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Analysis and numerical modelling of eddy current damper for vibration problems

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A B S T R A C T

This work discusses a contactless eddy current damper, which is used to attenuate structural vibration. Eddy currents can remove energy from dynamic systems without any contact and, thus, without adding mass or modifying the rigidity of the structure. An experimental modal analysis of a cantilever beam in the absence of and under a partial magnetic field is conducted in the bandwidth of 01 kHz. The results show that the eddy current phenomenon can attenuate the vibration of the entire structure without modifying the natural frequencies or the mode shapes of the structure itself. In this study, a new inverse method to numerically determine the dynamic properties of the contactless eddy current damper is proposed. The proposed inverse method and the eddy current model based on a lineal viscous force are validated by a practical application. The numerically obtained transfer function correlates with the experimental one, thus showing good agreement in the entire bandwidth of 01 kHz. The proposed method provides an easy and quick tool to model and predict the dynamic behaviour of the contactless eddy current damper, thereby avoiding the use of complex analytical models.

1. Introduction

The concept of eddy currents has been investigated since the late 1800s, and many researchers have proposed different uses of eddy currents for dynamic systems, such as braking systems, suppression of rotor vibration and damping of structural vibrations [1].

The main advantage of using the eddy current phenomenon to dampen structural vibration is the possibility of removing energy from the system without any contact with the structure itself. This means that unlike in other damping techniques, such as viscoelastic materials or piezoelectric actuators, the system to be dampened remains unmodified and mass is not added to the structure.

Matsutzaki et al. [2,3] were among the first to highlight the possibility of using electromagnetic forces to dampen the vibrations of beams. They proposed attenuating the vibration of a periodically magnetised beam using electromagnetic forces generated by the passing of the current between the magnetised sections. Sodano et al. [4] analysed the vibration suppression capabilities of a cantilever beam by placing a magnet perpendicular to the beam motion and attaching a conductive sheet to the beam tip. In subsequent works, they proposed the use of two magnets with the same polarity facing each other and the active movement of magnets to increase the damping added to the beam [5,6]. Kwak et al. [7] proposed an eddy current damper comprising a flexible linkage with two permanent magnets and a fixed copper plate attached to the end of the cantilever beam

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to be damped. Cheng et al. [8,9] introduced an electromagnetic shunt damper to attenuate the vibrations of beams using eddy currents. Bae et al. [10,11] suggested combining the classical tuned mass damper with the eddy current phenomenon using a permanent magnet as a concentrated mass of the tuned mass damper, while Berardengo et al. [12] proposed an adaptive tuned mass damper based on shape memory alloys and eddy currents. Stein et al. [13] proposed the damping of transversal vibrations of a clamped-clamped beam with a centre mass loading by a simple ferro-magnetic circuit. Recently, Maddah et al. [14] developed a hybrid damper consisting of an eddy current damper and a magnetorheological damper. Thus, the latest trend regarding eddy currents is to design special devices that magnify the damping added to the structure due to eddy currents or combine the eddy current phenomenon with other damping techniques. In such cases, the system to be damped is modified and so are the mass and rigidity of the structures. However, as stated by Sodano and Bae [1], the phenomenon of eddy currents can be used to remove energy from the system without ever contacting the structure; the studies that focus on this contactless characteristic have shown that the natural frequencies of the structure remain unmodified in those cases [4,5].

In this work, a contactless eddy current damper, which consists of applying steady state magnetic fields to conductive structures in order to dampen their vibration, is analysed. To the best of the author's knowledge, this work reflects the first time a detailed experimental modal analysis of a cantilever beam in the absence of and under a partial magnetic field in the bandwidth of 01 kHz has been conducted. The influence of the induced eddy currents on the natural frequencies and the mode shapes of the structure as well as the vibration attenuation is studied. Once the dynamic behaviour of the contactless eddy current damper is known, a new inverse method is proposed to model it. The influence of induced eddy currents is modelled by a lineal viscous force whose proportionality constant is termed the eddy camping coefficient. The proposed inverse method determines the eddy damping coefficient of the contactless eddy current damper of any configuration.

This remainder of this paper proceeds in the following manner: First, the theoretical background of the eddy current phenomenon is presented. Then, the experimental procedure and the analysis of the dynamic properties of the contactless eddy current damper are shown. Finally, the foundation of the inverse method is presented, and a practical application is shown in order to validate the proposed eddy force model and inverse method.

2. Theoretical background

In this section, the generation mechanism of eddy currents is described, and the theoretical approaches proposed by other authors to model the eddy force generated on vibrating structures exposed to a steady-state magnetic field are reviewed.

When a conductive material experiences a time-varying magnetic field, electrical currents are induced. The induced currents circulate in such a manner that they induce their own magnetic field to oppose the change in the magnetic field that created them. By the iteration of the induced eddy currents with the magnetic field, a repulsive force is generated. Due to the electrical resistance of the conductor, eddy currents are dissipated into heat, and the force disappears. However, in dynamic systems with vibrating structures, there is a constant change in magnetic flux, and the eddy currents are regenerated constantly, thereby allowing energy to be removed from the system.

The force generated due to eddy currents can be obtained from the Lorentz force law, given by

$$\mathbf{F} = \int_V \mathbf{J} \times \mathbf{B} \mathrm{d}V, \tag{1}$$

where $\mathbf{J}$ is the induced total eddy current density, $\mathbf{B}$ is the total magnetic flux density and V is the volume of the conductor [15].

In vibrating structures, the eddy currents are induced through two different mechanisms [15]:

- If the magnetic flux density varies in the space, the structure is exposed to a time-varying magnetic field when it begins vibrating. According to Faraday's law of induction, an electromotive force is induced in the conductor and then an electric current flows through it, which can be obtained from

$$\mathbf{J} = \sigma \left(-\frac{\mathrm{d}}{\mathrm{d}t} \int_S \mathbf{B} \mathrm{d}S \right), \tag{2}$$

where σ is the conductivity of the conductor and S is the surface area.

- If the magnetic flux, $\mathbf{B}$, and the velocity of the beam, $\mathbf{v}$, are not parallel, a motional induced electromotive force is generated. The motional induced current density is given by

$$\mathbf{J} = \sigma \left(\mathbf{v} \mathbf{B} \right) . \tag{3}$$

The contactless eddy current damper analysed in this work consists of applying a steady-state magnetic field to a vibrating conductive beam. Fig. 1 presents a scheme of the contactless eddy current damper composed of a cantilever beam and a permanent magnet placed on one side of the beam. In this system, the eddy current is induced according to Equation (2) and Equation (3), consequently, the vibration is attenuated.