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Experimental Study of an Innovative Rotating Actuator for Structural Vibration Control

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ABSTRACT
In this paper, an innovative actuator in the AMD system for structural vibration control is proposed. Different from the linear actuator in traditional AMD systems, a rotating actuator is introduced to suppress structural vibration. With the introduction of rotational movement nonlinearity arises in the system. Therefore, using the Lagrange equations, the modeling of the nonlinear structure-AMD system is accomplished. Based on this model, a stable controller is designed considering the sliding mode control method. Exprimental analysis based on the dSPACE control system are conducted to prove the validity of the control algorithm.

KEYWORDS: *structure-AMD; structural vibration control; sliding mode control; dSPACE; exprimental analysis*

1. INTRODUCTION

AMD control systems have been widely researched in structural vibration control of civil structures. They own more potential than TMD systems because of superior effectiveness and high spectral band-width [1,2]. The prototype of AMD system is the Dynamic Vibration Absorber proposed by Frahm and Den Hartog in the early twentieth century. Aizawa et al. accomplished the active control experiment of a four-story structure with AMD installed on the top floor in 1987 [3], and it's the first try of active control experiment around the world. In the same year, Kobori et al. fulfilled the 1:4 bench-scale tests of a three-story structure [4]. In 1988, the 1:4 bench-scale experiment of six-story structure was completed in the American national earthquake engineering research center by Soong [5]. Ou et al. studied the feasibility of application of AMD systems on the offshore platforms, and active control of the ice induced vibration was studied on the 1:10 bench-scale structure [6,7].

In the traditional AMD systems for structural vibration control, hydraulic system and motor servo system are always adopted as actuators. However, problems difficult to solve exist in these systems. For hydraulic system, structural complexity, expensive maintenance, large space occupation and low efficiency of energy utilization set a limit to its application. In motor servo system, motor torque is transferred to the structure through mechanical parts, like ball screws. As a result, extra inertia and friction of mechanical contact slow the response of the control system, and bring down the efficiency. For the purpose of enhancing the performance of actuators, some researches are conducted. Achievements are made including the design of swing-style AMD [8] and the introduction of electromagnetic devices with semi-active control property [9]. Moreover, Zhang et al. proposed a kind of electromagnetic mass damper system, which can impose electromagnetic force on structure directly, making mechanical contact unnecessary [1,10]. Nevertheless, limited mass stroke of AMD actuator is still unsolved fundamentally. Limited mass stroke will trigger nonlinearity consequentially [11], and effectiveness of control system could be limited as well.

To solve the problem of limited mass stroke of AMD system, an innovative rotating actuator is proposed in this paper. Instead of rectilinear motion in traditional AMD, inertial mass has rotational movement driven by a rotating actuator. In this way, limited mass stroke problem is worked out.
In this paper, the modeling of the nonlinear structure-AMD system featured with rotating actuator is accomplished. Based on this model, a hierarchical sliding mode controller [12] is designed to realize the displacement control of the structure under earthquake excitation. Besides, elimination of the chattering

phenomena of sliding mode control is considered. Experimental results are conducted to validate the effectiveness of control strategy and the reliability of AMD device.

2. MATHEMATICAL MODELING

Structure-AMD system with rotating actuator is depicted in Figure 2.1, which consist of one-floor target structure and the rotating actuator incorporated on the top. Target structure has mass *M*, stiffness coefficient *K* and damping coefficient *C*. The rotating mass is *m* driven by the motor torque *N*. Rotating radius is *R*, and rotating angle is *θ*. Moment of inertia of the mass with respect to its barycenter is *J*. Target structure has rectilinear motion in horizontal plane, and its displacement is *x*. Displacement of structure in vertical direction is not taken into consideration here because it's negligible with respect to *x*.

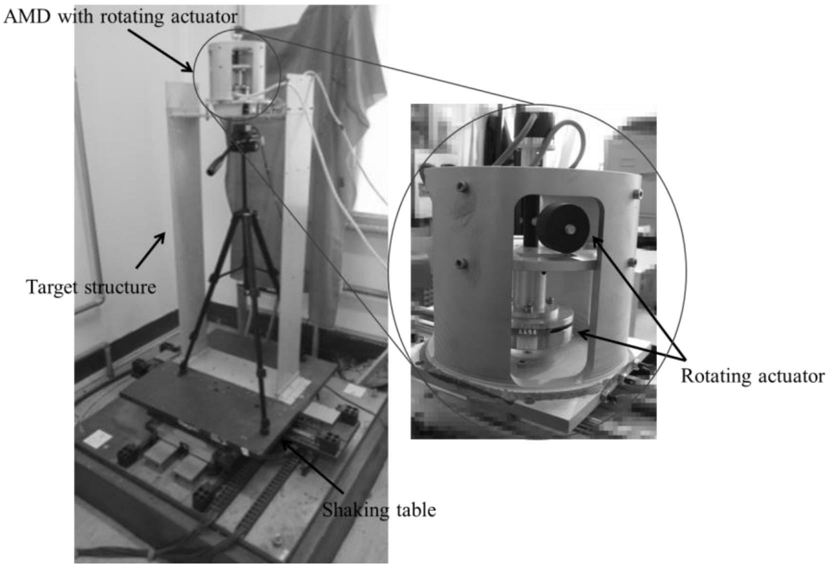


Figure 2.1 Structure-AMD system with rotating actuator

The Lagrange equations are adopted to fulfill the modeling of the entire system. The Lagrange equations can be expressed as

$$\frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{\partial L}{\partial \dot{q}_n}\right)-\left(\frac{\partial L}{\partial q_n}\right)=Q_n\,(n=1,2\ldots) \tag{2.1}$$

Where *L* is the Lagrangian of system of particles, and q_n are generalized coordinates, *n* is the degree of freedom, and Q_n are generalized forces. According to the Lagrange equations, the dynamics of the whole system should be

$$\begin{aligned}&\frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{\partial L}{\partial \dot{x}}\right)-\frac{\partial L}{\partial x}=F_x\\&\frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{\partial L}{\partial \dot{\theta}}\right)-\frac{\partial L}{\partial \theta}=N\end{aligned} \tag{2.2}$$

Where $F_x=-(M+m)\ddot{x}_g$ is the force exerted into the structure by earthquake. The Lagrangian of the system is

$$L=T-P=\frac{1}{2}(M+m)\dot{x}^2+mr\dot{x}\dot{\theta}\cos\theta+\frac{1}{2}(mr^2+J)\dot{\theta}^2-\frac{1}{2}Kx^2 \tag{2.3}$$

T and *P* are the kinetic energy and potential energy of the system. By substituting the Lagrangian (2.3) into (2.2), the dynamics of the whole system can be obtained

$$(M+m)\ddot{x}+mr\cos\theta\ddot{\theta}-mr\sin\theta\dot{\theta}^2+C\dot{x}+Kx+(M+m)\ddot{x}_g=0$$
$$mr\cos\theta\ddot{x}+(mr^2+J)\ddot{\theta}=N \tag{2.4}$$

For the convenience of controller design, the dynamics can be rewritten as follows

$$\begin{aligned}\dot{x}_1 &= x_2\\ \dot{x}_2 &= f_1(X)+b_1(X)N\\ \dot{x}_3 &= x_4\\ \dot{x}_4 &= f_2(X)+b_2(X)N\end{aligned} \tag{2.5}$$

where

$$[x_1,x_2,x_3,x_4]^T=\left[x,\dot{x},\theta,\dot{\theta}\right]^T$$
$$f_1(X)=\frac{(mr^2+J)[mr\sin\theta\dot{\theta}^2-Kx-C\dot{x}-(M+m)\ddot{x}_g]}{(M+m)(mr^2+J)-(mr\cos\theta)^2}$$
$$b_1(X)=-\frac{mr\cos\theta}{(M+m)(mr^2+J)-(mr\cos\theta)^2}$$
$$f_2(X)=-\frac{mr\cos\theta[mr\sin\theta\dot{\theta}^2-Kx-C\dot{x}-(M+m)\ddot{x}_g]}{(M+m)(mr^2+J)-(mr\cos\theta)^2}$$
$$b_2(X)=\frac{M+m}{(M+m)(mr^2+J)-(mr\cos\theta)^2}$$

3. HIERARCHICAL SLIDING MODE CONTROLLER

Frequently used linear control methods like LQR and LQG are no longer applicable for the structure-AMD system with rotating actuator, because of the existence of nonlinearity in (2.4). Thus, the sliding mode arithmetic is adopted to design the controller because its potential to suppress the inaccuracy in modeling, and uncertainty of disturbance. Apparently, the system has more independent state variables than control inputs, which makes it an underactuated system. Therefore, the special Hierarchical Sliding Mode Control method is adopted to design the controller [12].

Two groups of state variables (x_1,x_2) and(x_3,x_4) can be treated as two subsystems of the entire system. For the two subsystems we construct a pair of sliding surfaces as first-level surfaces

$$s_1=c_1x_1+x_2,\, s_2=c_2x_3+x_4 \tag{3.1}$$

where c_1 and c_2 are positive constants. Apparently, if the two groups of state variables can reach the first-level surfaces, x and θ will attenuate to zero exponentially.

Using the equivalent control method, the equivalent control law of the subsystems when the system is on the first-level surfaces can be obtained as

$$\begin{aligned}u_{eq1}&=-\frac{f_1(X)+c_1x_2}{b_1(X)}\\ u_{eq2}&=-\frac{f_2(X)+c_2x_4}{b_2(X)}\end{aligned} \tag{3.2}$$

To ensure that each subsystem follows its own sliding surface, the total control law must include some portion of the equivalent control law of each subsystem. We define the total control

$$N=u_{eq1}+u_{eq2}+u_{sw} \tag{3.3}$$

Where u_{sw} is the switch control part of the sliding controller. Then construct the second-level sliding surface as follows

$$S = \alpha s_1 + \beta s_2 \tag{3.4}$$

The switch control can be figured out using the Lyapunov stability theory. The Lyapunov energy function of structure-AMD system can be defined as

$$V(t) = \frac{1}{2} S^2 \tag{3.5}$$

Differentiating V (t) with respect to time t obtains

$$\dot{V}(t) = S\dot{S} = S(\alpha \dot{s}_1 + \beta \dot{s}_2) = S\left[\beta b_2 u_{eq1} + \alpha b_1 u_{eq2} + u_{sw}(\beta b_2 + \alpha b_1)\right] \tag{3.6}$$

Let

$$\beta b_2 u_{eq1} + \alpha b_1 u_{eq2} + u_{sw}(\beta b_2 + \alpha b_1) = -\eta \,\mathrm{sgn}(S) - \kappa S$$

Then

$$u_{sw} = -(\beta b_2 + \alpha b_1)^{-1}[\beta b_2 u_{eq1} + \alpha b_1 u_{eq2} + \eta \,\mathrm{sgn}(S) + \kappa S] \tag{3.7}$$

We find

$$\dot{V}(t) = -\eta |S| - \kappa S^2 \leq 0 \tag{3.8}$$

Thus the second-level sliding surface is stable, and the final control input is

$$N = u_{eq1} + u_{eq2} - \frac{\beta b_2 u_{eq1} + \alpha b_1 u_{eq2} + \eta \,\mathrm{sgn}(S) + \kappa S}{\beta b_2 + \alpha b_1} \tag{3.9}$$

In Reference [12], W. Wang et al. proved the stability of all the sliding surfaces, so we don't discuss that any more. The existence of sign function in (3.9) will cause chattering phenomena in the control input *N*. The chattering has adverse effect on the control effectiveness. To solve this problem, the boundary layer method is introduced to eliminate the chattering in *N*. This method is to replace the sign function *sgn*(*S*) with *sat*(*S*), which is a linear function with saturation.

$$sat(S) = \begin{cases} +1 (S > \triangle) \\ \lambda S (|S| \leq \triangle) \\ -1 (S < \triangle) \end{cases} \tag{3.10}$$

Where λ is a positive constant. In this way, control input *N* becomes continuous when *S* varies within the range of (-Δ, Δ) for the introduction of linear part. Replacing *sgn*(*S*) with *sat*(*S*) in (3.9), the control input *N* with chattering elimination can be obtained.

4. EXPERIMENTAL ANALYSIS

In order to study the validity of AMD system with rotating actuator in structural vibration control, we construct the experimental platform as depicted in Figure 4.1. Single board dSPACE (RS1104) system is used as the control unit. Control torque *N* is provided by the Maxon EC flat 244879 motor, and Nemicon OVW2-1024-2MD encoder is adopted to measure the rotating angle of the mass *m*. The displacement of target structure is measured with the Sensopart FT 80 RLA laser displacement sensor.

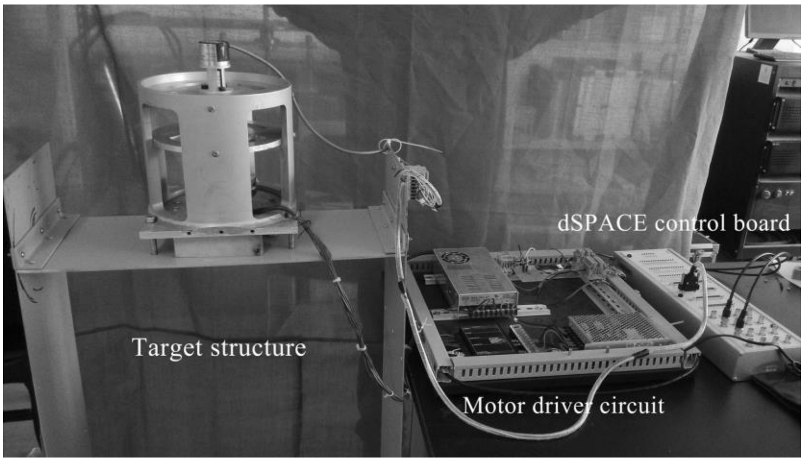


Figure 4.1 Experimental platform of structure-AMD system with rotating actuator

Through parameter identification, we can get the parameters of the platform we build, which are presented in Table 4.1.

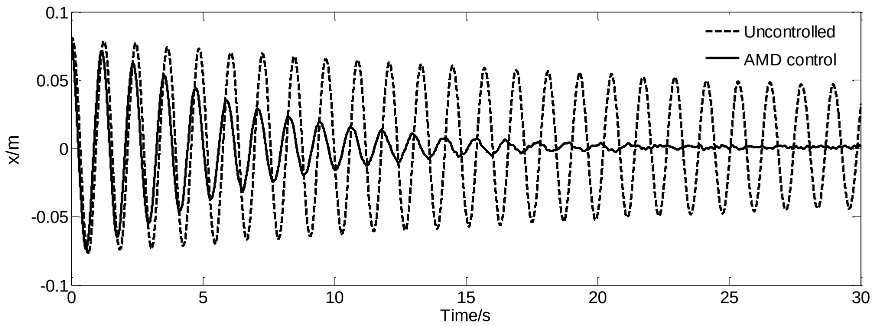
Table 4.1 System parameters

Items	Value	Items	Value
M	10.235kg	*K*	295N/m
m	0.71kg	*C*	0.643Ns/m
r	0.05m	Height of structure	1.8m
J	0.001kgm^2	Width of structure	0.5m

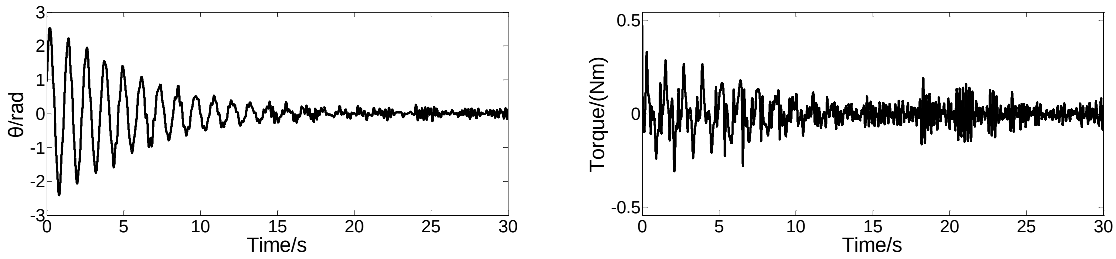
Then, control tests of structure-AMD system with initial displacement and earthquake excitation are conducted on the experimental platform. The peak and RMS value of structural displacement are shown in Table 4.2. Figure 4.2 and Figure 4.4 show the specific experimental results with two different excitations.

Table 4.2 Experimental analysis: Peak and RMS of structural displacement

Excitations		Initial displacement excitation	Earthquake excitation
Peak values	uncontrolled/mm	-	40.2
	AMD control/mm	-	31.0
	Peak reduction	-	22.9%
RMS values	uncontrolled/mm	42.6	18.0
	AMD control/mm	19.5	7.3
	RMS reduction	54.23%	59.4%



(a) Structural displacement response



(b) Angle of rotating mass under AMD control (c) Control torque

Figure 4.2 Control test of AMD-structure with initial conditions: $(x, \dot{x}, \theta, \dot{\theta}) = (0.08, 0, 0, 0)$

Figure 4.2(a) shows the different structural response without control and under AMD control. For the without-control situation, it takes 140 seconds for the structural displacement reducing to 10% of initial value. As a contrast, it only takes 14 seconds when control force is imposed on the structure. Judging from the RMS of displacement, the RMS reduction is 54.23%.

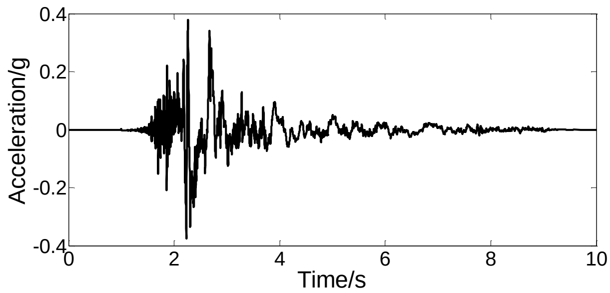
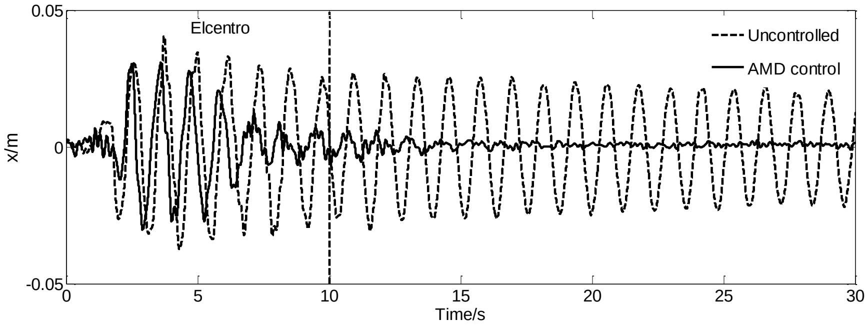
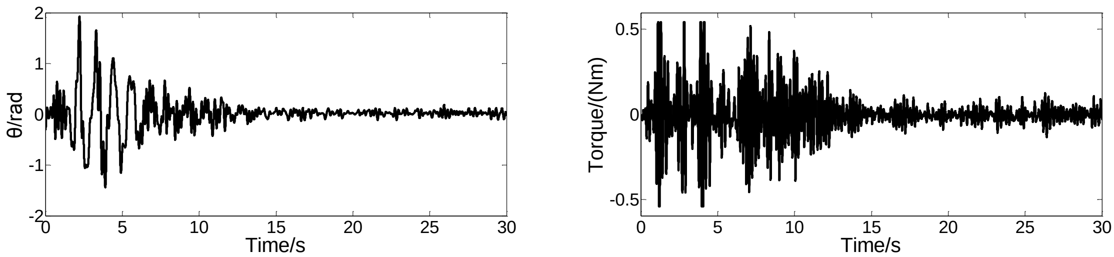


Figure 4.3 Elcentro quakewave



(a) Structural displacement response



(b) Angle of rotating mass under AMD control (c) Control torque

Figure 4.4 Control test of AMD-structure under Elcentro quakewave excitation

Figure 4.4(a) shows the structural response with earthquake disturbance. The El centro earthquake is considered as the environmental disturbance in these tests, whose acceleration time history is presented in figure 4.3. It can be observed that, control force from the AMD device makes an significant contribution to suppress the structural vibration. More specifically, the peak reduction and RMS reduction of displacement are 22.9% and 59.4% under the AMD control.

Through making a comparison between different structural responses with/without control, it concludes that the AMD system with rotating actuator can suppress the structural vibration effectively for different excitations.

5. CONCLUSIONS

An innovative rotating actuator in AMD system for structural vibration control is proposed in this paper, and its modeling and control are discussed. Experimental results validate the effectiveness of AMD with rotating actuator in the suppression of structural vibration. The inertial mass driven by rotating actuator has circular movement which solves the problem of limited mass stroke. The AMD device proposed hereinbefore is effective in the structural vibration control for one kind of steel-frame structure. However, because of the complex nonlinearity of civil structures, randomness of environmental disturbance, and the fact that rotating actuator has not been researched sufficiently, the application of AMD with rotating actuator in structural vibration control needs further research.

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