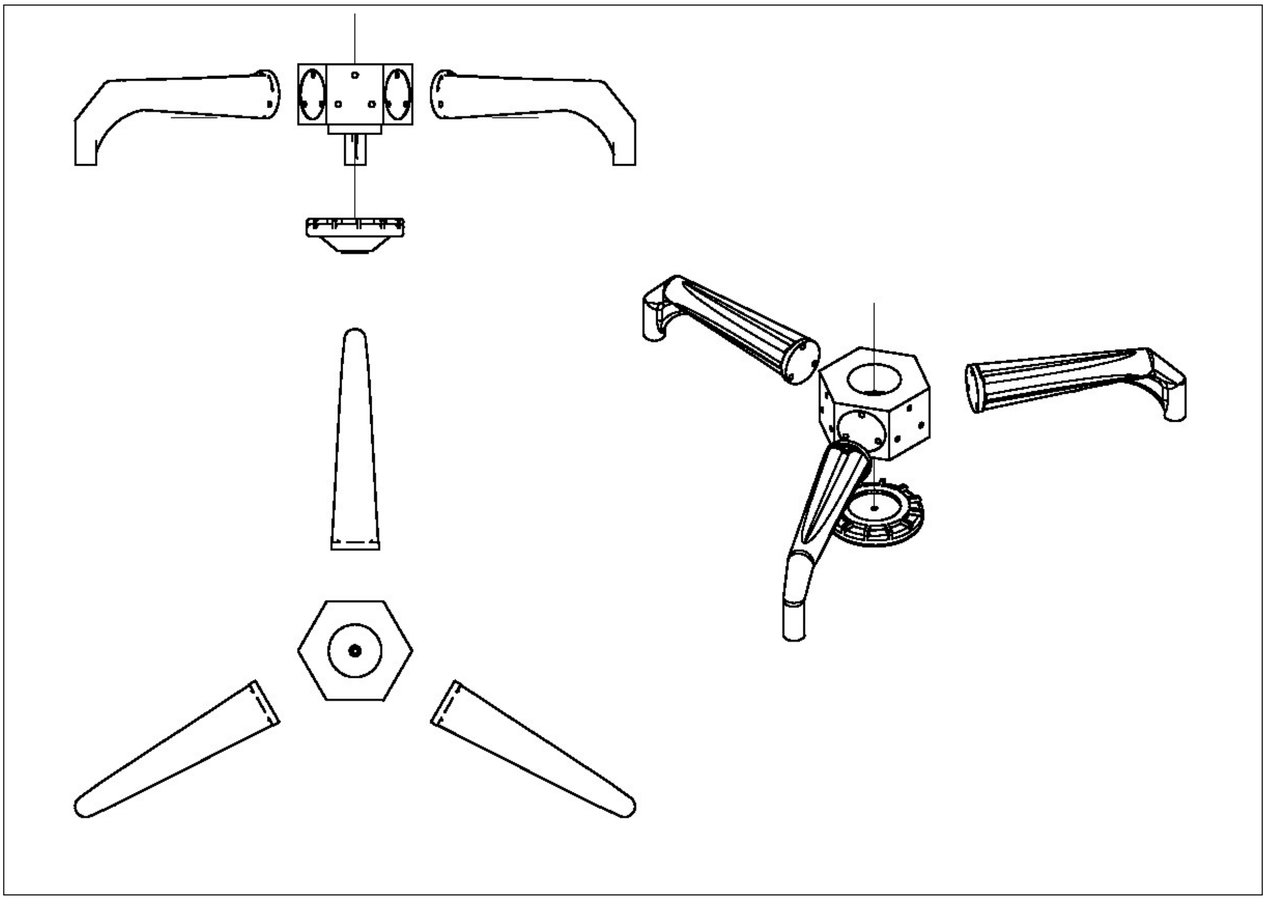

Figure 1. Schematic of a tripod structure attached to the inertial actuator. [8]

2. TRIPOD-SUPPORTED ELECTROMAGNETIC ACTUATOR

This study focuses on a novel electromagnetic actuator design that does not require a grounded frame for installation, nor relies on inertia. Instead, it can be directly mounted onto the target structure using a magnetic attachment system (employing neodymium magnets attracted to steel structures). The actuator features a unique tripod geometry, making contact with the vibrating structure at four distinct points: three legs provide mechanical support and anchorage, while a central piston, also magnetically coupled to the target structure, is actively driven by a control signal. As the piston applies force, a reactive force is simultaneously generated through the legs, resulting in a distributed stress and strain pattern across the contact area. This interaction enables the actuator, which becomes an integral part of the structure, to bend the target itself using it as the supporting frame. Conceptual schematic of the actuator is shown in Figure 1. The design is intended to deliver substantial actuation force and displacement, promoting consistent control over a distributed surface area. This minimizes the risk of ineffective operation due to the piston coinciding with a vibrational nodal line.

The prototype of the actuator, presented in Figs. 2-3, consists of 3D-printed body (the hexagonal central part), to which three 3D-printed legs are attached. To the bottom of the body, a formerly inertial actuator Dayton Audio DAEX32EP-4 if firmly attached, acting now as a voice coil actuator driving the piston.

Utilization of a ready-made inertial actuator not only solves difficulties in manufacturing our own dedicated voice coil actuator. It also allows a fair comparison of the exactly same actuator operating based on inertia principle and employing the tripod support.

Figure 2. Prototype of the actuator attached to the steel metal plate in the test rig.

3. EXPERIMENTAL MEASUREMENTS

In order to experimentally evaluate the performance of the actuator, it was attached to a thin steel plate of dimensions 420 mm $\times$ 420 mm $\times$ 1 mm. The plate was rigidly clamped to a heavy frame, as depicted in Fig. 3. The actuator has been evaluated in three configurations. The first consisted in using the actuator in its original form, basing of the inertia principle. In the second configuration, the 3D-printed hexagonal body was attached to the actuator. The actuator still operated basing of the inertia principle, but this test was done of investigate the impact of adding an extra mass to the actuator. Finally, in the third configuration, the legs have been attached, altering the actuator's operating principle. The actuator, in this paper, was always mounted centrally on the plate.

Two main measurement series were done for each aforementioned configurations. In the first series, the actuator excited the plate with a frequency sweep, generating single tone at a time, in the range between 20 Hz and 500 Hz, with an increment of 2 Hz. The vibrations of the excited plate were measurement with a laser vibrometer PDV-100 centrally, at the location of the actuator's piston. Based on this series, both excitation efficiency and non-

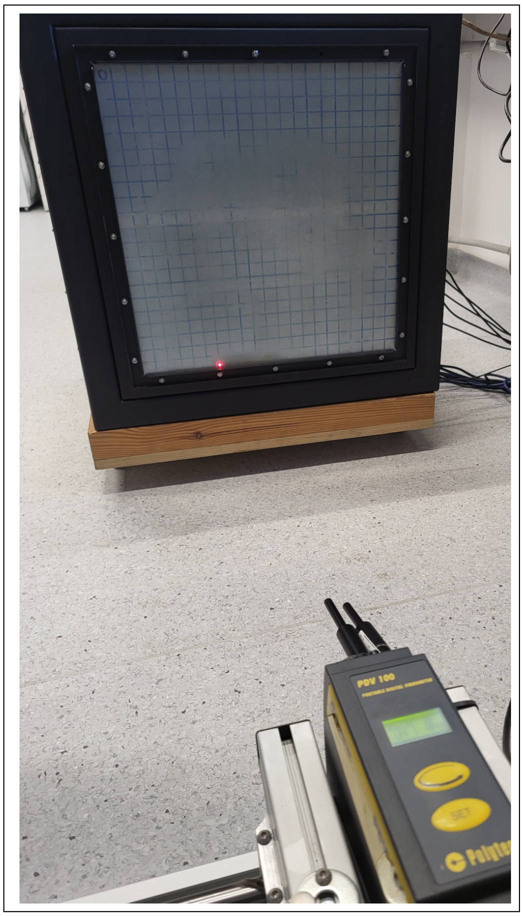

Figure 3. Other side of the steel metal plate, which vibrations are measured with a laser vibrometer PDV-100.

linearity was studied. The obtained plots are presented in Figs. 4-6. The Total Harmonic Distortion (THD) measure was calculated based on the following equation:

$$\mathrm{THD} = \frac{\sqrt{V_2^2 + V_3^2 + V_4^2 + \cdots}}{V_1}, \tag{1}$$

where V_n is the RMS value of the n^{th} harmonic voltage, and V_1 is the RMS value of the fundamental tone.

The second series was measured for a plate exposed to a broadband signal, exciting all frequencies in the considered frequency range at once. Then, the laser vibrometer measured vibrations at a grid of 22 $\times$ 22 points, uniformly distributed over the plate with an interval of 20 mm. The surface-averaged vibration frequency response of the plate is presented in Fig. 7. This series allowed to capture all excited modes, showing a certain advantage of the tripod support—the third configuration of the actuator allowed to control more modes in the same frequency range than former two configurations. This leads to a conclusion that the multiple points of contact prevents the lack of controllability for certain modes with a nodal line going through the actuator's piston. The actual modes of the plates with and without the tripod support cannot be directly compared, because the presence itself of the additional structure at the plate surface alters its mode shapes, but there were no uncontrollable modes observed for the tripod configuration, which were present in the case of the former two actuator configurations.

4. CONCLUSIONS

This paper presented the design and preliminary analysis of a novel tripod-supported electromagnetic actuator. A series of tests were carried out to evaluate its performance. While the tripod configuration successfully excited multiple target modes at very low frequencies, the improvement over conventional inertial actuators was somewhat less than initially anticipated. However, the tripod configuration allowed to control more modes in the considered frequency range than the former two configurations, most probably due to multiple points of contact with the plate.

Another key outcome of the study was the measurement of Total Harmonic Distortion (THD), where the tripod actuator demonstrated significantly lower nonlinearity within the same frequency range compared to the inertial type. This results in notable benefits for signal fidelity, system efficiency, and operational stability. An actuator with low THD maintains signal clarity, allowing for accurate transfer of vibrational energy with minimal spectral distortion. This improves control precision, reduces unwanted harmonic components, and enhances the predictability of system behavior.

Although in this paper the actuator has been centrally mounted on the plate, it is noteworthy that the further study should involve the optimization of the tripod position and orientation, taking into account the overall mathematical model of the plate and attached actuator [9].

5. ACKNOWLEDGMENTS

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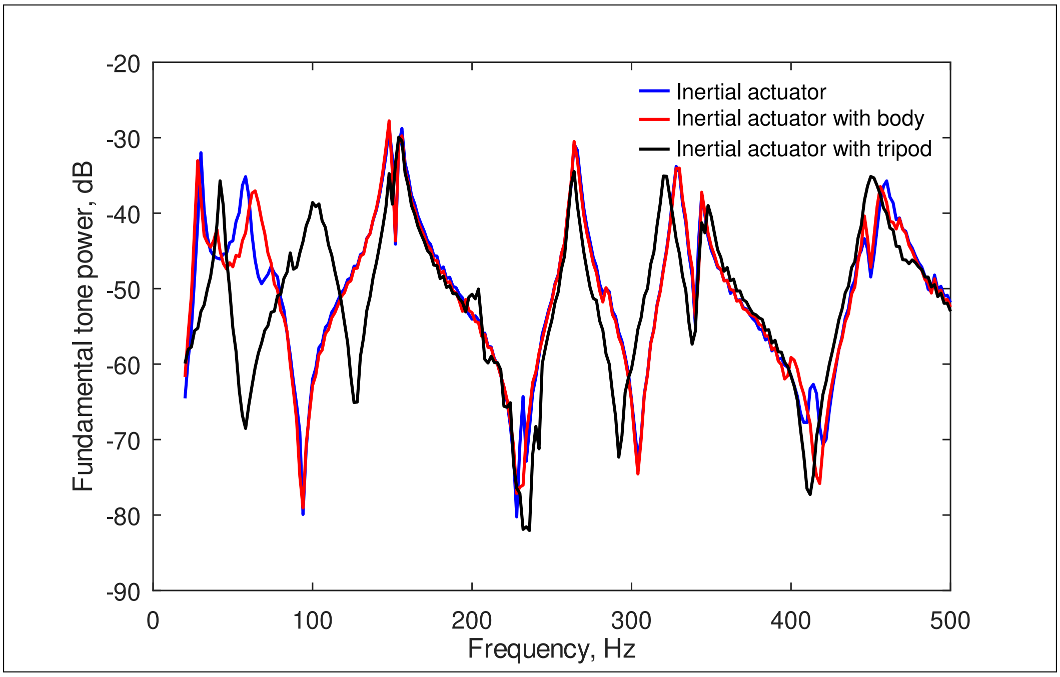

Figure 4. Fundamental frequency power of the three configurations of the actuator. The resulted were obtained using the frequency-sweep excitation by the actuator.

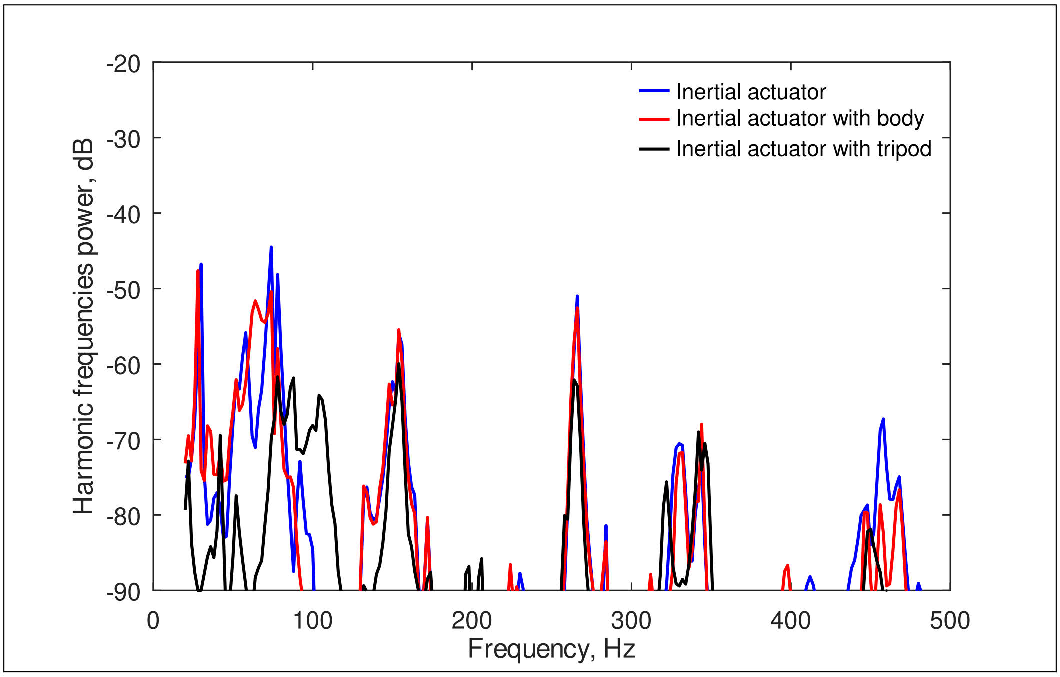

Figure 5. Power of the harmonic frequencies of the three configurations of the actuator. The resulted were obtained using the frequency-sweep excitation by the actuator.

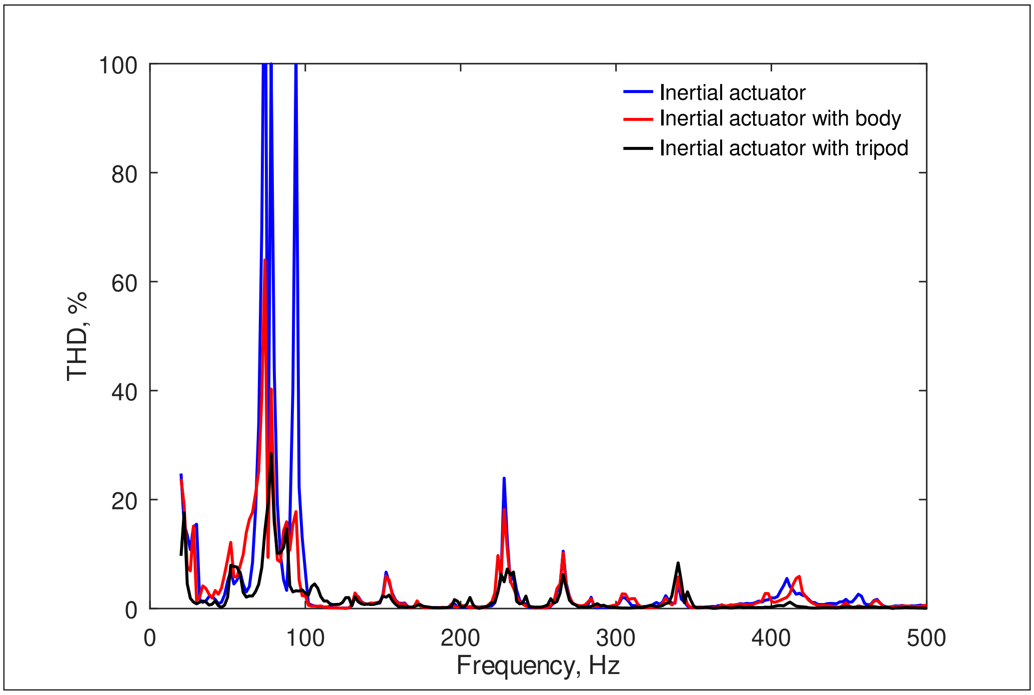

Figure 6. Total Harmonic Distortion (THD) of the three configurations of the actuator. The resulted were obtained using the frequency-sweep excitation by the actuator.

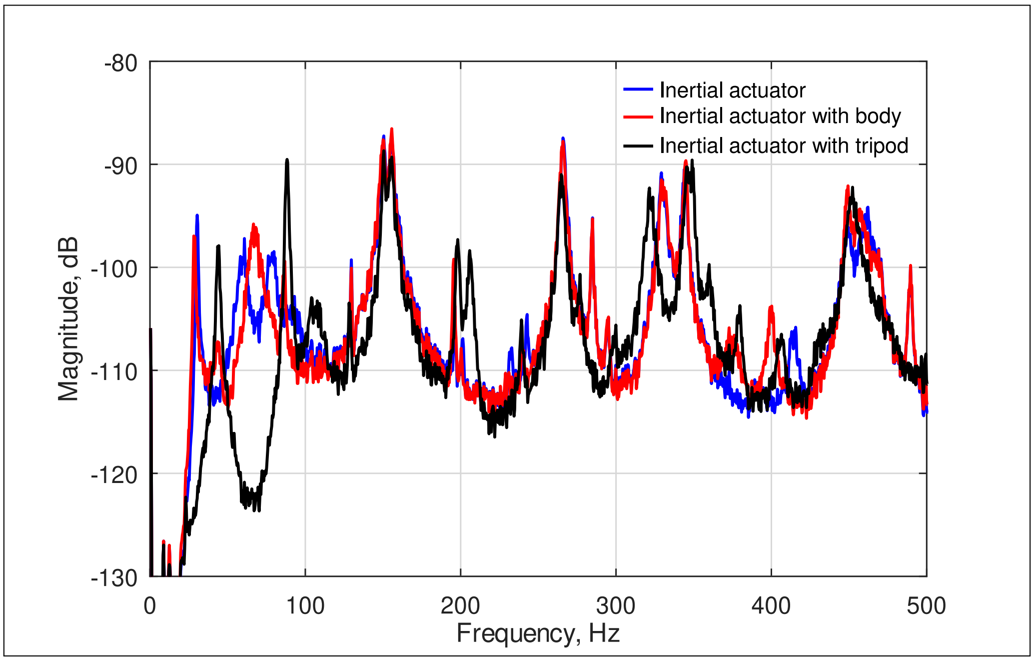

Figure 7. Surface-averaged vibration frequency response of the plate due to broadband excitation by the actuator.