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Active vibration control of structure by Active Mass Damper and Multi-Modal Negative Acceleration Feedback control algorithm

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ABSTRACT

In this study, an Active Mass Damper (AMD) consisting of an AC servo motor, a movable mass connected to the AC servo motor by a ball-screw mechanism, and an accelerometer as a sensor for vibration measurement were considered. Considering the capability of the AC servo motor which can follow the desired displacement accurately, the Negative Acceleration Feedback (NAF) control algorithm which uses the acceleration signal directly and produces the desired displacement for the active mass was proposed. The effectiveness of the NAF control was proved theoretically using a single-degree-of-freedom (SDOF) system. It was found that the stability condition for the NAF control is static and it can effectively increase the damping of the target natural mode without causing instability in the low frequency region. Based on the theoretical results of the SDOF system, the Multi-Modal NAF (MMNAF) control is proposed to suppress the many natural modes of multi-degree-of-freedom (MDOF) systems using a single AMD. It was proved both theoretically and experimentally that the MMNAF control can suppress vibrations of the MDOF system.

1. Introduction

The reduction of vibrations in structures is a main engineering objective for human, machineries, sensitive instruments, automobiles, airplanes and buildings since excessive vibrations may harm the human body and cause structural failure. To this end, many new devices and control algorithms have been proposed. All of these devices and control algorithms have both advantages and disadvantages. In some cases, structural modification may not be possible and an auxiliary system which can absorb the vibration of the main structure is preferred. A Tuned Mass Damper (TMD) which can be easily attached to the structure of interest was developed to suppress the vibration of the primary structure. The TMD is a passive system that suppresses the vibration of the primary structure by tuning its natural frequency to the excitation frequency [1]. However, the TMD has limited performance due to fixed damper parameters, a narrow suppression frequency range, ineffective reduction of non-stationary vibration, and a sensitivity problem because of detuning.

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In order to overcome the limitations of the traditional TMD, the Semi-active Tuned Mass Damper (STMD) and the Active Tuned Mass Damper (ATMD) or the Active Mass Damper (AMD) were proposed. Both technologies utilize the electronic circuit and control board to sense the motion of structure and to activate the control force. However, the STMD does not produce a direct force but rather changes its natural frequency by changing either stiffness or damping properties to suppress vibrations. This is advantageous compared to the AMD when the electrical power is not available since it can still provide existing damping or stiffness to structure. The AMD applies a control force computed by using a sensor signal and control algorithm, thus resulting in active vibration control. The AMD is capable of suppressing vibrations due to the frequently varying external environment since it uses actuators, sensors, and a feedback control algorithm. However, it may destabilize a main structure if structural parameters change. Hence, the reliability of the control system should be guaranteed before implementation.

Hrovat et al. [2] proposed a STMD consisting of a control-valve actuator and a Linear Quadratic Regulator (LQR). Pinkaew and Fujino [3] investigated a STMD that uses variable damping under harmonic excitation and also used a LQR. Lin and Chung [4] employed the magneto-rheological (MR) damper and developed a clipped optimal control, which compares the state-output-feedback LQR control force and the estimated MR damper force. Varadarajan and Nagarajaiah [5], Nagarajaiah and Vardarajan [6], Nagarajaiah and Sonmez [7], Lin et al. [8], and Kwak et al. [9] proposed a STMD which can adjust the modulus of stiffness thus tuning to the changing excitation frequency.

Chung et al. [10] proposed control algorithms for the active tendon control of seismic structures based on instantaneous optimal control. Kobori et al. [11,12] proposed the design method of the active mass driver system and simplified the control algorithm obtained by applying the optimal control theory. Chang and Yang [13] studied the AMD using velocity feedback and a complete feedback control that utilizes displacement, velocity and acceleration measurements. Ankireddi and Yang [14] investigated the AMD using complete feedback control. Cao et al. [15] applied the AMD to a tall TV tower using the Linear Quadratic Regulator (LQR) and a nonlinear feedback control algorithm. Baoya and Chunxiang [16] developed a robust control algorithm for the AMD. Samali and Al-Dawod [17] applied the Fuzzy logic controller to the AMD. Cao and Li [18] proposed new control strategies for the AMD. Wang and Lin [19] developed the variable structure control and Fuzzy sliding mode control for the AMD. The AMD has been successfully applied to skyscrapers to cope with earthquake and wind excitations.

Research on control algorithms for the AMD mentioned above assumed that the displacement, velocity and acceleration are measurable. However, it is difficult to directly measure the displacement and velocity of a real vibrating structure since the most popular sensor for vibration measurement is an accelerometer. The displacement and velocity can be thought to be obtainable by integrating the acceleration signal. However, bias and drift involved in the acceleration signal may cause problems in the integration process. Hence, researchers have proposed the direct use of the acceleration signal to produce a proper control action.

Dyke et al. [20] showed that H2/LQG frequency domain control methods employing acceleration feedback can be effectively used for the vibration suppression of seismic structures. Nishimura et al. [21,22] developed a feedback control algorithm using acceleration. Dyke et al. [23] developed a state feedback control algorithm using acceleration as the sensor output. Sim and Lee [24] proposed the acceleration feedback control and proved its stability. Christenson et al. [25] proposed the active coupled building control using acceleration feedback and used the H2/LQG approach to obtain the control algorithm. Mahmoodi, et al. [26] proposed the modified acceleration feedback control for collocated piezoelectric actuators and accelerometer. Enrizuea-Zarate et al. [27] proposed the positive acceleration feedback control when one beam-column of a building-like structure is coupled with a PZT stack actuator. These controllers are more realistic than the other controllers mentioned above because they use acceleration to generate the control signal for piezoelectric actuators. However, the above studies did not deal with the AMD actuated by an AC servo motor that can provide accurate position tracking rather than control force.

This study is concerned with the AMD actuated by the AC servo motor and a ball-screw mechanism, which appears to be the most feasible mechanism for the real application of AMD when the target natural frequency is low. Also, the proposed AMD system doesn't require high-voltage power source to activate large control force. Watanabe et al. [28] proposed the LQ control combined with a low-pass filter for the active vibration control of high-rise buildings but their algorithm requires complicated computations. The advantage of our mechanism is that the movement of the active mass can be accurately controlled by the AC servo motor. In general, the AC servo motor is operated with either the position, velocity or torque modes. The rotation of the AC servo motor is accurately controlled by the internal PID controller according to the input command. The sensor for the proposed AMD is of course an accelerometer for practical purposes. Hence, a control algorithm that utilizes acceleration and produces the desired position of the active mass needs to be developed. To this end, the Negative Acceleration Feedback (NAF) control is proposed for the proposed AMD system. The proposed NAF control is different from other control algorithms that produce control force. Also, the NAF control theory that directly uses accelerometer signal as a sensor input is different from other control theories that require displacement or velocity. The effectiveness of the NAF control was first investigated by applying it to the single-degree-of-freedom (SDOF) system. The Routh-Hurwitz method was employed to examine the stability of the NAF control. It was theoretically determined that the stability condition is static. The Multi-Modal NAF (MMNAF) control was then developed to increase the damping of the many natural modes of a multi-degree-of-freedom (MDOF) system using a single AMD. Theoretical result shows that the proposed multi-modal NAF control can be successfully applied to the MDOF system if the gain matrix is sufficiently small. The test bed was built to examine the performance of the proposed MMNAF control. Experimental results show that the MMNAF control can successfully suppress vibrations in the structure.

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