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OPTIMAL PASSIVE CONTROL OF SHEAR BUILDINGS

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Abstract: *In the paper, the analysis of damping parameters for vibration reduction of buildings with use of optimization algorithm is presented. Optimal values of damping coefficients are determined at fundamental structural mode of shear buildings in order to attain desired added damping ratios. The cost function is defined as the sum of damping coefficients of the dampers to be minimized. Proposed optimization problem is solved by using three different numerical algorithms that are namely: Simulated Annealing, Nelder Mead and Differential Evolution algorithms, respectively. Numerical example is presented to prove the validity of the proposed method. The changes of optimal distributions of the dampers with respect to target damping ratios and structural periods in a particular range are investigated for two-story shear building model. The numerical results show that the proposed damper optimization method is easy to apply and efficient to find optimal damper distribution for a target damping ratio.*

Keywords: Optimal dampers, Target damping ratio, Added dampers, Optimal passive control, Optimal design of dampers.

1. Introduction

The concept of supplemental dampers within a structure suggests that part of the input energy will be absorbed, not by the structure itself, but rather by supplemental damping elements. The usage of the added dampers can increase the damping level of buildings ranging from 20 % to 40 %.

The effects of variations support member stiffness of dampers upon the optimal damper allocation problem were investigated (Takewaki and Yoshitomi 1998). A procedure for obtaining the optimal stiffness and damping distributions based upon the optimality criteria was presented by Takewaki (1999a, 1999b). An optimal damper placement method was proposed to minimize the dynamic compliance of a building frame (Takewaki 2000a, Shukla et al. 1999, Fujita et al. 2010, Aydin et al. 2007) and beam (Takewaki 1998). A new objective function for finding optimal size and location of the added viscous dampers was proposed based on the elastic base moment in planar steel building frames (Aydin 2012). In this studies, a cost function that is the sum of damping coefficients of the added dampers is minimized to find optimal damping coefficients of the added dampers under a specified added damping ratio and both lower and upper bounds of each damping coefficient of the added dampers. Differential Evolution, Nelder Mead and Simulated Annealing are used to solve the simple optimization problem. Moreover, in the numerical examples, the effects of the changes of desired target damping ratio and the period of the structures above the optimal damper designs are investigated.

2. Theoretical background of the analysed problem

For the analysed model the equation of motion can be written as:

$$\boldsymbol{M}\ddot{\boldsymbol{u}}(t) + (\boldsymbol{C} + \boldsymbol{C_{ad}})\dot{\boldsymbol{u}}(t) + \boldsymbol{K}\boldsymbol{u}(t) = -\boldsymbol{M}\boldsymbol{r}\ddot{u}_g(t) \quad (1)$$

where $\boldsymbol{M}$, $\boldsymbol{C}$ and $\boldsymbol{K}$ present mass, structural damping and stiffness matrices, respectively $\ddot{\boldsymbol{u}}(t)$, $\dot{\boldsymbol{u}}(t)$ and $\boldsymbol{u}(t)$ are acceleration, velocity and displacement vectors, respectively. The $\boldsymbol{r}$ denotes influence

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vector that all elements is equal to one. $\ddot{u}_g(t)$ is defined as ground acceleration. The structural damping matrix, $\boldsymbol{C}$ can be calculated in proportion to only mass matrix, only stiffness matrix or linear combination of mass and stiffness matrices. It is given as

$$\boldsymbol{C} = \alpha \boldsymbol{M} \quad (2),$$

$$\boldsymbol{C} = \beta \boldsymbol{K} \quad (3),$$

$$\boldsymbol{C} = \alpha \boldsymbol{M} + \beta \boldsymbol{K} \quad (4),$$

where α and β are generally calculated in terms of first normal mode of vibration in Eqs. (2) - (3). In general, α and β in Rayleigh damping matrix, given in Eq. (4), are determined by using the first and second normal modes of vibration. While this is called as proportional damping matrix, $\boldsymbol{C_{ad}}$ is the non-proportional damping matrix that should be designed optimally to minimize an objective. The matrix, $\boldsymbol{C_{ad}}$ can be decomposed into corresponding added viscous dampers and is written as

$$\boldsymbol{C_{ad}} = c_1 \boldsymbol{C_1} + c_2 \boldsymbol{C_2} + \cdots + c_n \boldsymbol{C_n} \quad (5),$$

where c_i $(i = 1, \ldots, n)$ corresponds to the damping coefficient of i[th] added damper; and $\boldsymbol{C_i}$ $(i = 1, \ldots, n)$ denotes the location matrix of the i[th] added damper. Moreover, the location matrix is also equal to the partial differential of $\boldsymbol{C_{ad}}$ with respect to i[th] added damping coefficient of dampers as

$$\boldsymbol{C}_i = \frac{\partial \boldsymbol{C}_{ad}}{\partial c_i} \quad (6).$$

Two ends of the viscous dampers have different velocity since one end is attached to one building storey and the other end to a different storey. These devices produce damping forces in proportion to relative velocity between each one of the ends. These elements achieve the energy dissipation during an external vibration such as a wind and an earthquake excitation. The damping force of a linear viscous damper is given as

$$F_{ad} = c_{ad} . \dot{u} \quad (7),$$

where c_{ad}, $\dot{u}$ denote the damping coefficient of manufactured viscous damper and relative velocity between each one of the ends of damper, respectively

In the fundamental mode, the damping ratio is calculated as follows

$$2\zeta_1 \omega_1 = \frac{\boldsymbol{\phi_1^T (C + C_{ad}) \phi_1}}{\boldsymbol{\phi_1^T M \phi_1}} = \frac{\boldsymbol{\phi_1^T C \phi_1}}{\boldsymbol{\phi_1^T M \phi_1}} + \frac{\boldsymbol{\phi_1^T C_{ad} \phi_1}}{\boldsymbol{\phi_1^T M \phi_1}} \quad (8),$$

where ζ_1 denotes damping ratio after dampers are inserted to the structure, $\boldsymbol{\phi_1}$ is the normalized fundamental mode vector and ω_1 is the undamped natural circular frequency of the model structure. The first term on the right side of Eq. (8) covers proportional damping matrix, and therefore there are no couplings between first mode and any of the other modes. This situation is expressed as

$$\frac{\boldsymbol{\phi_1^T C \phi_i}}{\boldsymbol{\phi_1^T M \phi_i}} = \begin{cases} 2\zeta_s \omega_1 & i = 1 \\ 0 & i \neq 1 \end{cases} \quad (9),$$

where ζ_s denotes structural damping ratio for the fundamental mode. The second term on the right side of Eq. (8) include non-proportional damping matrix. However, only for purposes of a simplified design it is convenient to assume that

$$\frac{\boldsymbol{\phi_1^T C_{ad} \phi_i}}{\boldsymbol{\phi_1^T M \phi_i}} = \begin{cases} 2\zeta_{ad} \omega_1 & i = 1 \\ 0 & i \neq 1 \end{cases} \quad (10),$$

where ζ_{ad} denotes added damping ratio for the fundamental mode. The Eq. (8) can be rewritten using Eqs. (9) - (10) as follows

$$2\zeta_1 \omega_1 = 2(\zeta_s + \zeta_{ad})\omega_1, \ (11), \ \zeta_1 = \zeta_s + \zeta_{ad} \quad (12).$$

Structural damping ratio ζ_s is generally assumed to be constant as 0.02 in steel structures or 0.05 in RC structures. The parameter ζ_1 denotes the desired value of the damping ratio when the dampers are inserted to the structure. The parameterζ_{ad}, which occurs due to the effects of the added dampers, is the added damping ratio. The desired ζ_{ad} is determined from Eq. (12), if the structural damping ratio and the desired total damping ratio are known. Therefore, the desired added damping ratio is calculated as

$$\zeta_{ad} = \zeta_1 - \zeta_s \quad (13).$$

The Eq. (8) can be rewritten for only added damping ratio as

$$2\zeta_{ad} \omega_1 = \frac{\boldsymbol{\phi_1^T C_{ad} \phi_1}}{\boldsymbol{\phi_1^T M \phi_1}} = c_1 \frac{\boldsymbol{\phi_1^T C_1 \phi_1}}{\boldsymbol{\phi_1^T M \phi_1}} + c_2 \frac{\boldsymbol{\phi_1^T C_2 \phi_1}}{\boldsymbol{\phi_1^T M \phi_1}} + \cdots + c_n \frac{\boldsymbol{\phi_1^T C_n \phi_1}}{\boldsymbol{\phi_1^T M \phi_1}} \quad (14),$$

where the coefficients (μ_i) of the c_i can be written as follows

$$\mu_i = \frac{\boldsymbol{\phi}_1^T \boldsymbol{C}_i \boldsymbol{\phi}_1}{\boldsymbol{\phi}_1^T \boldsymbol{M} \boldsymbol{\phi}_1} \tag{15}$$

The formula of the desired added damping ratio for fundamental mode is written as below using Eqs. (14) - (15)

$$\zeta_{ad} = \frac{1}{2\omega_1}(\mu_1 c_1 + \mu_2 c_2 + \cdots + \mu_n c_n) = \frac{1}{2\omega_1}\sum_{i=1}^{n} \mu_i c_i \tag{16}$$

In this study, design variables are considered as the damping coefficients of the added dampers. Optimal damper problem is based on minimization of total cost of the dampers that is expressed as the sum of damping coefficients of the added dampers which is given as

$$\text{Min. } f = \sum_{i=1}^{n} c_i \tag{17}$$

The cost function to be minimized in Eq. (17) indicates total damping coefficient of the added dampers. Eq.(16) can be rewritten as an equality constraint in terms of the added damping ratio

$$\zeta_{ad} = \frac{1}{2\omega_1}(\mu_1 c_1 + \mu_2 c_2 + \cdots + \mu_n c_n) = \frac{1}{2\omega_1}\sum_{i=1}^{n} \mu_i c_i \tag{18}$$

where ζ_{ad} is a fixed damping ratio that can be given as a desired damping ratio. The fundamental natural circular frequency and the parameter μ_i are known parameters from the vibration characteristics of the structure. Both objective function and equality constraint are the linear function of the design parameters. Taking into account the inequality constraints on the upper and lower bounds of the damping coefficients of each added damper gives the following

$$0 \le c_i \le \bar{c}_i \quad (i=1,2,\ldots,n) \tag{19}$$

where $\bar{c}_i$ is the upper bound of damping coefficient of the damper in ith story. In practical applications, a damper capacity and size which corresponds to the upper bound of the added damper should be restricted because of commercial and manufacturing limitations.

3. Numerical analysis and discussion

Analysed 2-storey shear building model such as linear manufactured viscous dampers that are added to each story is shown in Fig. 1.

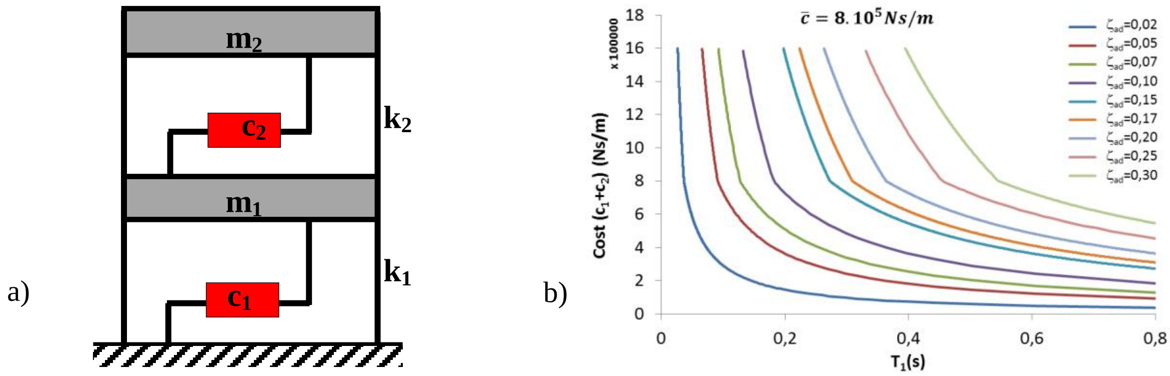

Fig. 1: a) 2-storey shear buildings with supplemental dampers; b) Variation of minimum values of cost function according to period of the structure for different added damping ratios.

The three various numerical minimization methods such as Differential Evolution, Nelder Mead and Simulated Annealing, which are well known in the optimization literature, are used to solve the optimization problem. The aim of using these three optimization methods is to verify the results obtained from a method with the other methods. The used optimization methods in the numerical minimization module of the Mathematica 5.0 (2003) are expressed in the following paragraph.

Optimization problem is applied to 2-story shear building to find optimal damping coefficient of added dampers under the upper and lower limits of the design variables and the target value of the damping ratio in the first mode. The target damping ratio is considered as $\zeta_{ad} = 0.20$. The change of the period depends on the structural stiffness. The story stiffness coefficients are equal in all stories. The stiffness coefficient is selected such that the period is fixed to 1.04305 s. For this period and target added damping ratio $\zeta_{ad} = 0.20$, the optimization is performed. While the period of the structure is decreased by increase of the stiffness, optimization is performed using three different method for fixed damping ratio $\zeta_{ad} = 0.20$. The target added damping ratio is taken as 0.02, 0.05, 0.10, 0.20, 0.15, 0.25 and 0.30, respectively. For each one of the added damping ratios, optimization is performed for these cases and the variations of the optimal damping coefficients (c_1, c_2) according to period of the structure are plotted in Fig. 2.

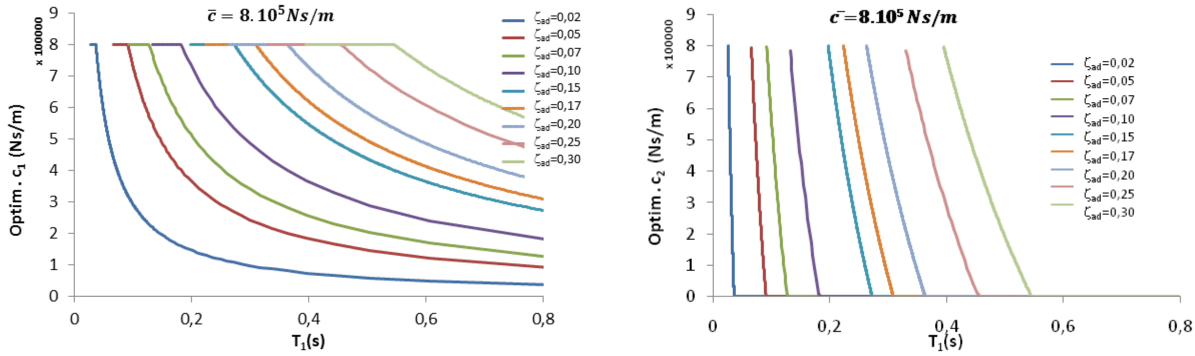

Fig. 2. The variation of optimal values of c_1 and c_2 according to period of the structure for different added damping ratios.

The variations of the minimum values of cost function for different added damping ratios are also presented in Fig. 1. It can be seen that the increase of the period results in decrease of the minimum values of the cost function.

4. Conclusions

A simple optimization method is proposed to find optimal damper placement. The optimization problem is constructed based on minimizing the sum of the damping coefficients of the added dampers under a target added damping ratio in the first mode and both upper and lower bounds of the added dampers. Both the cost function and the constraint functions are linear function of the design variables. Three different numerical minimization methods are used for justification in this study. The results obtained from minimization methods match with each other. The effects of variation of the fundamental period and the target added damping ratio above the optimal designs are also investigated. The numerical results reveal that the increase of the fundamental period results in the decrease of cost function value for a fixed upper bound of added damping coefficient and a specified target added damping ratio. The more added damping ratio is needed, the more the cost function value occurs. In the numerical examples, the upper bound of the added damping coefficients is taken as a fixed value. The numerical results state explicitly that the proposed method is effective in order to minimize the total damping coefficient and to attain a desired damping ratio in the first mode.

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