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Experimental test of asymmetrical cable-stayed bridges using MR-damper for vibration control

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ABSTRACT

In this paper, a semi-active control by MR-damper is researched; its purpose is to effectively control vibration of asymmetrical cable-stayed bridges when earthquake is loaded on the type of bridge. For an experimental study, a model of 10.2 m high and 28 m long asymmetrical cable-stayed bridge structure was built being similar to a real one in size and function. A MR damper was also designed in proper size suitable for the control of the model. The experiment was performed in the way in which three piers were fixed on three shaking tables with 30% of El-centro earthquake wave, and a control device was placed on the lower part of its upper deck for horizontal control. As for control algorithms, Lyapunov and Clipped-optimal control algorithms were applied. The effectiveness of the semi-active control with MR damper for the asymmetrical cable-stayed bridge was measured under five control conditions: Un-control, Passive-off, Passive-on, Lyapunov Control, Clipped-optimal Control. The experiment showed that the semi-active control applying Lyapunov and Clipped-optimal algorithms effectively increased controllability almost in double, and decreased displacement 75% compared with the condition of passive-off. Therefore the semi-active method suggested in this paper is proven effective in controlling asymmetrical cable-stayed bridges.

1. Introduction

Almost all structures are commonly exposed to unexpected and uncertain loads like moving traffic, typhoon, earthquake, and other natural disasters. Specially, cable-stayed bridges are even more vulnerable to such devastating loads for their structural flexibility. In spite of their vulnerability, cable-stayed bridges continue to be built by virtue of their beautiful appearance. For the reason, many researches are being done on how to control the harmful vibration of the bridges to secure their safety and effective long-term maintenance [1–4].

Among various methods to control the vibration of bridges, the semi-active control method is particularly being studied in terms of control device or control algorithm. As for the researches on control device, they study on MR (Magneto-Rheological)-damper, orifice fluid damper, controllable friction damper, smart tuned mass damper, etc. Specially, since MR developed by Carlson at Lord was introduced into civil engineering, its application has been studied for the control of structural vibration [5–7].

Although MR damper may not function well due to MR fluid's inherent viscosity when it is not used for a long time, the MR-damper applied semi-active control is highly effective with minimum power by making it possible to receive fast control response. Also its mechanical simplicity and sturdiness is found very useful for the vibration control of large-scale structures, and so it is consistently being researched [8–10].

In order to control the vibration of structures with the semi-active method and also eventually develop a unified control system, a choice of proper algorithm is very important. Spencer and Dyke et al. performed a research of contrasting and comparing various control algorithms and control devices in terms of strength and shortcoming, and also an interpretative research for criteria for their evaluation [11,12]. Anat et al. presented an ideal interpretation of MR damper along with its frictional and viscous quality, and performed an experiment on the semi-active control method with MR damper of Lord (RD-1005-5-2) applying two kinds of control algorithm and inflicting a repeated load on a connected three-span structure which was 1 m in length and was 0.49 m in height [13]. Besides that, there were many other researches most of which were numerical and interpretative ones [11,14], and only a few were experimental. Even those experimental researches focused merely on the constitution of wireless system and its evaluation rather than on control algorithm and effective control device. And their target structures were mostly buildings rather than bridges [15].

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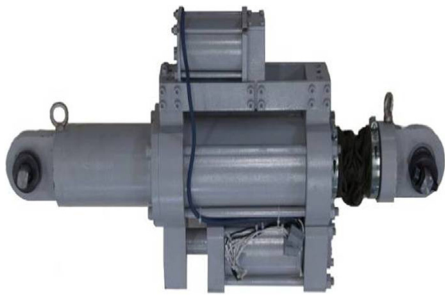

Fig. 1. Control device: MR damper.

Yet, this research is distinguished from the previous ones by being concerned with bridges instead of buildings, control algorithm and control device instead of wireless system. It also experimentally studies on how to control bridge vibration effectively with a control device, particularly with MR damper. It assumes its vibration is caused by earthquake. For an experiment, a MR damper is designed and manufactured to suit the bridge, and its performance is tested. It is important to secure the validity of the acquired data so that a dynamic model is defined theoretically and analytically. Also to verify the control capacity of MR damper, its dynamic model is simulated. Finally the MR damper's control performance is tested and verified through an experiment on an asymmetrical cable-stayed bridge loaded with earthquake. We also choose a semi-active control algorithm which suits well the structural feature of the bridge. And with its application, experiments are performed under five control conditions such as un-control, passive off, passive on, Lyapunov control, and Clipped-optimal control. As a result, we verify the semi-active control method with MR damper is effective for vibration control of asymmetrical cable-stayed bridges.

2. Semi-active control

The semi-active control has two ways: one is to directly control a structure and the other is to employ an algorithm which enables us to judge when to activate the control device. In this research, we designed and manufactured a MR damper of our own. In addition to that, as algorithms, we also selected and applied both Lyapunov and Clipped-optimal in virtue of their applicability to the structural uniqueness of asymmetrical cable-stayed bridges.

2.1. Control device

The model structure on which we performed an experiment is 28 m long, whose main tower is 10.2 m in height. Its three piers are designed to be placed on each different test table. Its design also considers and measures the propriety of possible controllability of the model structure. Fig. 1 shows the MR damper that we designed for this experiment.

After designing the MR damper of Fig. 1, we had SANWA TEKKi Corporation actually manufacture one that would have a controllability of 30 kN, a control displacement of ±70 mm, and a maximum velocity of 60 mm/s (Table 1).

Table 1
Specification of MR-damper.

Items	Condition
Stroke	140 mm (±70 mm)
Maximum force (nominal)	30 kN
Cylinder bore	100 mm
Piston rod diameter	50 mm
Coil diameter	⌀ 0.55 mm
Coil turns	3 @ 280 turns
MR fluid	Lord MRF
Gap	1.0 mm
Maximum velocity	60 mm/s

2.2. Control algorithm

2.2.1. Lyapunov algorithm

Lyapunov algorithm was employed by Leitmann who took a direct approach to the design of semi-active controller [16]. The Lyapunov algorithm is in the following equation:

$$V(z)=\frac{1}{2}\|z\|^2=\frac{1}{2}[z^TPz] \tag{1}$$

Here, $\|z\|_p$ refers to P-norm of system states, and P is a real number and a symmetric positive definite. In a linear system, $\dot{V}(z)$ is supposed to be a negative definite. To make sure $\dot{V}(z)$ is a negative definite, a determinant P is obtained by applying the Lyapunov equation as follows:

$$A^TP+PA=-Q_P \tag{2}$$

Here, Q_p is a positive definitive determinant, which is determined by the designer's assumption and experiences. To get a solution for Eq. (2), it is necessary to induce a state-space equation in a form of differential function of Lyapunov, which is as in (3), that is, a rate of chronological change ($\Delta V=\dot{V}$) of Lyapunov.

$$\dot{V}(z)=-\frac{1}{2}z^TQ_Pz+z^TPBf_c+z^TPE\ddot{x}_e \tag{3}$$

In that equation, P refers to a solution of Lyapunov equation for the system, Q_p to a weight matric, and T to transpose. The middle term including f_c is the only one that directly affects the voltage change for the control of the system. In the case where MR damper is applied for the stabilization of the system, the voltage v_i that would minimize $\dot{V}(z)$ can be generated in Eq. (4), which in turn becomes a control law of Lyapunov control algorithm-applied semi-active control system where feedback is possible.

$$v_i=V_{max}H((-z)^TPB_if_i) \tag{4}$$

$H(\cdot)$ is a function, Heaviside step function, which limits the input voltage for the controller to somewhere between 0 and V_{max}. The lower letter i is to express the number of controllers in the case where there are multiple. v_i refers to a specific control voltage which needs to be input at a specific stage, B_i to the i of B determinant which has the same number of controller as in the early state equation. f_i Refers to the control capacity which was generated and observed in the earlier i stage, while V_{max} indicates a maximum voltage which is to be input to the controller according to the limit condition at a current stage. Finally Lyapunov control algorithm determines the control performance by deciding on Q_p determinant which would be appropriate to the stabilization of a system.

2.2.2. Clipped-optimal algorithm

Clipped-optimal control algorithm was suggested by Dyke et al. as a semi-active control method [17]. It is for the design of a linear optimal controller $K_c(s)$, and calculates the control capacity $f_c=[f_{c1}, f_{c2}, \ldots, f_{cn}]^T$ of MR damper by using the observed control capacity f and the structural response y, as shown in the following