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Optimum Parameter of a Viscous Damper for Seismic and Wind Vibration

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***Abstract*—**Determination of optimal parameters of a passive control system device is the primary objective of this study. Expanding upon the use of control devices in wind and earthquake hazard reduction has led to development of various control systems. The advantage of non-linearity characteristics in a passive control device and the optimal control method using LQR algorithm are explained in this study. Finally, this paper introduces a simple approach to determine optimum parameters of a nonlinear viscous damper for vibration control of structures. A MATLAB program is used to produce the dynamic motion of the structure considering the stiffness matrix of the SDOF frame and the non-linear damping effect. This study concluded that the proposed system (variable damping system) has better performance in system response control than a linear damping system. Also, according to the energy dissipation graph, the total energy loss is greater in non-linear damping system than other systems.

***Keywords*—**Passive Control System, Damping Devices, Viscous Dampers, Control Algorithm.

I. Introduction

EXPANDING upon the use of control devices in wind and seismic isolation has led to the development of various control systems. Control systems in various applications are widely used in mechanical and electrical engineering. Shut on/off control devices in electric devices and shock absorbers in vehicles can be mentioned as examples of control systems in those fields of study. Today, it is common in structural engineering to use control systems to decrease structures' responses and control the interior and exterior excitations. These system devices may be classified as passive, active or semi-active. Recently, they have come to be considered successful system devices in increasing the resistance of structures by damping the excitation caused by an earthquake or wind, especially in tall buildings and suspension bridges.

Passive dampers include metallic dampers, friction dampers, viscous fluid dampers, viscoelastic dampers, tuned liquid dampers and tuned mass which are used in civil engineering structures. In 1969, about 10,000 viscoelastic dampers were installed in each twin tower of the World Trade Center in New York. They were designed to assist the tubular steel frame in limiting wind-induced building vibrations to levels below human perception and serviceability satisfaction. The quantities, shape and location of the dampers were chosen based on the dynamics of the towers and the required damping to achieve the performance objectives. After Hurricane Gloria in 1978, the total damping of the buildings was calculated and found to be in the range of 2.5% to 3% of critical damping [1]. According to past research, internal damping of a building is naturally 1 to 7 percent of the critical damping; the building's full optimum performance can be obtained with a damping equal to 25 to 30 percent of the critical damping by installing optimum linear damping devices. However, tests on building models showed that an increase of damping up to 50 percent of critical damping will improve the system's performance [4].

To reach this amount of damping in a structure, active or semi-active dampers with variable damping under harmonic excitation have been studied. However, these dampers are not economical to use because of the high costs of installation and powering. The disadvantages of using an active control system in structures force engineers to investigate passive or semi active systems for vibration control of structures [6]. To prevent malfunction and loss of functionality due to power failure in active control systems (a common problem occurring from severe earthquakes in active or semi active systems), and to maintain consistency and stability of damping performance, a new passive damper with non-linearity parameters is being considered in this study.

One of best system devices for the dissipation of transferred energy to structures in various external excitations is a viscous damper. Use of viscous fluid for shock and vibration mitigation is common in heavy industry and the military. For example, automotive shock absorbers were invented in the early 1900s. In the 1970s, the first full-scale implementation of viscous fluid dampers was done for bridges in Italy and New Zealand. In the 1980s, significant efforts were made toward the conversion of this industrial technology toward applications in civil engineering structures [1]. These efforts led to the development, analysis and modeling, and testing and full-scale implementation of viscous fluid dampers. The straightforward design is achieved with a classical dashpot, when dissipation occurs by converting kinetic energy to heat as a stroke moves and deforms a thick, highly viscous fluid. The relative movement of a damper stroke to the damper housing drives the viscous damper fluid back and forth through an orifice. Energy is dissipated by the friction between the fluid and the orifice. This kind of damper can provide motion and energy dissipation in all six degrees of freedom as vibration in any direction can shake the viscous fluid [1].

II. Damping System in Seismic Application

The current available viscous dampers in industry are highly priced. Many tall building designers avoid or limit using dampers in their design because of the cost. These

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dampers provide a constant damping coefficient (linear relationship between velocity and damping force) and they are classified as either seismic dampers or wind dampers. Therefore the dampers used for seismic isolation are not efficient for controlling the wind excitation. Nonlinear viscous dampers are also available in industry but because of the complexity in their design, they are not economic and consequently rarely have been used in civil engineering.

Generally speaking, in seismic application, it is not proper to choose passive systems with a constant character to control a system response where there is an inconsistent response content (maximum acceleration and frequency content) [7]. In fact, increasing the damping ratio in linear damping devices cannot dissipate the internal energy appropriately, and moreover, they transfer the total forces through themselves and behave as a rigid element. Consequently, the majority amount of force will be transferred to the connection (where the device is connected to the structure) which can cause damage to the damping device or the structure member. The parameter of an optimum damping coefficient in control system-devices cannot easily be obtained by a simple calculation. A study by Patel and Jangid showed that the optimizing condition requires to solve a forth-degree equation which is quite complex [5]. Therefore, this paper is studying a simple method to find the appropriate and optimum parameters of a viscous damper.

Theory of control has an optimum algorithm and the fundamentals of this theory are satisfying all the concepts and assumptions in civil structures. Recently, the theory of control was used by Gluck and Reinhorn to find the best location of linear dampers in a multi-story structure and to specify their constant damping coefficient [2]. In this study, theory of control with LQR algorithm is used in MATLAB programming to model the dynamic excitation of the whole system that includes the effect of active control vibration [3]. The performance of the suggested optimum passive damper is then compared to performance of an active damper in the same structure.

III. Model Manifestation of a Damping System

The theory of this project focuses on a new approach to optimize damping ratio of a structure by utilizing the nonlinear relationship of viscous dampers. A linear damping system has variable energy dissipation while the structure is going back and forth during its oscillation. According to Fig. 1, in a linear damping system, the damping force is variable and it changes from zero to the maximum. Making the damping force approximately uniform and uniform to its possible maximum amount regardless of the position of the structure is the solution to gaining maximum energy dissipation in a system. Considering the various amount of velocities while the structure is oscillating, a nonlinear damper is required to eliminate this variation on the damping force. As a schematic view, this kind of system can be designed with parameters which can convert the sinusoid form of the damping force to rectangular form (Fig. 1).

Similarly, in active control systems, if the time-optimal control problem is normal, the components of the optimal control force are a piecewise constant function of time. Such functions are known as bang-bang and the preceding statement is referred to as the bang-bang principle [4]. The implication of the bang-bang principle is that the time-optimal control is obtained by exerting maximum control force until the target set is reached [4].

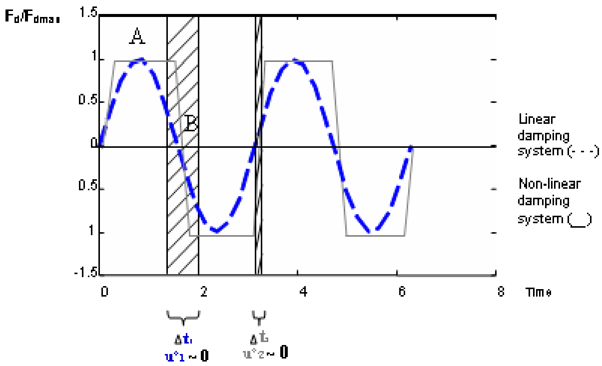

Fig. 1 Maximum damping in non-linear damping system by providing a uniform damping system over a longer time

Considering a nonlinear damping coefficient in a damper, an optimum-damping coefficient can be obtained as follows:

$$f_d(t) = C \cdot u^o \Rightarrow f_d(t)/u^o = C(t) \Rightarrow C = f(u, u^o) \tag{1}$$

where fd (t) is the damping force, C is the optimum-damping coefficient, u is the position of stroke in viscous dampers and u° is velocity of the stroke in the damper.

From (1), it can be concluded that damping coefficient changes with time and its value decreases to keep the damping force within the criterion where the internal force is at a minimum level while the amount of energy dissipation is maximum. Inversely, to prevent a decrease in the amount of energy dissipation, the damping coefficient can be increased to gain the maximum possible damping in the structure. The nature of damping device inevitably applies constraints and the damping coefficient hence needs to satisfy the lower and upper bounds as the following:

$$C_{\min} < C(t) < C_{\max} \tag{2}$$

The optimum characteristics of this system can be determined by LQR control algorithm. In this research, two kinds of performance are considered for the control system. First, the structure must have minimum displacement in the point of interest. Second, an optimization scheme is needed to be developed to minimize the internal force of the controlling system. A MATLAB code was developed to model a SDOF frame shown below that is connected to an active control system and excited by an earthquake record (El Centro Earthquake – USA 1979).

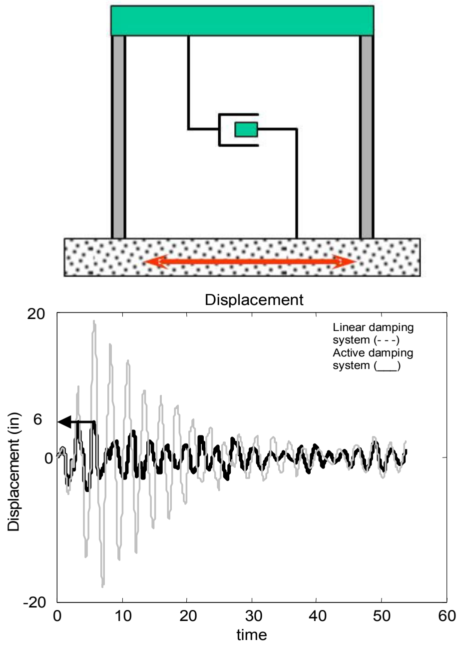

Fig. 2 Response of an active control system during El Centro Earthquake excitation and comparison to a response of a linear damping system

An optimum damping coefficient may be obtained from (1) consideration the damping force is equal to active control force. The variation of the damping coefficient for the top damper is shown in Fig. 3. In this figure, the value of "1" represents the optimum constant damping coefficient for the damper.

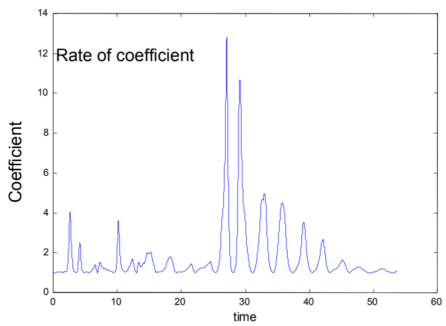

Fig. 3 The variation of damping coefficient in an optimum damping system

IV. Variable Viscous Fluid Damper

In most structures, even a relative low damping can also provide a significant energy dissipation which considerably decreases the vibration of a structure. The description below explains how a nonlinear characteristic is required for a damping system to optimize the vibration of a simple moment frame.

When the frame has flexed a maximum amount from its normal position, the velocity of structure decreases and therefore the related damping performance decreases significantly (Based on (1)). As the frame flexes back, the maximum damping force occurs when the velocity reaches its high value. This is the moment in which the column passes its natural position. To maintain the level of optimum damping performance, a variable cross section property may be used to provide the required variation. However, the produced damping force in these dampers is dependent upon the location of their strokes. Consequently, the application of these dampers is limited and cannot be adapted for different structures, different excitation content and even different locations in a structure.

However, a better expression of the characteristics of a non-linear damper can be obtained. Since velocity is the first derivation of displacement, if we consider a sinusoid behavior model like sin (α) for displacement response, then velocity will have a similar shape with a certain different phase as following:

$$u = u_{max}\sin(\omega t) \Rightarrow u^{o} = u_{max}\,\omega\cos(\omega t) = u_{max}\,\omega\sin(\omega t - \pi/2) \quad (3)$$

Fig. 4 shows the velocity and displacement of a single degree oscillator that has stiffness and damping during the excitation of El Centro earthquake. In this figure, the amounts of responses are normalized to the maximum values and velocity and displacement are shown in the same figure. The different phase of displacement and velocity can be observed in this figure.

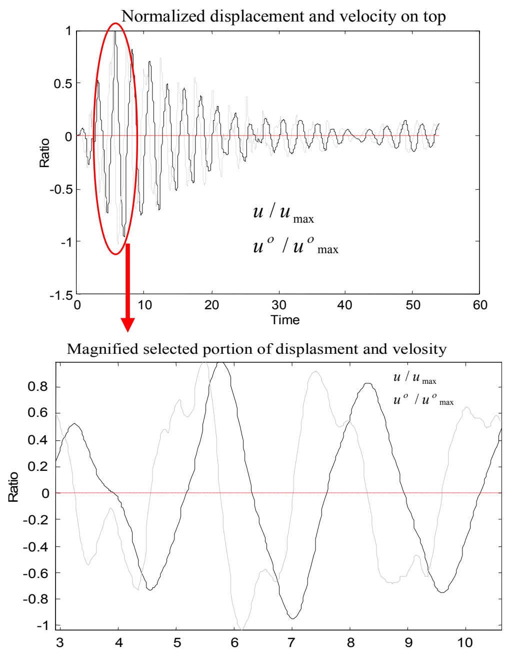

Fig. 4 Normalized displacement and velocity in the left – A zoomed-frame for the same figure only in 10 seconds

Considering a minimum damping for a control system as *Cmin*, a non-linear relation in terms of velocity and displacement can be obtained as the following:

$$Sin(u/u_{\max}) \approx Sin(\frac{\pi}{2} - u^o/u^o{}_{\max}) = Cos(u^o/u^o{}_{\max})$$
$$Cos(Arc\sin(u/u_{\max})) = u^o/u^o{}_{\max}$$
$$u^o/Cos(Arc\sin(u/u_{\max})) = u^o{}_{\max}$$
$$C_{\min} \times u^o/Cos(Arc\sin(u/u_{\max})) = C_{\min} \times u^o{}_{\max} = f_{D\max} \quad (4)$$

Therefore the non-linear damping coefficient "C*" is defined and cumulative energy loss can be obtained from (5);

$$C^* = C_{\min}/(\cos(Arc\sin(u/u_{\max}))$$
$$U_{D_{\max}} = \sum f_{D\max} \times u = \sum C_{\min} . u^o{}_{\max} \times z = \sum C^* . u^o \times u \quad (5)$$

Equation (5) further can be used to make a comparison between the results of the active damping system and the damping system which theoretically governs this equation.

V. Expected Result

Using a fluid viscous damper with a variable damping coefficient (obtained from (5)), it is expected that the damping performance become more uniform (Fig. 1) and therefore can increase energy dissipation in the system when comparing to the performance of a system with a linear damping coefficient. To compare the results of these damping systems (a Linear, a Non-linear, an Active system), a single degree oscillator is considered and analyzed in a time-history analysis program using MATLAB program. The results are compared between the three same structures (oscillator with same damping and stiffness property) with different damping systems. One is isolated by the active control system, the other is isolated by the linear dampers (with constant damping coefficient) and the last one is isolated by the nonlinear dampers (with variable damping coefficient).

Obviously, active system performance is expected to be the most optimum and according to the LQR algorithm, the active system can control the structure's responses with the minimum damping force in the system. Therefore, in this comparison, the maximum damping force is the limit for all cases and should not be exceeded. Therefore, the maximum possible damping force for all damping system is the same.

Evaluation and comparison of how structure responses are controlled by an active control system versus a linear or non-linear system are presented in Fig. 5. According to the damped energy plot in Fig. 5, the energy loss, which is calculated by multiplying damping force to the displacement vector, is greater in non-linear passive control system than other systems. Since the value of maximum damping force in all three cases (i.e. active control, passive control with linear behavior and passive with non-linear behavior) were equal, it can be concluded that the only reason for having more energy loss is the non-linearity characterization of the damper.

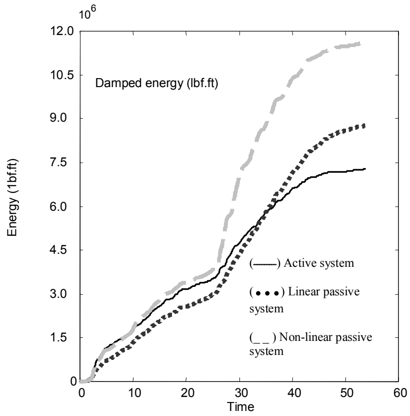

Fig. 5 Damped energy by control systems

VI. A Suggested Model

The proposed schematic design of viscous fluid damper is independent of the position of the stroke in the damper. Fig. 5 shows a variable behavior in a viscous damper based on the variable velocity response of structure. Since the velocity increases, the internal pressure increases simultaneously. The internal pressure dictates the expansion in the orifice and makes viscous flows through the bypass easier. The friction between flow and the orifice produces the damping ratio in this viscous damper.

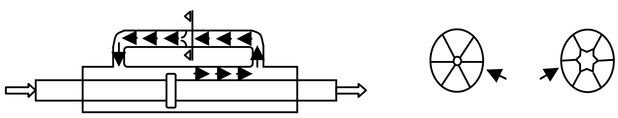

Fig. 6 Variable damping coefficient due to orifice expansion

Since the internal force in viscous dampers is directly related to velocity of the stroke inside, an elastic orifice (opening) sensitive to internal pressure of the damper is the proposal to achieve a variable damping coefficient. Therefore, while the velocity of the structure tends to increase, increase in the internal pressure of the damper causes the orifice to expand and the damping coefficient to decrease. Inversely, while the velocity of the structure decreases, the decrease in the internal pressure causes the orifice return to its original shape, thus increasing the damping coefficient.

VII. Conclusion

Theoretically, with the use of a control algorithm and the analysis of the structural response, a velocity/displacement dependent relationship can be determined for the characteristics of damping systems, which is optimum in regards to maximizing energy dissipation and minimizing the internal force and response of the structure (Displacement, Velocity or Acceleration). For the design of such a damping system, a fluid viscous damper has been chosen because of broad applications of this device in seismic and wind isolation.

Since internal force in a fluid viscous damper is directly related to the stroking velocity of the damper, an elastic orifice (opening) that is sensitive to the internal pressure of the damper is a simplified and suggested model which may provide a variable damping coefficient. Therefore, whenever the velocity of the stroking damper tends to increase, the resultant increase in the internal pressure of the damper causes the orifice to open and, in turn, the damping coefficient to decrease. Inversely, while the stroking velocity of the damper decreases, the decrease in the internal pressure causes the orifice to return to its original shape, increasing the damping coefficient. The characteristics of this damper is highly variable and will be efficient in both seismic and wind isolation. The suggested damper is just a simplified model and it needs to be investigated in more depth. However, the design of such damper is beyond the main scope of this study.

Comparing the results from the above graphs, it can be concluded that the proposed system (variable damping system) has better performance in system response control (controlling the displacement) than the linear system. According to the energy dissipation plot, the energy loss is greater in the non-linear damping system than other cases. Finally, it can be concluded that the only reason for having more energy loss in variable damping case is the non-linear characterization of the damping system.

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