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Identification and analysis of nonlinear dynamics of inertial actuators

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ABSTRACT

This paper presents an experimental study of the nonlinear dynamics of electrodynamic proof mass actuators. When inertial actuators are used in velocity feedback controllers, their nonlinear dynamics can affect the stability margin of the feedback loop. Thus, it is crucial to identify the nonlinearity sources and to build reliable models that can be implemented in the stability analysis. Firstly, the underlying linear model parameters of an inertial actuator are identified for small excitation signals. The inductance losses at high frequencies due to eddy currents have also been included in the electrical impedance model. Secondly, the nonlinear model of the inertial actuator is determined using the detection, characterisation and identification process. Finally, a numerical analysis is carried out to highlight the implications of nonlinear dynamics of inertial actuators. The proposed methodology is applied to several electromagnetic proof mass actuators, including when the proof mass is not accessible to be directly instrumented.

1. Introduction

Extensive research has shown the importance of active devices to control vibrations of lightweight and flexible structures [1–7]. A notable example are velocity feedback controllers, which can add viscous damping to the structure, reducing its level of resonant vibration [5]. A velocity feedback controller consists of an actuator attached to a structure with a collocated sensor of vibration (usually an accelerometer) and a controller, which feeds back the velocity of the structure to the actuator [5]. The use of an electromagnetic inertial, or proof mass actuator as the active forcing device in velocity feedback controllers has also been well documented [2,5,7–14]. An inertial actuator consists of a magnetic proof mass, an electrical winding and a suspension, which connects the proof mass to a casing or a base mass [7]. An example of such a device is shown in Fig. 1(a) and its schematic representation is displayed in Fig. 1(b).

An inertial actuator operates as a coil-magnet electrodynamic transducer. The control, or secondary, force on the structure is generated by the interaction between the constant magnetic flux of the magnet and the variable magnetic flux produced by the current flowing through the coil. The transducer supplies the control force on the structure by reacting against the proof mass, which consequently starts to accelerate [7]. Electromagnetic proof mass actuators have a wide variety of applications, among which the most important are: space structures, buildings, bridges and other civil structures, and internal noise reduction in aircraft [15–18]. A large amount of literature has shown that the internal dynamics of the inertial actuator affects the stability and performance of the controller when implemented for structural vibration reduction [12,19–21]. This motivates

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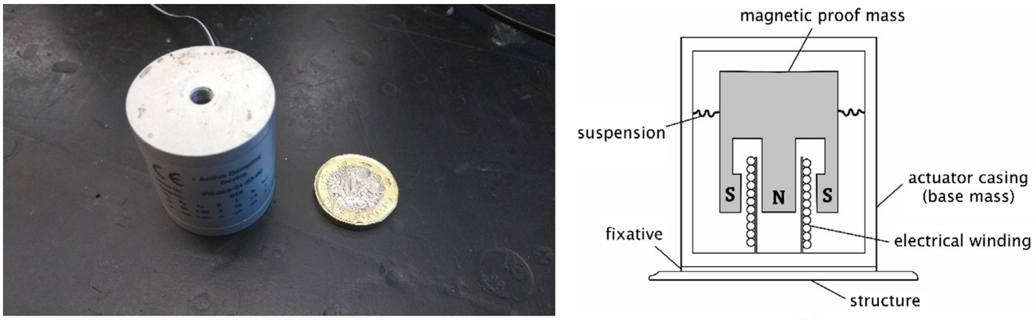

(a) (b)

Fig. 1. (a) Picture of the Micromega Dynamics IA-01 inertial actuator; (b) Schematic of an inertial actuator in cross-section.

for having an accurate model of the inertial actuator and in particular to look for nonlinearities that may affect the dynamics of such a device for large excitation signals. Most studies in this area have not dealt with accurate nonlinear models of inertial actuators. In fact, there is little published data on the nonlinear behaviour of inertial actuators. To date, Baumann et al. [22,23], Wilmshurst et al. [24–26] and Dal Borgo et al. [27,28] have highlighted the implications of their nonlinear dynamics. Although there exists few publications based on experiments [25,29,30], a systematic methodology of measuring and identifying the nonlinearity in inertial actuators is still lacking. This study aims to determine the mechanical nonlinearities of inertial actuators through the detection, characterisation and identification of the nonlinear parameters in order to build reliable models. The electrical nonlinearities are neglected since they mainly affect the behaviour at high frequencies, which are beyond the frequency region where the instability of velocity feedback loops with inertial actuators occur. One of the harshest nonlinearity that affects the dynamic behaviour of an inertial actuator is stroke saturation, which has been studied in [8,22,24,25,30–32]. We investigate in detail the phenomenon of stroke saturation, and also show the results of the same nonlinear identification methodology applied to several actuators with weaker and different kind of nonlinearities.

This paper investigates the nonlinear behaviour of inertial actuators and provides a methodology for detection, characterisation and identification of the nonlinear parameters. Initially, the experimental analysis is presented to determine the underlying linear parameters of the inertial actuator, in Sections 2 and 3. Secondly, the detection, characterisation and identification of the nonlinearities are presented in Sections 4 and 5, where the experimental data is analysed. Finally, a theoretical investigation on the experimentally identified model is reported in Section 6. This highlights the implications of the nonlinear behaviour of the inertial actuator for its usefulness in velocity feedback controller through the analysis of nonlinear frequency response curves and frequency-amplitude plots.

2. Experimental set-up

In this section the experimental set-up for the identification of the linear and nonlinear dynamics of an inertial actuator is presented. The inertial actuator initially used in the experiments is a Micromega Dynamics IA-01, which is shown in Fig. 1(a) and is documented in [33]. The methodology used for the identification is explained in detail for this specific actuator. However, the same methodology can be applied for the identification of any other inertial actuator. As evidence, a number of different actuators have been tested and their results are provided in Appendices A and B. To characterise the inertial actuator, two experiments are required. The first experimental set-up is to measure the structural response of the actuator subject to a base excitation, as shown in Fig. 2(a). In this case, the actuator is mounted on a PCB Piezotronics 208C01 ICP force sensor, which is rigidly connected to an LDS V406 electrodynamic shaker. The shaker is powered by an LDS PA25E voltage driven

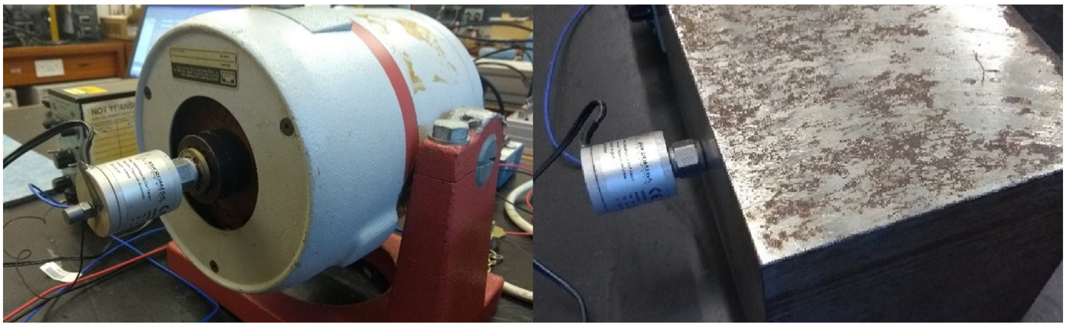
(a) (b)

Fig. 2. (a) Picture of the set-up for the base excitation experiment; (b) picture of the set-up for the blocked base experiment.