Optimum Parameter of a Variable Damping System for Seismic Applications*

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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-linear 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 code is developed to produce the dynamic motion of the structure considering the stiffness matrix of an SDOF frame and the non-linear damping effect. This study demonstrates 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 linear damping as well as active control systems.**

Keywords- Passive Control System; Damping Devices; Viscous Damper; 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 a common practice in structural engineering to use control systems to decrease structures' responses and control the excitations. These system devices may be classified as passive, active or semi-active. Recently, numerous examples of successful implementation of system devices for increasing the resistance of structures by damping the excitation caused by an earthquake or wind have been reported, especially in tall buildings and suspension bridges [1].

Passive dampers which include metallic dampers, friction dampers, viscous fluid dampers, viscoelastic dampers, tuned liquid dampers and tuned mass have been used in many civil engineering structures. In 1969, about 10,000 viscoelastic dampers were installed in each twin tower of the World Trade Centre in New York [2]. 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 WTC towers was calculated and found to be in the range of 2.5% to 3% of critical damping [3]. 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 have shown 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 requirement for external powering. The disadvantages of using an active control system in structures have forced engineers to investigate passive or semi-active systems for vibration control of structures [3]. To prevent malfunction and loss of functionality due to loss of power 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-linear parameters is being considered in this study.

Small in size and simple in installation have made viscous dampers one of the best system devices for the dissipation of transferred energy to structures during various external excitations. 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

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1980s, significant efforts were made toward the conversion of this industrial technology toward applications in civil engineering structures [5]. These efforts led to the development, analysis and modelling, 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 [5].

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 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 [6].

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, since a damping device with very high damping will essentially act as a rigid element which merely passes the forces to the connections on its ends, where the device is connected to the structure. This can in turn cause damage to the damping device or the structural 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 [8]. On the other hand, the theory of control has shown to be able to find the best location of linear dampers in a multi-story structure and to specify their constant damping coefficient [9].

In order to overcome the limitations explained above; this paper provides a simple method to find the appropriate and optimum parameters of a non-linear viscous damper. Theory of control has been utilized to develop an optimum algorithm to determine the parameters of a damping device where the response of structures is being controlled with a limited amount of control force. The fundamental of the control theory satisfies all the concepts and assumptions needed. In the present study, theory of control with LQR algorithm is implemented in an MATLAB code to model the dynamic excitation of the system which includes the effect of active control vibration [10]. The performance of the suggested optimum passive damper is then compared to the performance of an active damper in the same model.

II. MODEL MANIFESTATION OF A DAMPING SYSTEM

The present study 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 moving back and forth during its oscillation. According to Fig. 1, in a linear damping system, the damping force is variable and changes from zero to the maximum. Making the damping force approximately to its possible maximum amount regardless of the position of the stroke in dampers 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 the variation of 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).

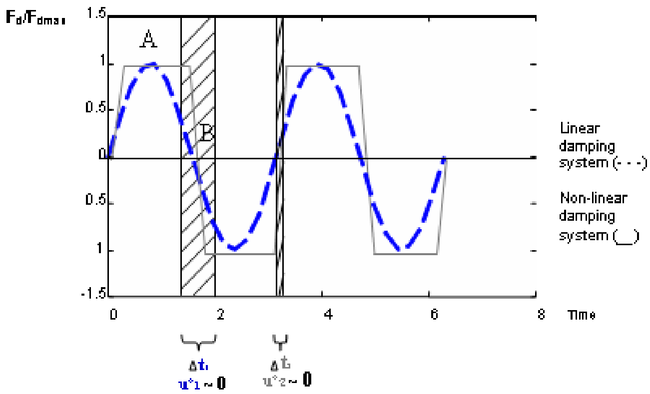

Fig. 1 Maximum damping in non-linear damping system by providing a uniform damping system over a longer time

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 performing similar to bang-bang principal [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].

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 f_d *(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 (Note: Since damping coefficient in a viscous dampers may also relate to the position of the stroke, the damping function can be interpreted as a function of velocity and displacement).

From Eq. (1), it can be concluded that optimum damping coefficient changes with time and its value may decrease or increase in order to keep the damping force within a criterion where the internal force stays at maximum allowable level and the energy dissipation in the structure is maximised. 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 response of a structure provided with a damping device is shown in Fig. 2. The following dynamic equilibrium equation has been established to determine the response of this frame.

$$M.\ddot{u}(t) + C.\dot{u}(t) + K.u(t) = L.E(t) + D.f(t) \tag{3}$$

Where, *M*, *C*, *K* are the mass, the damping and stiffness matrices, respectively, and *u(t)*, $\dot{u}$ *(t)* and $\ddot{u}$ *(t)* are the displacement, velocity and acceleration vectors, respectively; *f(t)* is the vector of control forces in the supplemental devices, and *E(t)* is the earthquake excitation. According to the control theory, a performance index is minimized at each instance, *t* [9, 11]. The performance index, *J(t)* is time-dependent and is defined by the following equation:

$$J(t) = z^T(t).Q.z(t) + f^T(t).R.f(t) \tag{4}$$

where *R* and *Q* are weighting matrices which define the priorities between the energies dissipated in the structural elements and in the damper. In this study the matrices *R* and *Q* are assumed to be

$$R = 10^{-m}.I\text{, } Q = I_{2n \times 2n} \tag{5}$$

where *I* is a 2n x 2n unit diagonal matrix, and m is a parameter which keeps the damping forces within the dampers' practical capacity. This second-order differential equation (Eq. (3)) may be simplified by a transformation into the space-state form as follows:

$$\dot{z}(t) = A.z(t) + B.f(t) + H.E(t) \tag{6}$$

where $z(t) = [u(t), \dot{u}(t)]^T$ is the 2n space state vector of the displacements and velocities for each of the n degrees of freedom of the structure, *A* is a system matrix, *B* defines the control location, and *H* is the excitation forces location matrix [9]:

$$A = \begin{bmatrix} 0 & 1 \\ -M^{-1}K & -M^{-1}D \end{bmatrix}, \quad B = \begin{bmatrix} 0 \\ M^{-1}D \end{bmatrix}, \quad H = \begin{bmatrix} 0 \\ M^{-1}L \end{bmatrix} \tag{7}$$

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 an SDOF frame shown below that is connected to an active control system and excited by an earthquake record. The MATLAB code solves the dynamic equation of the structure which is excited under the base. The stiffness and damping matrixes are provided and also the lateral motion of the structure is being controlled by a control force. For the purpose of demonstrating the effectiveness and performance of the proposed system, El Centro Earthquake (USA 1979) is used in this study although any other seismic excitations can be used in the developed computer program.

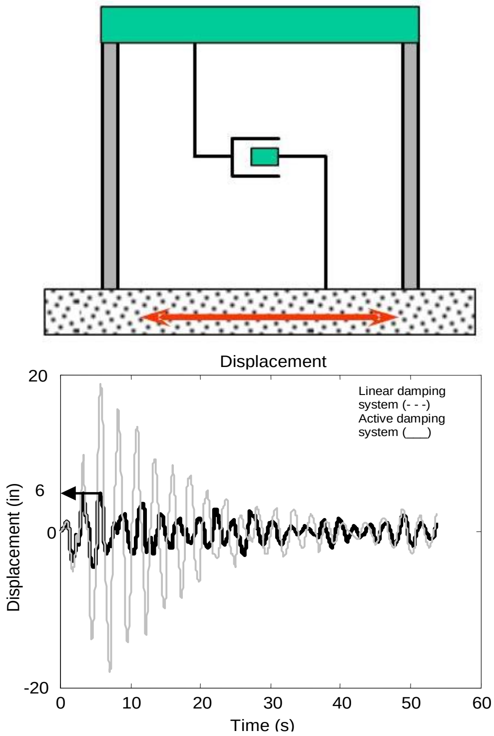

Fig. 2 Comparison of Response of an active control system with a linear damping system during El Centro Earthquake

Fig. 2 shows the response of the story displacement during the El Centro Earthquake excitation with linear damping system and active damping system. An optimum damping coefficient may be obtained from Eq. (1). Considering the force in the damping device is equal to active control force *f(t)*; the variation of the damping coefficient for the damper is shown in Fig. 3. In this figure, the value of "1" represents the optimum constant (linear) damping coefficient for the damper. As it is shown in Fig. 3, the non-linear optimum damping coefficient varies from a constant (linear) value (here represent as unit "1") to a damping coefficient with twelve times greater.

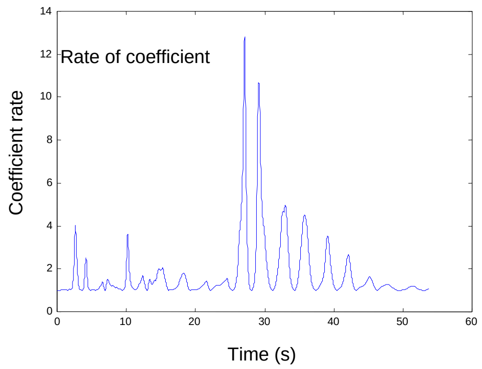

Fig. 3 The variation of damping coefficient in an optimum damping system

III. VARIABLE VISCOUS FLOUID DAMPER

In most structures, even a relative low damping can also provide significant energy dissipation which considerably mitigates the vibration of a structure. The description below explains how a nonlinear characteristic can be described for a viscous damper 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 Eq. (1)). As the frame flexes back, the maximum damping force occurs when the velocity reaches its highest 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 cylindrical damper 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 derivative of displacement, with consideration of sinusoid behaviour model like *sin (α)* for displacement response, then velocity will have a similar shape with a certain different phase as following:

$$u = u_{\max} \sin(\omega t) \Rightarrow u^o = u_{\max} \omega \cos(\omega t) = u_{\max} \omega \sin(\omega t - \pi / 2) \quad (8)$$

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 phases of displacement and velocity can be observed in this figure.

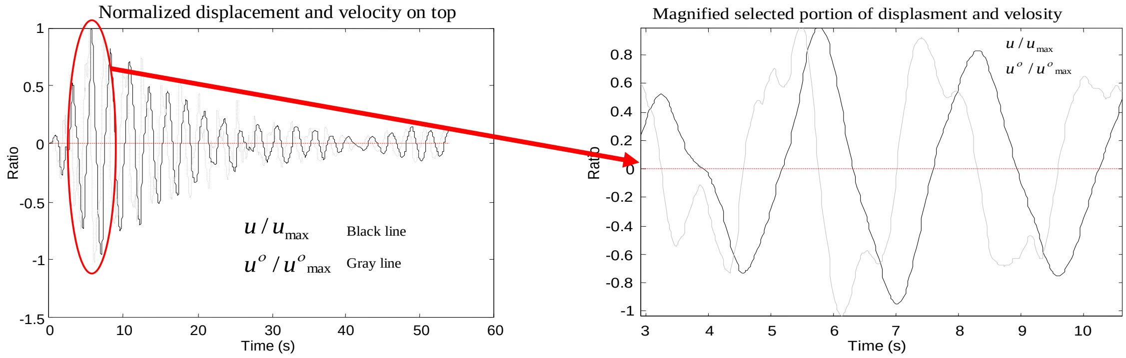

Fig. 4 Normalized displacement and velocity in the left – A close-up for the same figure only in 10 seconds

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

$$\begin{aligned}
&Sin(u/u_{\max}) \approx Sin(\frac{\pi}{2} - u^o / u^o{}_{\max}) = Cos(u^o / u^o{}_{\max}) \\
&Cos(Arc\sin(u/u_{\max})) = u^o / u^o{}_{\max} \\
&u^o / Cos(Arc\sin(u/u_{\max})) = u^o{}_{\max} \\
&C_{\min} \times u^o / Cos(Arc\sin(u/u_{\max})) = C_{\min} \times u^o{}_{\max} = f_{D\max}
\end{aligned} \quad (9)$$

Therefore the non-linear damping coefficient "*C**" is defined and cumulative energy loss can be obtained from (10);

$$\begin{aligned}
&C^* = C_{\min} / (\cos(Arc\sin(u/u_{\max})) \\
&U_{D_{\max}} = \sum f_{D\max} \times u = \sum C_{\min} . u^o{}_{\max} \times u = \sum C^* . u^o \times u
\end{aligned} \quad (10)$$

Eq. (10) can be further used to make a comparison between the results of the active damping system and the damping system which theoretically governs this equation (passive control).

IV. EXPECTED RESULT

Using a fluid viscous damper with a variable damping coefficient (obtained from Eq. (10)), it is expected that the damping performance becomes optimum (Fig. 1). Therefore the energy dissipation increases in the system when comparing to the performance of a system with a linear damping coefficient [11]. To compare the results of these damping systems (a Linear, a Non-linear, and an Active system), a single degree oscillator is considered and analysed in a time-history analysis program using MATLAB program. The results are compared between the three same structures (oscillator with same mass 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). In all cases, the maximum control force (damping force) remained unchanged.

Obviously, active system performance is expected to be optimum according to the LQR algorithm. The active control system was first investigated to obtain the structure's response and the minimum damping force in the active control system was determined. To make a comparison with other cases, the maximum calculated control force was chosen to limit the damping force in passive systems (linear damping and non-linear damping). 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 behaviour and passive with non-linear behaviour) were equal, it can be concluded that the only reason for having more energy loss is the non-linearity characterization of the damper.

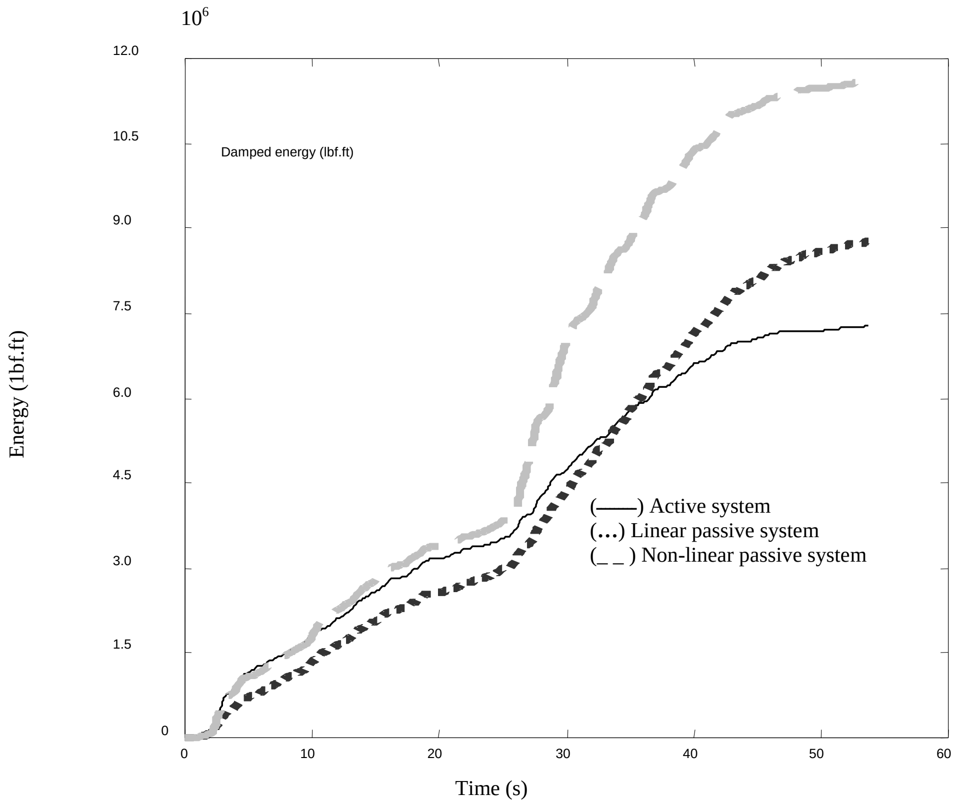

Fig. 5 Damped energy by control systems (calculated by MATLAB from Eq. (10))

V. SUGGESTED MODEL

The proposed schematic design of viscous fluid damper is independent of the position of the stroke in the damper and the performance of the damper can be predicted as Eq. (10). Fig. 6 shows a variable behaviour in a viscous damper based on the variable velocity response of structure. As the velocity increases, the internal pressure increases simultaneously. The internal pressure dictates the expansion in the orifice and enables the viscous fluid to flow through the bypass more easily. The friction between flow and the orifice produces damping in this viscous damper.

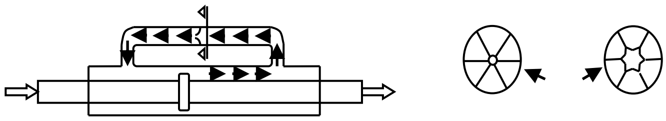

Fig. 6 Proposed variable damping device based on orifice expansion

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 can be properly designed 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 to return to its original shape, thus increases the damping coefficient.

VI. 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 proposed 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 needs to be investigated in more depth. However, the design of such damper is beyond the scope of this study.

Comparing the results from the above graphs indicates that the proposed system (variable damping system) has a 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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