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Scissor-Jack-Damper System for Reduction of Cable Vibration

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ABSTRACT

In this paper, the feasibility of the high-performance damping device vibration suppression of stay cables has been investigated. The proposed damping system consists of a linear viscous damper and a scissor-jack-type toggle linkage. Since the mechanism of the scissor-jack-type toggle linkage amplifies the relative displacement of the linear viscous damper, it is expected that the capacity of the viscous damper used in the scissor-jack-damper energy dissipation system can be reduced without the loss of the control performance. Numerical simulation results demonstrate the efficacy of the damping system employing the scissor-jack-type toggle linkage. Therefore, the proposed damping system could be considered as one of the promising candidates for suppressing vibration of stay cable.

INTRODUCTION

Cable-stayed bridges have become a popular type of bridges throughout the world because of its aesthetic shape, structural efficiency, and economical construction. These bridge structures tend to become longer and slender through advance of analysis and design technologies and development of high-strength/high-quality materials. However, these long-span bridges might be challenged by many problems caused by their flexible characteristics of their cable-superstructure system and low structural damping. Especially, long steel stay cables, such as are widely used in cable-stayed bridges, are highly susceptible to vibration

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caused by wind, rain and support motion due to their large flexibility, relatively small mass and extremely low inherent damping. The cable vibration can result in reduction of cable and connection life due to premature failure and/or breakdown of corrosion protection as well as the risk of losing public confidence in such structures.

A number of methods, such as tying multiple cables together, passive, semiactive, and active control, have been proposed and/or implemented to suppress cable vibrations, though each method has its limitations. Tying cables together deteriorates the aesthetics of the cable-stayed bridge and changing the surface of the cable is impractical for retrofitting applications and may increase motion during high winds. Active transverse and/or axial control of cable vibration may require power sources beyond practical limits, given the number of cables on a typical cable-stayed bridge and the isolated locations at which they are often placed. To overcome weak points of the active control, semiactive control, whether of the variable orifice, controllable friction, or controllable fluid varieties, have been proposed(Housner et al 1997; Spencer and Sain 1997) and can potentially achieve performance levels nearly the same as comparable active devices with few of the detractions. However, semiactive control system have difficulties applying to the long steel cables at severe weather conditions because of realistic limitations such as the need of power sources and control systems including complex computational device and measuring instruments. In structural fields, discrete passive viscous have been used on lots of bridges. It has been, however, demonstrated that the damper attachment location should be typically restricted to be within 5% of the cable length from the cable anchorage and passive damper cannot provide supplemental damping with damper location smaller than 2% of the cable length. In such a case, passive linear viscous dampers may add insufficient damping to the cables. Thus, for sufficient vibration suppression of stay cables, it needs large capacity of the damper or a special device using mechanism of amplifying the capacity of a linear viscous damper.

This paper introduces a special type of toggle systems which can reduce the optimal capacity of a linear viscous damper without the loss of the control performance. It will be demonstrated via numerical simulation that the scissor-jack-damper system is eminently suitable for stay cable affected by wind and earthquake-induced vibrations.

HIGH-PERFORMANCE DAMPING DEVICE USING TOGGLE SYSTEM

Introduction to Toggle system

Energy dissipation systems are being employed to provide enhanced protection for new and retrofit building and bridge construction. Particularly, Engineers are familiar with and have extensively used diagonal and chevron brace configurations for the delivery of forces from energy dissipation devices to the structural frame. Illustrated in Fig. 1, the displacement of the energy dissipation devices is either less than (case of diagonal brace) or equal to (case of chevron brace) the drift of the story at which the devices are installed. That is

$$u_D = \alpha \cdot u \qquad (1)$$

Where u_D = device (or damper) relative displacement along the axis of the damper; u = interstory drift; and α = magnification factor. For the chevron brace configuration, $\alpha = 1.0$, whereas for the diagonal configuration, $\alpha = \cos\theta$, where θ = angle of inclination of the damper.

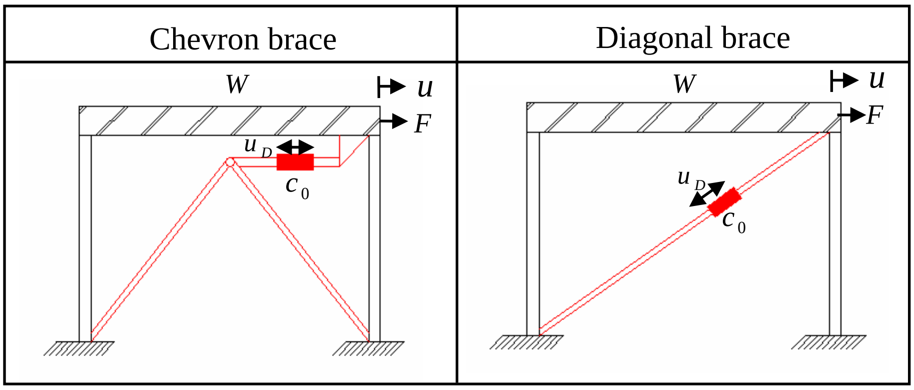


Fig. 1. Illustration of a single-story structure with diagonal and chevron brace.

It is generally recognized that stiff structural systems under seismic load or wind load undergo small drift and small interstory velocities. The required damping forces are large. However, illustrated in Figure 2, toggle configurations utilize shallow trusses to magnify the effect of the structural drift on the damper displacement and also to magnify the small damper force and deliver it to the structural frame.

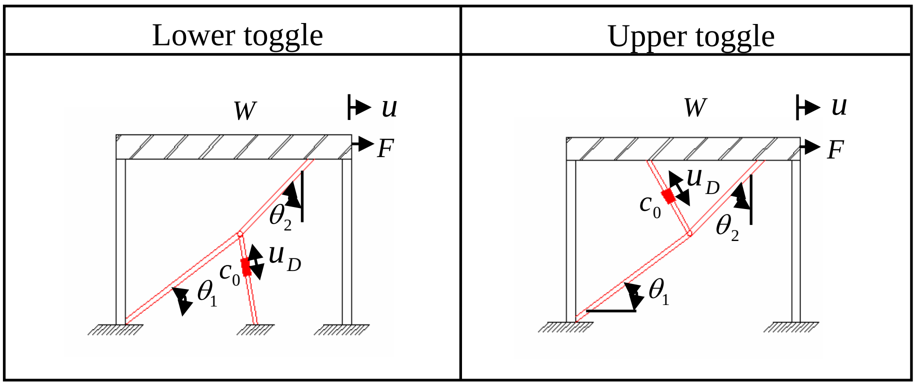


Fig. 2 Illustration of toggle-brace-damper configuration.

Moreover, energy dissipation devices cannot be used in certain areas due to open space requirements and the ineffectiveness of damping systems when installed at near-vertical configurations. With this intent, the scissor-jack-damper system (Fig. 3) was developed as a variant of the toggle-brace-damper system.

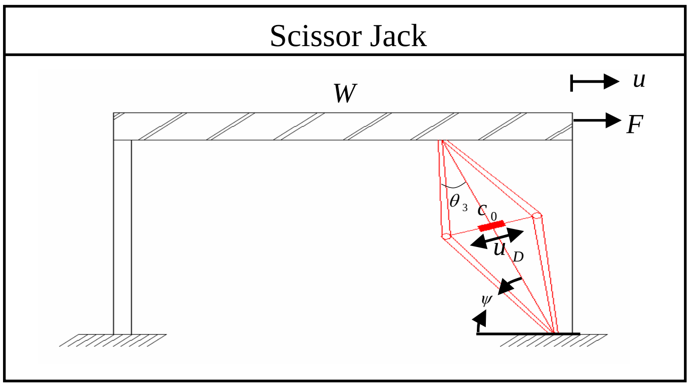


Fig. 3. Illustration of scissor-jack-brace damper configuration.

The system combines the displacement magnification feature with small size, which is achieved through compactness and near-vertical installation. These damper configurations have a complex nonlinear relation between the damper displacement u_D and drift u. Accordingly, under the assumption of small rotations, simple expressions for the magnification factor can be obtained as follows.

· for the lower toggle system

$$\alpha = \sin\theta_2 / \cos(\theta_1 + \theta_2) \tag{2}$$

· for the upper toggle system

$$\alpha = \sin\theta_2 / \cos(\theta_1 + \theta_2) + \sin\theta_1 \tag{3}$$

· for the scissor-jack-damper system

$$\alpha = \cos\psi / \tan\theta_3 \tag{4}$$

Equations (2)-(3) reveal that if angles of $\theta_1, \theta_2, \theta_3$ and ψ are $31.9°$, $43.2°$, $9°$, and $70°$ respectively, they have magnification factor values of 2.66 (lower toggle system), 3.19 (upper toggle system), 2.16 (scissor-jack-damper system) substantially greater than unity.

Scissor-jack-damper system for suppressing vibration of stay cable

Several damper systems that introduce in the preceding section have almost been studied for and applied to architectural structure. This paper shows that the scissor-jack-damper system is eminently suitable for stay cable affected by wind and earthquake-induced vibrations. The scissor-jack damping system can be installed in configuration as shown in Figure 4. As the figure suggests, angle ψ, the angle between the displacement of the scissor-jack damper and the displacement of the cable, is $0°$. It follows that the magnification factor of the scissor-jack-damper system can be written as

$$\alpha = 1/\tan\theta \tag{5}$$

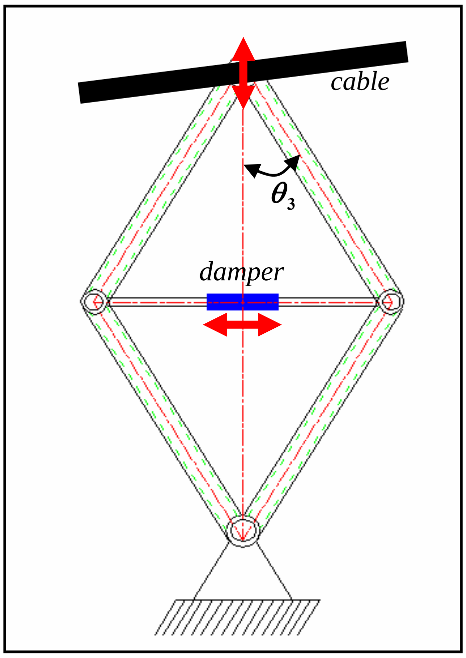


Fig. 4. Illustration of Scissor-Jack-Brace Damper Configuration for stay cable.

It is essential to realize that the magnification factor of the cable is greater than that of the structural frame because the angle ψ approaches $0°$; if angles of θ is $9°$, it has magnification factor values of 6.31 substantially greater than the value that is obtained from Equation (4). Also, the damping force F, exerted on the cable by the damper assembly is given by

$$F = c_0 \cdot \alpha^2 \cdot \dot{u} \tag{6}$$

in which $c_0 =$damping coefficient, and $\dot{u} =$velocity of cable. As Equation (6) suggests, scissor-jack-damper system can amplify the small damper force f and deliver it to the cable. Furthermore, it provides the advantage that it can obtain the same performance for suppressing vibration of stay cable compared with that of stay cable equipped with linear viscous damper system and reduce the required damping force.

Cable Model

Stay cables typically have small sag (1% sag-to-length ratio of less) with high tension-to-weight ratio. With small sag, the motion of the cable may be modeled by the motion of a taut string (Irvine 1981). Therefore, the transverse motion of the cable with a damper attached transverse to the cable is described as shown in Figure 5, where $v(x,t)$ is the transverse deflection of the cable, L is the length of cable, x_d is the loation of the of the damper, $F_d(t)$ is the damper force, T is the cable tension, m is the cable mass per unit length and ς is the modal damping ratio.

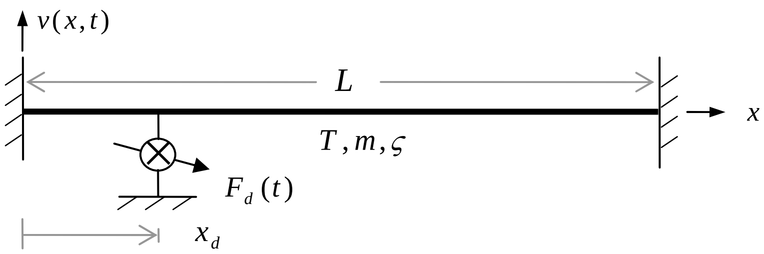


Fig. 5. Cable with attached damper

The motion of the taut cable in the linear range is described by the following partial differential equation,

$$m\ddot{v}(x,t) + c\dot{v}(x,t) - Tv''(x,t) = f(x,t) + F_d(t)\delta(x - x_d) \tag{7}$$

where $f(x,t)$ is the external load and c is the cable viscous damping coefficient per unit length.

Assuming that the transverse deflection may be approximated using a finite series as

$$v(x,t) = \sum_{j=1}^{n} \phi_j(x)\ \eta_j(t) \tag{8}$$

where n is the number of modes considered, $\eta_j(t)$ is the generalized displacement and $\phi_j(x)$ is the shape function.

Several hundred terms in the sine series are usually used as shape functions, even though it takes considerable computation effort. However, controllers with such complexity can cause various problems in the control design and implementation stages. Johnson et al. (2000) showed that introducing shape function (equation 9) based on the deflection due to a static force at the damper location can reduce the number of terms required for the comparable accuracy.

$$\phi_1(x) = \begin{cases} x / x_d & 0 \le x \le x_d \\ (L-x) \; / (L - x_d) & x_d \le x \le L \end{cases} \tag{9}$$

$$\phi_{j+1}(x) = \sin \pi \; jx \qquad\qquad j \ge 1 \tag{10}$$

We can get the equation of motion written in matrix form from a standard Galerkin approach as

$$M\ddot{\eta}(t) + C\dot{\eta}(t) + K\eta(t) = \mathrm{f}\,(t) + \varphi\, F_d\,(t) \tag{11}$$

resulting in the mass matrix M ,

$$M = [m_{ij}], \;\; m_{ij} = m\int_0^L \phi_i\,(x)\,\phi_j\,(x)dx \tag{12}$$

the stiffness matrix K ,

$$K = [k_{ij}], \;\; k_{ij} = -T\int_0^L \phi_i{}'\,(x)\,\phi_j{}'\,(x)dx \tag{13}$$

the load vector f ,

$$\mathrm{f} = [\, f_i \,], \quad f_i = \int_0^L f\,(x,t)\phi_i\,(x)dx \tag{14}$$

and the damper force vector φ ,

$$\varphi = \phi(x_d) = [\phi_1(x_d) \;\; \phi_2(x_d) \;\; \cdots \;\; \phi_n(x_d)]^T \tag{15}$$

And the damping matrix C can be derived from mass, stiffness matrices and the given set of modal damping ratios.

NUMERICAL ANALYSIS

System Identification for Cable Damping Model

To evaluate the performance of scissor-jack-brace damper system with linear viscous damper of cable vibration, a numerical example is considered in which a flat-sag cable is controlled with scissor-jack-brace damper system or linear viscous damper system. All of dampers is positioned at 0.253m (2% of the cable length) from the bottom support and provides in-plane forces transverse to the cable.

The flat-sag cable is a stainless wire rope and the cable characteristics identified by Christenson (2001) are shown in Table 1, where L is the length of the cable, m is the cable mass per unit length, T is the cable tension, ς is the modal damping ratio, and ω_1 is the first natural frequency of cable

Table 1. Cable characteristics

parameter	value
L	12.65 m
m	0.747 kg/m
T	2172 N
ς	$\varsigma_1 = 0.0015$ $\varsigma_2 = 0.003$ $\varsigma_3 = 0.005$ $\varsigma_{i\geq 4} = 0.0005$
ω_1	2.89 Hz

External Load

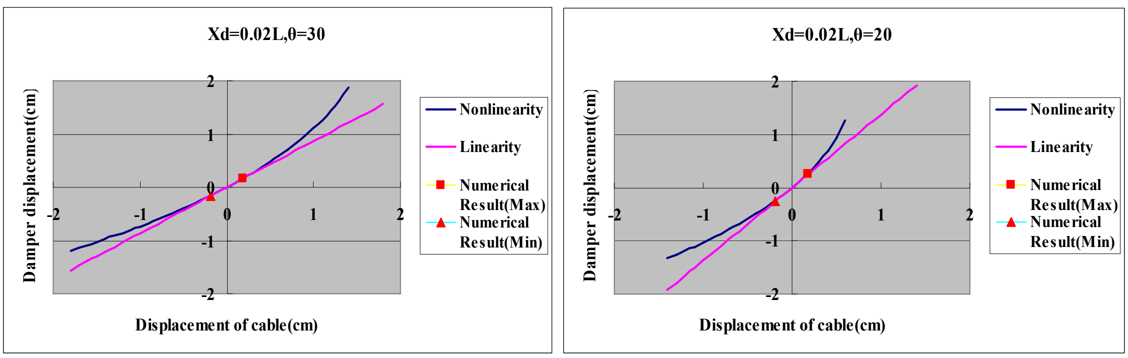
The phenomena that cause various complicated nonlinear cable behaviors are not well understood and there is no well established model of cable motion. However, it has been observed that the response tends to be dominated by the first few modes. The excitation is assumed to be a subset of the series in equation (10) using one term

$$f(x,t) = W(t)\sin \pi \frac{x}{L} \tag{16}$$

where $W(t)$ is assumed as zero-mean Gaussian white noise process with $E[W(t)W(t+\tau)] = \delta(\tau)$ and wind load from Third Generation Benchmarks for Building (Yang et al. 2000). In the absence of a damper, this excitation would result in mainly first mode response (Johnson et al. 2001).

The consideration of Nonlinearity of Scissor-Jack-Damper

The proposed magnification factor of scissor-jack-brace damper system (equation 5) can be obtained under the assumption of linearity. Accordingly, it needs to examine that the numerical analysis using the proposed linear magnification factor is reasonable. As mentioned about nonlinearity of the toggle system (Hwang, Jae-Seung et al. 2005), Equation (5) cannot be expressed in the strict sense of the word because of the nonlinear relation between device (or damper) relative displacement (u_D) and displacement of cable (u). However, as illustrated in Figure 6, the results of numerical analysis with the proposed linear magnification factor show that damper relative displacement is no difference between case of nonlinearity and linearity in the range of maximum relative displacement of cable. Accordingly, using simple expression for magnification factor (equation 5) is comparatively appropriate for applying to scissor-jack-damper configuration attached on the cable.



(a) In case of $\theta = 30°$ (b) In case of $\theta = 20°$

Fig. 6. The magnification displacement of Scissor-Jack-Brace Damper System

Comparative Study on the Performance Verification between Scissor-Jack-Damper System and linear Viscous Damper

To compare the proposed high-performance damping system with the general damping system using a conventional viscous damper, identical linear viscous damper, which is directly proportional to velocity of the device, is considered. In the case of a linear viscous damper with a damper coefficient, C_0, the damper force is described by

$$F_d(t) = C_0 v(x_d, t) \tag{17}$$

In the stay cable attached on the linear viscous damper, considered a different range of values of the damper coefficient C_0, including the optimum, maximum displacement at midspan, quarter span, RMS displacement and velocity of the cable is estimated. For an attached linear viscous damper, it has been demonstrated that an optimal damper coefficient exists for a given cable configuration (Pacheco et al. 1993). In this case, the optimal value using viscous damper is $C_{0,viscous} = 600 N \cdot \sec/m$ at damper location ($x_d = 0.02$) as shown in Fig. 7.

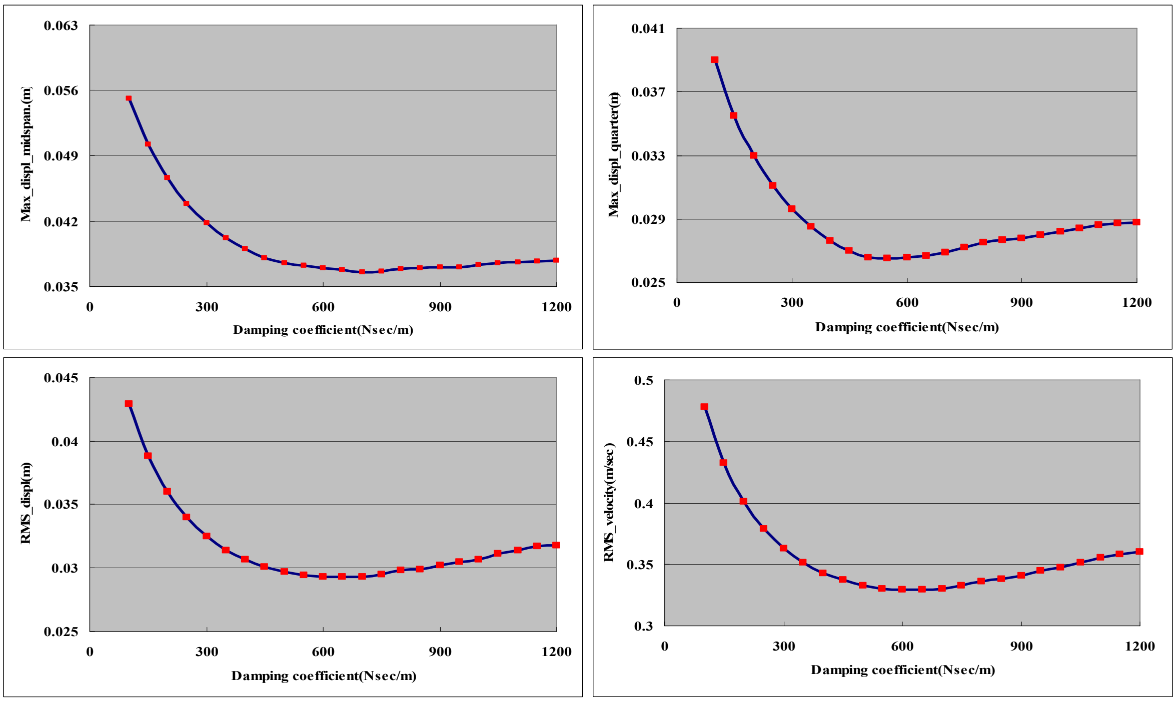


Fig. 7. Numerical results using gaussian white noise process
(The linear viscous damper)

As illustrated in Figure 8, 9, an optimal damper coefficient using the proposed damper system also exists for a given cable configuration. The optimal value is $C_{0,proposed} = 150 N \cdot \sec/m$ at damper location ($x_d = 0.02$) shown in Fig. 8. In this case, angles of θ is $30°$, and it has magnification factor values of 1.73 (equation 5). Furthermore, the optimal value is $C_{0,proposed} = 50 N \cdot \sec/m$ at damper location ($x_d = 0.02$) shown in Fig. 9. In this case, angles of θ is $20°$, and it has magnification factor values of 2.75 (equation 5).

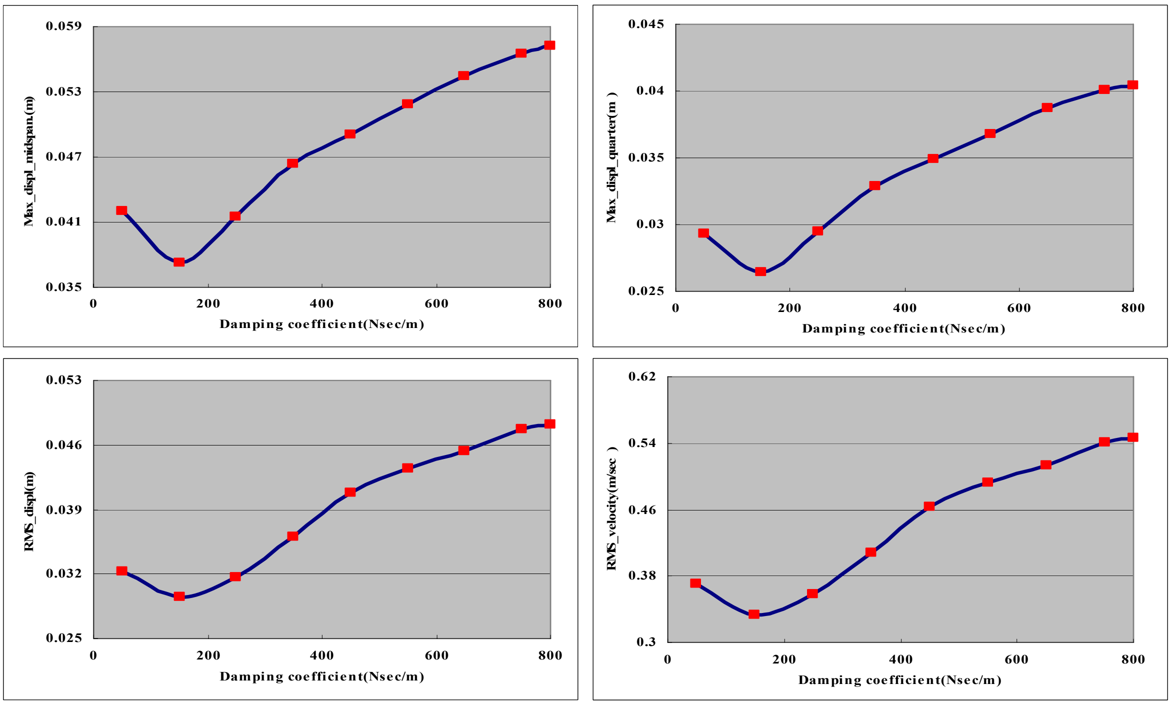


Fig. 8. Numerical results using gaussian white noise process
(The proposed high-performance damping system; $\theta = 30°$)

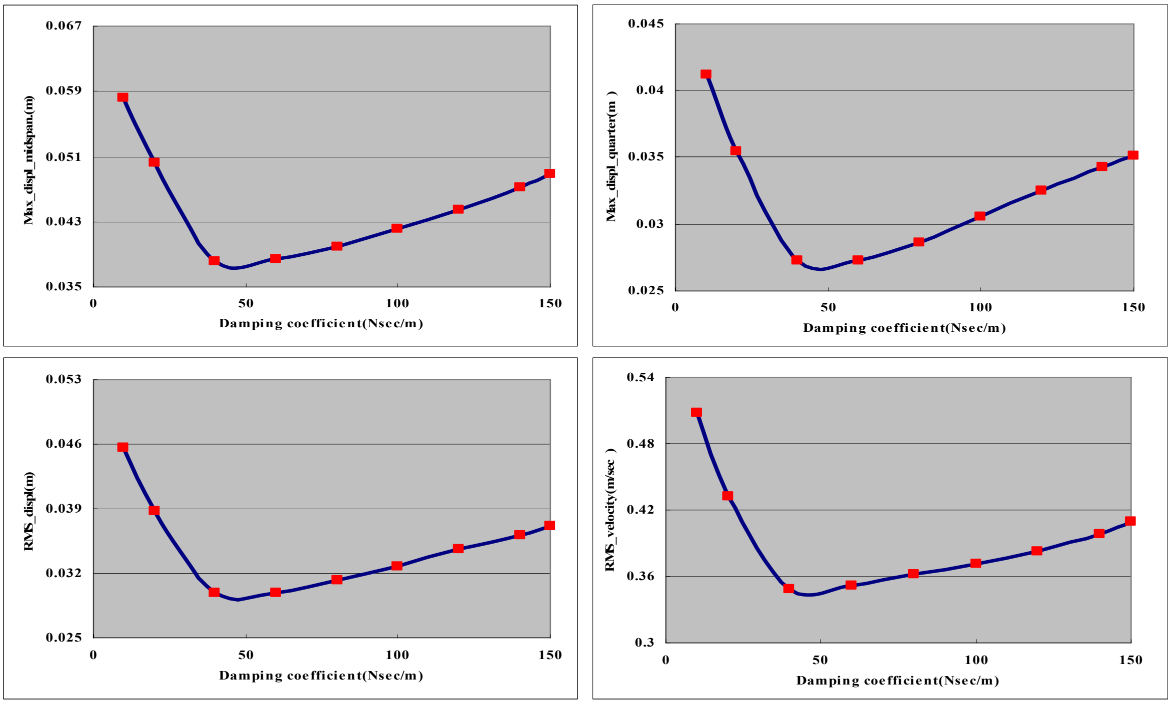


Fig. 9. Numerical results using gaussian white noise process
(The proposed high-performance damping system; $\theta = 20°$)

As mentioned above, the proposed high-performance damping system with linear viscous damper amplifies the relative displacement of the linear viscous damper. In this reason, the capacity of the viscous damper used in the scissor-jack-damper is reduced without the loss of the control performance. The numerical results represent that the scissor-jack-damper system reduce the capacity of the viscous damper by 75% using $\theta = 30°$, by 92% using $\theta = 20°$ over the linear viscous damper. The numerical simulation results demonstrate the efficacy of the damping system employing the scissor-jack-damper system.

CONCLUSION

The potential of using scissor-jack-dampers to control stay cable vibration has been demonstrated through numerical analysis of comparison with both scissor-jack-dampers and a linear viscous damper. The proposed high-performance damping system provides the advantage that it can obtain the same performance for suppressing vibration of stay cable compared with that of stay cable equipped with optimal linear viscous damper and reduce the required damping force. In other words, it provides economical effects reducing the required capacity of the linear viscous damper.

There are several issues that must be studied to further prove the concept of scissor-jack-dampers of stay cables. First, while the level of sag in cables of cable-stayed bridges is typically small (Irvine 1981), some studies have shown that passive damper performance is reduced some by sag(e.g., Sulekh 1990; Xu and Yu 1998). A study by the authors of the performance of the proposed high-performance damping system for inclined flat-sag cables with axial flexibility is in progress. Furthermore, laboratory experiments and full-scale applications are needed to prove the potential indicated herein. Finally, structural buckling of truss members consisted of a scissor-jack-damper system should be considered.

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