

# MITIGATION OF INELASTIC BRIDGE RESPONSE BY VARIABLE DAMPERS WITH VISCOUS-PLUS-VARIABLE-FRICTION DAMPING FORCE ALGORITHM

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### SUMMARY

In this study, the damping force algorithm called the viscous-plus-variable-friction damping force algorithm was proposed to combine advantageous features of typical viscous and friction dampers. The proposed damping force algorithm can be represented by a viscous element placed in series with a variable-friction element. As a piston velocity increases from zero, the damping force is generated by the viscous element. This is aimed to allow energy dissipation at a small velocity. When the damping force reaches a peak value of the viscous element or a preset force limit, the sliding of the variable-friction element occurs, resulting in a constant damping force. Analyses were conducted on a highway bridge subjected to the JMA Kobe ground motion record. Variable dampers were installed between a deck and a column. From the analysis, it is found that the deck displacement of the bridge with variable dampers is smaller than that with viscous dampers for almost the entire range of damping force levels, while significantly smaller than that with friction dampers for the damping force level larger than about 30% of a deck weight. The stroke requirement of variable dampers is slightly more than that of friction dampers. The ductility demand of the column with variable dampers is significantly smaller than that with friction dampers at a large damping force. Finally, a series of cyclic loading tests of a MR damper was conducted to develop the mathematical model of the MR damper for control purpose. The MR damper was controlled to exhibit the viscous-plus-variable-friction damping force. It is found that the proposed damping force algorithm can be realized by the MR damper with a good accuracy.

### **INTRODUCTION**

Passive control systems have been widely applied to civil engineering structures to mitigate seismic responses [1]. Typical passive control devices are viscous dampers and friction dampers. The damping force of a viscous damper is linearly proportional to a piston velocity. The smooth change in a damping force leads to energy dissipation even when a piston velocity is small. However, a damping force is small at the end of a stroke due to a decrease in a velocity. It results in a large relative displacement of

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components in which the damper is installed. On the other hand, a friction damper provides a constant level of a damping force over an entire stroke, resulting in a large amount of energy dissipation if properly designed. And the relative displacement can be effectively controlled. However, at a slightly large damping force level, the amount of energy dissipation decreases significantly [2]. With an emerging semi-active control technology [3, 4], the benefits of both damping force algorithm called the viscous-plus-variable-friction damping force algorithm was proposed to combine advantageous features of typical viscous and friction dampers. Analyses were conducted on a highway bridge with variable dampers. The effectiveness of the proposed damping force algorithm was investigated. Finally, a variable damper with the proposed damping force algorithm was developed using a magnetorheological (MR) damper.

### VISCOUS-PLUS-VARIABLE-FRICTION DAMPING FORCE ALGORITHM

The combination of viscous and friction damping force algorithms called "viscous-plus-variable-friction damping force algorithm" is proposed. The model representing the proposed damping force algorithm is illustrated in Fig. 1. A viscous damping element is connected in series with a variable-friction element having a variable slipping force level. As a velocity increases from zero, the viscous damping element is mobilized to dissipate energy. Once the damping force of the viscous damping element reaches its peak value or a force limit, the slipping force of the variable-friction element is set equal to the value, resulting in the sliding of the variable-friction element. In the reverse direction, the damping force changes in the similar manner. Fig. 2 shows the damping force vs. velocity relationship of the proposed damping force algorithm is characterized by two parameters: the damping coefficient ( $C_D$ ) of the viscous damping element and the force limit ( $F_L$ ) of the variable-friction element. The force limit represents the force capacity of a variable damper.



Fig. 1 Model representing the proposed damping force algorithm



Fig. 2 Damping force vs. velocity relationship of the viscous-plus-variable-friction damping force algorithm

### ANALYTICAL MODEL AND PARAMETERS

Fig. 3 shows a highway bridge consisting of a five-span continuous deck considered in this analysis. The foundation of each pier is composed of nine cast-in-place piles with a diameter of 1.2 m. The reinforcedconcrete piers are 10 m high. The decks are of steel I-girders. The deck is 5@40 m long and 12 m wide. The deck weight is 31.4 MN. The deck is supported by five 96mm-thick elastomeric bearings on each pier. The size of the elastomeric bearings is 700mm x 700mm. Variable dampers are installed between a deck and supporting piers. The segment for the pier P3 was idealized as a two-degree-of-freedom system shown in Fig. 4. The pier was idealized by an elastoplastic model with a yielding displacement of 0.0349 m. The bearings are modeled by a linear horizontal spring. The tributary mass of the deck is 628 ton and that of the pier is 243 ton. Natural periods are 1.10 s and 0.24 s for the first and the second modes, respectively. A damping ratio is assumed to be 0.05 for two modes. Fig. 5 shows the ground acceleration used in the analysis. The ground motion is the N-S component of the strong motion recorded at the Japan Meteorological Agency Kobe Observatory in the 1995 Hyogo-ken Nanbu earthquake. The earthquake had a magnitude of 7.3 and a focal depth of 14 km. The peak ground acceleration is  $8.18 \text{ m/s}^2$ . In the analysis, viscous, friction, and viscous-plus-variable-friction damping force algorithms were investigated. The damping coefficient of the viscous damping force algorithm was varied from 0 to 30 MN-s/m. For the friction damping force algorithm, the friction force level was varied from 0 to 4 MN. For the viscousplus-variable-friction damping force algorithm, the damping coefficient was 4 MN-s/m, and the force limit was varied from 0 to 4 MN.



(a) Bridge overview

(b) Bridge column





Fig. 4 Idealized model

Fig. 5 Ground acceleration of the JMA Kobe record

### ANALYTICAL RESULTS

Fig. 6 shows time histories of a deck displacement and a pier displacement for the bridge without control. The maximum deck displacement is 0.330 m and the maximum pier displacement is 0.147 m, corresponding to a pier response ductility of 4.2. Figs. 7 and 8 shows time histories of a deck displacement and a pier displacement for the friction damping force algorithm with friction force levels of 2 MN, and 3 MN, respectively. At the friction force level of 2 MN, the deck displacement reduces to 0.197 m and the pier displacement reduces to 0.073 m, corresponding to a pier response ductility of 2.1. But when the friction force level increases to 3 MN, deck and pier displacements increase to 0.233 m and 0.209 m, respectively. Fig. 9 (a) shows the damping force vs. stroke relationship of dampers with the friction damping force algorithm. It is seen that as the friction force level increases, the stroke decreases. The amount of energy dissipation which is the area inside the hysteresis tends to decrease as the friction force level increases. Fig. 9 (b) shows the damping force vs. stroke relationship of dampers with the viscous-plus-variable-friction damping force algorithm. It is obvious that at the same force level of 3 MN, the amount of energy dissipation increases in the viscous-plus-variable-friction damping force algorithm. Fig. 10 shows time histories of a deck displacement and a pier displacement for the bridge controlled by the viscous-plus-variable-friction damping force algorithm with a force limit of 3 MN. The deck displacement and pier displacement becomes 0.185 m and 0.069 m, respectively. The effect of friction, viscous, and viscous-plus-variable-friction damping force algorithms on maximum bridge responses is presented in Fig. 11. The friction damping force algorithm yields more reduction of the deck displacement and the pier response ductility for the maximum damping force less than about 1.5 MN. When the maximum damping force is larger than 2 MN, the pier response ductility increases significantly. The viscous damping force algorithm yields more reduction of the pier response ductility for the maximum damping force larger than 2 MN. It is seen that the stroke requirement for the viscous damping force algorithm is much larger than that for the friction damping force algorithm. For the viscous-plus-variable-friction damping force algorithm, it is found that the deck displacement of the bridge controlled by the viscous-plus-variable-friction damping force algorithm is smaller than that with the viscous damping force algorithm for almost the entire range of damping force levels, and significantly smaller than that with the friction damping force algorithm for the damping force level over about 2 MN. The response ductility of the pier with the viscous-plus-variable-friction damping force algorithm is significantly smaller than that with the friction damping force algorithm for a damping force over 1.5 MN. The stroke requirement for the viscous-plus-variable-friction damping force algorithm is slightly more than that of the friction damping force algorithm. The energy dissipation of the viscous-plusvariable-friction damping force algorithm is shown in Fig. 11 (d). It is seen that the amount of energy dissipation is larger than that of the viscous and friction damping force algorithms.



Fig. 6 Time histories of responses for the bridge without control



Fig. 7 Time histories of responses for the bridge controlled by the friction damping force algorithm with a friction force level of 2 MN



(a) Deck displacement

(b) Pier displacement





Fig. 9 Damping force vs. stroke relationships of dampers



Fig. 10 Time histories of responses for the bridge controlled by the viscous-plus-variable-friction damping force algorithm with a force limit of 3 MN



Fig. 11 Maximum responses vs. maximum damping forces for various damping force algorithms

### **REALIZATION OF PROPOSED DAMPING FORCE ALGORITHM BY MR DAMPER**

#### **Dynamic Properties of MR Dampers**

To realize the proposed damping force algorithm, a RD-1084 MR damper developed by Lord Corporation was used in this study. The damper is 237 mm long in its extended position and 197 mm long in its compressed position. So, the stroke of the damper is +/- 20 mm. The cylinder is 28 mm in diameter. The force capacity of the damper is about 60 N. The damper operates at the current of 0-400 mA. The current is supplied to the damper by a Lord RD-3002 current driver. The current driver outputs a current proportional to an input voltage in the range of about 0.5-1.5 V. In order to apply the MR damper as a semi-active control device, it is necessary to identify the damping properties of the MR damper. A series of cyclic loading tests was conducted for various loading conditions. The damping force was measured by a load cell. The load cell was connected between the reaction frame and the damper. The displacement was measured by a laser displacement transducer. The current to the damper was controlled by a microcomputer. The voltage was generated by an I/O board which was installed in the computer. Then, the current driver supplied a current proportional to the voltage. A hydraulic actuator with displacement control was used to load the damper. The damper was subjected to sinusoidal excitations. The loading frequencies were 0.01, 1, 2, and 3 Hz. The loading amplitudes were 7.5 and 15 mm. The current levels were varied as 0, 100, 200, 300, and 400 mA. The force-displacement relationships of the MR damper are presented in Fig. 12. It is seen that the damping force increases as the current to the damper increases. The force-displacement relationship of the MR damper is close to that of a friction damper. It is seen that the shape of force-displacement relationship is slightly affected by the loading conditions.



Fig. 12 Force vs. displacement relationship of the MR damper

#### **Control of Damping Force**

To control the MR damper, the mathematical model of the MR damper is required. The MR damper was modeled from the relationship between the maximum damping force and maximum velocity as shown in Fig. 13. From a linear regression analysis, the following equation is obtained:

$$f = (3.78 + 0.123c) + (0.03 - 0.0000577c)v \tag{1}$$

where *c* is the current to the MR damper (mA), *v* is the piston velocity (mm/s), and *f* is the damping force (N). The current commanded to achieve a damping force can be computed from the back calculation of Eq. (1) with a known piston velocity. As it have been realized that there is a discrepancy in the damping force, a simple correction of the damping force was introduced after the back calculation. An additionally-supplied voltage ( $\Delta V$ ) is set as a function of the instantaneous difference between the commanded and actual (measured) damping force ( $\Delta f$ ), as shown in Fig. 14. The effect of the slope *k* was investigated. Fig. 15 shows the damping force algorithms can be realized by the MR damper for *k* = 0.04 V/N. It is found that the proposed damping force algorithms can be realized by the MR damper with a good accuracy. For a frequency of 2 Hz, small spikes in damping forces occur after the direction of excitation is reversed. It is due to the delay in predicting the velocity of the MR damper. This may limit the application of the control algorithm for a high-frequency excitation.





Fig. 13 Damping force vs. velocity relationship

Fig. 14 Function for correcting a damping force



Fig. 15 Damping force vs. displacement relationship for the viscous-plus-variable-friction damping force algorithm

#### CONCLUSIONS

In this study, the damping force algorithm called the viscous-plus-variable-friction damping force algorithm was proposed. From the analysis, it is found that the deck displacement of the bridge with proposed damping force algorithm is smaller than that with viscous dampers for almost the entire range of damping force levels, while significantly smaller than that with friction dampers for the damping force level larger than about 30% of a deck weight. The stroke requirement of variable dampers is slightly more than that of friction dampers. The response ductility of the pier with variable dampers is slightly smaller than that with friction dampers is slightly more than that with friction dampers at a large damping force. Finally, the proposed damping force algorithm was realized by a magnetorheological (MR) damper. It is found that the proposed viscous-plus-variable-friction damping force can be generated by the MR damper with a good accuracy. The response of MR dampers at a frequency of 2 Hz shows some discrepancies due to the delay in predicting a velocity. This should be considered in the application of the MR damper.

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