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Modeling and dynamical performance of the electromagnetic mass driver system for structural vibration control

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ABSTRACT

This paper presents the designing, theoretical modeling and dynamical testing of an innovative Electromagnetic Mass Driver (subsequently called the "EMD") system for structural vibration control. Firstly, a set of bench-scale EMD system was developed. Then, based on the electromagnetic field theory, the Kirchhoff's circuit law, and the analogous analysis, electro-mechanical models of the EMD system were developed, which utilizes the control voltage and relative velocity to predict active control force generated by the EMD system. To validate these models, as well as to examine the dynamic performance of the EMD system, a series of tests under open-loop control mode and closed-loop control mode were carried out. All the test results show that the EMD system functions linearly under low levels of input voltage and low frequencies. Furthermore, step inputs based transient response of the EMD system was also examined. The results show the EMD system is a fast and well controllable actuator. At last, all the experimental results were compared with theoretical predications based on the proposed electro-mechanical model. Successful experimental validation of the force–voltage relationship lays out the foundation for structural vibration control utilizing such kind of innovative EMD system.

1. Introduction

In 1972, concept of modern control theory was introduced into vibration control of civil engineering structures, which started the new era of research on structural active control [30]. During the subsequent development of more than 40 years, Active Mass Driver/Damper (AMD) control, with the better control effect and cheaper control cost, has taken the lead in various active control occasions, becoming the most extensively used and researched control method in practical applications [22,11,24,16,32,23]. Selective special issues from influential journals in civil engineering field, such as ASCE Journal of Engineering Mechanics (issue *4th*, in 2004), ASCE Journal of Structural Engineering (issue *7th*, in 2003), Earthquake Engineering and Structural Dynamics (issue *11th*, in 2001 and issue *11th*, in 1998), reviewed the-state-of-the-art in research and engineering applications of semi-active control and active control, especially AMD control. The applications of active control in civil engineering have been systematically reviewed [24]. Up to date, more than 50 high-rising buildings, television towers and about 15 large-scale bridge towers have been equipped with AMD control systems for reducing wind-induced vibration or earthquake-induced vibration of the structure. A systematical comparison for different control schemes under the background of the Benchmark control problem, and disclosed that the AMD control was the superior control scheme due to the merits, such as the best ratio of control effect over control effort, simple and easy to be implemented. Moreover, through analysis of typical important large-scale structures subjected to different excitations, the effectiveness and feasibility of employing AMD control for civil structures has been successfully proven, where wind and earthquake induced vibration control of high-rising buildings and bridge towers, ice induced vibration control of offshore platforms, wind-wave-current coupling excited control of deep sea platforms are all studied [33]. Damping and stiffness optimization related to structural responses have been studied [2]. Control designs considering nonlinearity of structures have been investigated [3,20]. A novel semi-active friction-type multiple tuned mass damper for vibration control of seismic structures has been proposed to keep all of its mass units to be activated in an earthquake with arbitrary intensity [14]. The effects of actuator dynamics and control-structure interaction for an electric motor, namely he impact of the mechanical design to actuator power consumption has been studies [25]. An actuator model which includes the electric motor and friction characteristics within 10 Hz bandwidth,

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the electromechanical low-power active suspension design is investigated for heavy vehicle systems [8]. Inertial actuators for control of human-induced vibrations in pedestrian structures, namely the issues of active control stability pertaining to low frequency dynamics which interacts with the dynamics of target, and the nonlinearities especially stroke and force saturation have been investigated [5].

Usually, an AMD control system is composed of a mass unit, an actuator, stiffness component (coil spring is commonly used), a damper, a stroke limiting device, a brake protector, sensors, a data acquisition and processing system, computerized real-time control software and hardware system [6,7,19]. In addition, a power supplying system is needed for operating all the electrical devices mentioned above. Although ball screw represented rotation motor systems are still dominant as feed drivers and industry applications, their dynamics are limited, due to the nature of intrinsic mechanical transmission elements for coupling rotation motion with linear motion. Linear motors can generate linear motion directly, however, dynamic stiffness or rigidity are dominantly determined by the controller loop. Solid-state actuators are now part of the field of modern machining and are capable of providing high force and stiffness under motion with nanometer scale accuracy under high bandwidth operation, but are limited by very short working stroke. The dual stage actuation systems, which are the combination of a linear motor used as the coarse actuator and a magneto-strictive actuator as the fine actuator has been studied [26]. However, for vibration control of large scale structure, e.g. civil engineering structures, the dynamic positioning precision is not the key issue, thus linear motor is feasible for such applications into civil engineering structures and infrastructures, whereas, ultra-precision machines are recent foci in order to meet the rising demand for miniaturized and micro-machined components, particularly in biomedical, electronics, opto-mechatronics and automotive [4].

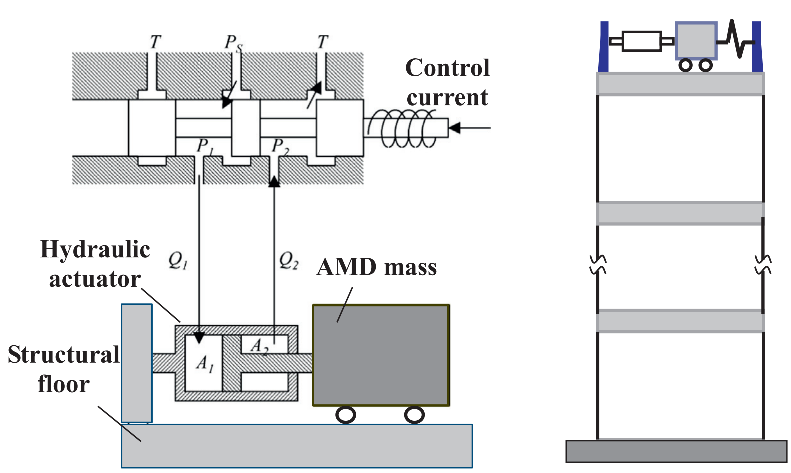
In traditional AMD system, the mostly used actuators are hydraulic cylinders or electrical servo motors, which may have the following disadvantages, such as large in system volume, complicated in construction, time delay, slow to response, and limited mass stroke. Aiming at this, several new special devices were put forward to replace the traditional actuators [10,9,15,21]. Learning from the motion control principle of magnetic suspended vehicle, the Electromagnetic Mass Driver (subsequently called the "EMD") control system, as an innovative active control system, was proposed for structural vibration control [33], which uses the driving technology of linear electric machines, transforming the electric energy directly into mechanical energy of EMD system, for example, the kinetic energy of EMD mass. Fig. 1(a) shows the conception sketch of hydraulic actuated AMD system and its implementation illustration in a three-floor structural model, as shown in Fig. 1(b). By comparison, Fig. 2(a) and (b) shows the corresponding sketch and implementation sketch of the EMD control system.

As shown in Fig. 2, through coupling force generated in the electromagnetic field between mass unit and the structure, control power is exerted into the structure without the aid of any interlink. Therefore, compared with traditional AMD control system, EMD system possesses the following merits: no mechanical contact, low wearing of operation parts, high transmitting efficiency, fast response ability, large thrust force, unlimited mass stroke, and low operating noise, etc. In addition, the construction of a hydraulic system is complicated and it needs many supporting apparatus, thus it is hard to be integrated. By contrast, the EMD system is simple and can be integrated. In short summary, the EMD system is promising for vibration control of civil structures.

2. Design of the EMD control system

According to the requirement of the Bench Scale structural model [1,18], one scaled EMD control system is designed and fabricated. The experimental EMD system is composed of a mass unit with direct current excitation coils encapsulated in high-strength engineering plastics. It is also designed with mounting holes on its surface for expanding mass if necessary. The EMD system also consists of a permanent magnet rod made of high energy rare earth material, a linear sliding bearing and a system chassis. In addition, in order to establish a closed-loop control system, an optical scale and an accelerometer are also integrated into the EMD system to measure the stroke and absolute acceleration of the mass, respectively. Photo of the whole integrated system is shown in Fig. 3.

The excitation coil in the sealed mass package is 87 mm long, made by Copley Controls Inc., and the weight of the integrated mass unit is 186 g. The length of the permanent magnet rod is 332 mm with the diameter of 11 mm. The other electrical specifications of this EMD control system are summarized as: peak force constant is 5.74 N/A, root mean square (abbreviated as RMS) force constant is 8.12 N/A, back electro-motive force (abbreviated as EMF) constant is 6.63 V s/m, the coil resistance at 25 °C is 5.35 Ω, and the coil inductance is 1.73 mH. The mass stroke of EMD system is measured using a Renishaw optical scale, which is fixed on the system chassis as shown in Fig. 3, while the reading head is fixed



(a) Sketch of hydraulic AMD (b) Structural implementation

Fig. 1. Sketch of structure with hydraulic AMD control system.