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Design and verification of a negative resistance electromagnetic shunt damper for spacecraft micro-vibration

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ABSTRACT

Active control techniques are often required to mitigate the micro-vibration environment existing on board spacecraft. However, reliability issues and high power consumption are major drawbacks of active isolation systems that have limited their use for space applications. In the present study, an electromagnetic shunt damper (EMSD) connected to a negative-resistance circuit is designed, modelled and analysed. The negative resistance produces an overall reduction of the circuit resistance that results in an increase of the induced current in the closed circuit and thus the damping performance. This damper can be classified as a semi-active damper since the shunt does not require any control algorithm to operate. Additionally, the proposed EMSD is characterised by low required power, simplified electronics and small device mass, allowing it to be comfortably integrated on a satellite. This work demonstrates, both analytically and experimentally, that this technology is capable of effectively isolating typical satellite micro-vibration sources over the whole temperature range of interest.

1. Introduction

The unprecedented endeavour to build the Hubble Space Telescope in the early 1970s and the desire to achieve the highest-ever imaging resolution bolstered the research on the modelling and control of micro-vibration on board spacecraft. Micro-vibrations are typically generated by several on-board subsystems and devices, such as reaction wheel assemblies, momentum wheel assemblies, control moment gyros, pointing systems and cryo-coolers. The increasingly stringent stability requirements imposed by advanced, high-resolution payloads have produced an increased interest in the development of better-performing micro-vibration dampers. Several devices aimed at mitigating micro-vibrations have been investigated and tested, and depending on the nature of their functioning they can be classified as passive, active or semi-active dampers.

The passive dampers are mostly preferred due to their constructive simplicity, relative low cost and reliability. Among this kind of damper, viscoelastic materials are the cheapest and lightest damping solutions and are widely used by companies in the space sector [1–3]. However, the limited loss factors achievable with these materials, along with the strong dependency on the operating temperature and frequency ranges, make the design of viscoelastic dampers quite complex. Other passive dampers studied in the last 25 years include Eddy-current dampers [4–6], D-struts [7,8] and piezoelectric

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transducers shunted with passive electrical networks [9,10]. Nevertheless, it is still a challenge to employ pure passive isolation techniques to dampen low frequency micro-vibrations onboard a spacecraft [11].

Active control techniques [12] and active dampers are sometimes necessary in order to achieve more stringent conditions of isolation. Active dampers are fully controllable and capable of producing higher-order vibration attenuation with respect to passive dampers, but they also require a significant amount of power to operate. Active isolation can be obtained by using external actuators and sensors to provide control forces and feedback signals. Piezoelectric patches have been used extensively in active vibration control applications [13–15], and thanks to the development of the self-sensing technique these smart materials can be employed simultaneously as sensors and actuators [16,17]. The main advantages of this technique are the realisation of a very robust, truly collocated control (given by the sensor and the actuator being placed in the same position) as well as the reduction of system mass and complexity due to the elimination of independent sensors. However, variations of the piezoelectric properties produced by environmental and operating conditions would require a continual tuning of the circuit that, if not effectuated, could destabilise the closed-loop system. Also, electromagnetic transducers can be used either as velocity sensors or force actuators [18,19], or simultaneously as both in the self-sensing technique [20,21]. These transducers are characterised by large strokes, high bandwidth and low cost, but they may also suffer serious spillover (e.g. actuator saturation) and stability issues.

Recently, the use of negative impedances was proved to considerably improve the damping performance when connected to piezoelectric transducers [22,23] or electromagnetic transducers [24–26]. Negative impedances are used to cancel or reduce the inherent electrical properties of the transducers (e.g. piezoelectric patches are characterised by an inherent capacitance). In the case of electromagnetic transducers (characterised by an inductance and a resistance), the reduction of the overall resistance by means of the negative resistance increases the induced current flowing in the circuit and thus the damping performance.

This paper presents an electromagnetic shunt damper (EMSD) connected to a negative-resistance circuit, and demonstrates its vibration attenuation performance by applying the isolator to a single-degree-of-freedom (SDOF) system. Although the shunt circuit requires power to operate, this type of EMSD can be considered as a semi-active damper for two reasons: (i) the negative-resistance circuit acts overall as a passive electrical component having a constant negative magnitude, without requiring any control algorithm; (ii) the damper requires little external power to function because part of the energy is self-provided by the relative motion between the magnet and the coil (i.e. the damper would work as a passive damper if the coil terminals were short-circuited). The proposed damper is analysed not only in terms of damping performance, but also as a satellite subsystem that needs to withstand certain physical and environmental criteria. Therefore, the mass and power budgets of the damper have been taken into account, as well as stability conditions derived from considering an operating temperature range from −20 °C to +50 °C.

This work differs from previous articles on similar dampers [24,26,27] by proving, both analytically and experimentally, that this technology is able to effectively isolate typical sources of micro-vibration in space (in the region of 5 kg) without using any active control algorithm to adjust for changes in the environmental conditions. In fact, the damper transmissibility shows a final decay rate of −40 dB/dec, while drastically reducing the force amplification at the resonance frequency throughout the whole temperature range of interest. Therefore, the improved damping performance, along with the low power required to operate it and an overall mass that is less than 4 percent of the suspended mass, are among the main features of the proposed EMSD, which make it highly competitive when compared with other well-established micro-vibration dampers.

The rest of the paper is organised as follows. Section 2 presents the analytical model of the proposed EMSD. Section 3 describes the experimental set up. Section 4 reports the tests results and shows the correlation with the analytical data. The conclusions are drawn in Section 5.

2. Analytical model

A schematic of the system studied in this paper is shown in Fig. 1. This model consists of a mass suspended on a metal

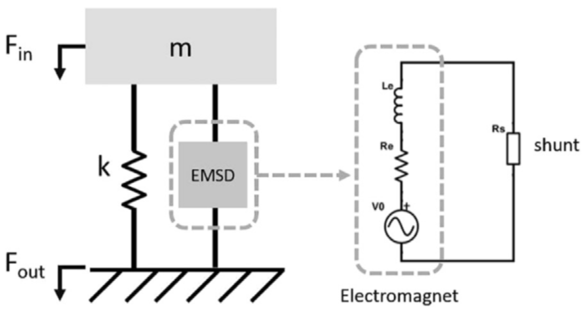

Fig. 1. Schematic representation of the SDOF model, with the electrical schematic of the shunt circuit of the EMSD.