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A SURVEY OF MODERN SYSTEMS OF VIBRATION REDUCTION OF CIVIL ENGINEERING STRUCTURES

1. Introduction

In civil engineering we observe a permanent tendency to design and construct light and economically designed structures. However, light structures are more sensitive to dynamic loads induced by environment and/or man. The most dangerous environmental dynamic loads are created by earthquakes and strong winds. These loads may destroy or make serious damage to structures. Also machines at work, road traffic, railway traffic, construction works and human body motions can be the sources of significant structural vibrations. In these cases, vibrations are unpleasant to anyone present in the building and they can be dangerous to human health and mental condition. Man-induced vibrations may also cause safety problems, including the risk of structure failure. These reasons justify an urgent necessity for developing methods and technologies which are able to reduce undesirable vibrations of structures. Such vibration reduction systems can be divided into four broad categories i.e.: passive, active, semi-active and hybrid systems.

The passive control systems can be defined as systems which do not require any external power sources for operation. The passive systems use structural motion to produce control forces. These systems cannot destabilize the structure because the system can only dissipate energy.

The main parts of the active system are sensors, measuring the state of the structures, the controller computing the desired active forces and actuators. The active system usually requires a big power source for operation of actuators which produce the control forces acting on the structures. The control forces are determined by the controller based on the feedback from the sensors that measure the response of the structures and/or excitation. The active system introduces additional energy to the structure and for this reason it can destabilize the structure motion if it is not properly designed.

The semi-active systems are similar to the active systems and contain all parts of the active one but the most important difference is that the semi-active system requires a very small power source for its operation. The semi-active system can also be understood as a system in which the damper parameters (stiffness, damping or friction coefficients) can be changed very fast. The semi-active system can also only dissipate energy and cannot destabilize the structure.

The hybrid system is a combination of the two systems belonging in two different categories of the above-mentioned ones. The base isolation system with the semi-active damper is an example.

Compared with other areas of application such as, for example, the space structures, the structural control has distinctive features that must be taken into account. Civil engineering structures are statically stable and large objects requiring very large control forces to reduce their vibrations. Environmental forces, such as wind or earthquake forces, acting on structures are great though random in nature. These forces are highly uncertain with respect to magnitude and time of occurrence. The structures are modeled as systems with many degrees of freedom, which significantly complicates the process of analysis and designing. The structural parameters are known only in approximation and can change values during the lifetime of the structure. The actuators are typically very large, the dynamics of actuators can be complex. The control systems must be fail-safe.

The objective of this paper is a brief introduction to the problems of structural control of civil engineering structures. Description of the most popular passive, active and semi-active systems together with their concept of working is provided. Moreover, the main methods of analysis and design of the above-mentioned systems are described.

A more detailed introduction to the problems and methods of structural control is given in papers [1 – 9].

2. Passive systems

Passive control systems increase the energy-dissipation capacity of structures or transfer energy from lower to higher modes of vibration. Kinetic energy can be converted using such phenomena as frictional sliding, yielding of metals, deformation of viscoelastic solids and fluids, and fluid orificing. Dynamic vibration absorbers are used to transfer energy to higher modes.

Modern structural passive systems can be divided into two groups, i.e. base isolation systems and passive-energy dissipation systems.

The base isolation system is placed at the structure foundation. The structure is mounted on a sufficiently flexible base that is working as a filter, cutting out high frequencies. Moreover, base isolation systems can dissipate energy. The most popular isolation systems are elastomeric or lead-rubber bearings and sliding friction pendulum systems. The base isolation system partially reflects and partially absorbs the earthquake energy before this energy is transferred to the structure. The base isolation systems are widely used in buildings and bridges in seismic areas.

The main types of passive energy dissipation systems are: metallic dampers, friction dampers, viscoelastic dampers and viscous fluid dampers. Moreover, tuned mass dampers and tuned liquid mass dampers are often used to reduce the vibrations of structures. A schematic view of the viscous fluid damper and the viscoelastic damper is shown in Fig. 1. The dampers are connected with structures at two points, usually with the help of straight or chevron braces, as shown in Fig.2.

The methods of mathematical modeling of structures with dampers depend on the type of dampers used. The metallic dampers dissipate energy through inelastic deformations of, for example, ADAS devices. In this case, the viscoplastic theory is used to describe the behavior of such systems. The modeling details of structures with metallic dampers can be found in [7]. The metallic and friction devices are primarily used for seismic applications where deformations of structures are significant.

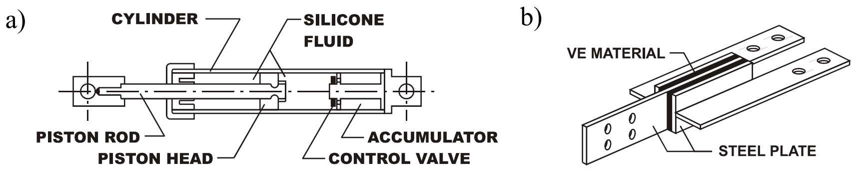

Fig. 1 Schematic view of: a) fluid damper, and b): VE damper

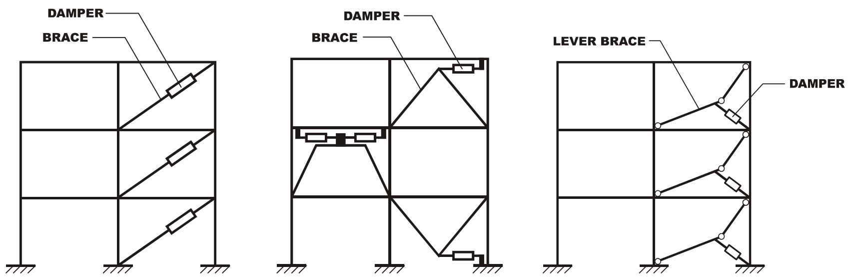

Fig. 2 Typical arrangements of passive dampers within structural frame

The viscoelastic and viscous fluid dampers can dissipate energy at all deformation levels and for this reason these dampers can be used to protect structures loaded both by wind and earthquake forces. The recent list of applications of fluid dampers is given in [10]. Viscoelastic materials used in civil engineering are copolymers or glassy substances. The dynamic behavior of viscoelastic materials depend on excitation frequency, strains and temperature. The force-displacement relationship for the harmonically loaded viscoelastic damper can be written as [11]:

$$u(t) = k_d(\lambda)x(t) + c_d(\lambda)\dot{x}(t)\,, \tag{1}$$

where λ is the excitation frequency, $x(t)$ - the damper displacement, $u(t)$ - the damper force, $k_d(\lambda)$ - the damper stiffness in which the brace stiffness can be taken into account, $c_d(\lambda)$ - the damper's damping factor.

The frequency and temperature dependence of parameters $k_d(\lambda)$ and $c_d(\lambda)$ are the sources of difficulties in the analysis of structures with viscoelastic dampers in a time domain. In some circumstances, it is enough to determine the values of the above-mentioned parameters for one specific value of excitation frequency and to keep them as constant parameters. In this case, the equation of motion of a structure with viscoelastic dampers could be written in the following matrix form:

$$\mathbf{M}\ddot{\mathbf{q}}(t) + (\mathbf{C} + \mathbf{C}_d)\dot{\mathbf{q}}(t) + (\mathbf{K} + \mathbf{K}_d)\mathbf{q}(t) = \mathbf{P}(t)\,, \tag{2}$$

where $\mathbf{q}(t)$ is the vector of structure nodal displacement, $\mathbf{P}(t)$ - the vector of excitation forces, $\mathbf{M}$ - the mass matrix, $\mathbf{C}$ - the structure damping matrix, $\mathbf{C}_d$ - the damping matrix of dampers, $\mathbf{K}$ - the structure stiffness matrix, $\mathbf{K}_d$ - the dampers stiffness matrix. Eqn (2) is easy to solve by standard methods both in time and frequency domains.

It is a simple mathematical model of structure with viscoelastic dampers. More sophisticated models of viscoelastic dampers are presented in [12], where the generalized Maxwell model and the fractional derivative model are described. The evolutionary model of viscoelastic dampers is discussed in [13].

The typical viscous fluid damper, which is shown in Fig. 1a, consists of a piston in the cylinder filled with a highly viscous silicon oil. Forced by the action of the piston, the silicon oil flows trough orifices in the piston. In this way energy is dissipated. The behavior of viscous dampers can be approximately described by the following equation

$$u(t) + \tau_d^{\alpha} D^{\alpha}[u(t)] = c_d D^{\beta}[x(t)] \quad , \tag{3}$$

where τ_d, c_d, α, β are material constants and $D^{\alpha}[\circ]$, $D^{\beta}[\circ]$ are fractional derivatives.

Eqn (3) results from the generalized Maxwell model presented in [14]. Very often it is assumed that $\alpha = \beta = 1$, which significantly simplifies the dynamic analysis of structures with dampers. The dynamic analysis of structures with viscous dampers described by the Maxwell model is given in [15].

If additionally, the second term in Eqn (3) is of no significance (i.e. $\tau_d \leq 0{,}006$), then for $\alpha = \beta = 1$ we have

$$u(t) = c_d \dot{x}(t) \quad , \tag{4}$$

and the motion equation of structure with dampers takes the form of Eqn (2) with $\mathbf{K}_d = \mathbf{0}$.

In many cases the force-velocity relationship of viscous dampers takes the form:

$$u(t) = c_d \dot{x}^n(t) \quad , \tag{5}$$

where the value of parameter n is taken from a range of 0.3 – 2.0.

In designing a structure with viscoelastic dampers the modal strain energy method described, for example, in [7, 16] is used very often. Many important questions concerning the desired damping ratio, selection of damper parameters and location in the building need the right answers during the designing process. A designing procedure is described in [17]. Optimization techniques proposed in [18 - 20] can help us determine damper parameters and locations. The optimal control theory is also used in [21] to design viscoelastic dampers.

The tuned mass damper (TMD) consists of a secondary mass attached to the main structures with the help of properly tuned spring and damping elements. The TMD is the most frequently used passive system to suppress the structural vibration in civil engineering. In typical cases, the secondary mass is not greater than 1% of the total mass of structure. The TMD can significantly reduce vibrations caused by wind forces. The reduction of vibration excited by earthquakes is significant when the dominant harmonics of ground motion are close to the frequency to which the TMD is tuned. To overcome this limitation more than one TMD, each tuned to different natural frequencies of structure, are used. Recently, in [22] the concept of megasubcontrol system is discussed. The idea is that the structure is divided into a few parts, each working as a TMD.

3. Active control systems

In civil engineering, research on active control systems began in 1972 when Yao, in paper [23], proposed the concept of structural concept based on the control theory. The active control systems are still a very attractive research area. Many problems have not been fully clarified. A lot of papers concerning the active and semi-active systems describing the results of theoretical and experimental works are published, mainly in the Journal of Mechanical Engineering, Earthquake Engineering and Structural Dynamics and Journal of Structural Engineering. Despite of it, in the present time there exist a number of structures with the active control systems built in Japan, USA and China. The first active control system was mounted in 1989 on Kyobashi Seiwa Building in Tokio. A list of 33 buildings and 9 bridges with active or semi-active control systems is given in [4, 24]. These systems are used to reduce the vibrations caused by winds and earthquakes.

The main parts of the active control systems and their functions are described in the introduction. In almost all cases, sensors measure the response of structures (i.e. accelerations, velocities and/or displacements) which means that mainly control systems with the closed-loop systems are used. The hydraulic actuators are very popular because civil engineering structures require large control forces to reduce vibrations. The actuators are mounted on structures in a similar way as the passive dampers (see Fig. 2).

Several assumptions are introduced in the analysis of structures with active and semi-active systems. The structures are treated as systems with many degrees of freedom. Modal transformation is often used to reduce the dimension of the problem. In many instances, the dynamics of actuators and time-delay effects are neglected. Often, full information about the dynamic state of structures is assumed. In recent papers, the state estimators (mostly the Kalman-Bucy filter) or direct output approach are used [25, 26].

Taking into account all of above mentioned assumptions, we can derive the following motion equation of a structure with the active or semi-active system

$$\dot{\mathbf{z}}(t) = \mathbf{A}\mathbf{z}(t) + \mathbf{B}\mathbf{u}(t) + \mathbf{f}(t) \ , \tag{6}$$

where

$$\mathbf{A} = \begin{bmatrix} \mathbf{0} & \mathbf{I} \\ -\mathbf{M}^{-1}\mathbf{K} & -\mathbf{M}^{-1}\mathbf{C} \end{bmatrix} , \qquad \mathbf{B} = \begin{bmatrix} \mathbf{0} \\ \mathbf{M}^{-1}\mathbf{D} \end{bmatrix} , \tag{7}$$

$\mathbf{u}(t)$ is the vector of control forces, $\mathbf{z}(t) = \text{col}(\mathbf{q}(t),\ \dot{\mathbf{q}}(t))$ is the state vector, $\mathbf{f}(t) = \text{col}(\mathbf{0},\ \mathbf{P}(t))$. $\mathbf{D}$ is the location matrix defining the positions of actuators within the structure.

A variety of control algorithms, based on several control design criteria, are proposed or applied to design the controllers. The most popular ones are based on the theory of linear quadratic regulators (LQR) [27, 28], instantaneous optimal control [29, 30], and the linear quadratic Gaussian theory (LQG) [31 – 33]. The H_2 and H_∞ methods are used if the control problems in the frequency domain are analyzed [31, 34 – 36]. Moreover, the pole placement [37], modal control [38], sliding mode control [39], fuzzy control [40] and the artificial neural nets [41] are applied to control the vibrations of civil engineering structures. Both the continuous-time and discrete-time approach are analyzed (see, for example, [27, 38, 42, 43]).

In the LQR method, the control vector $\mathbf{u}(t)$ is chosen in such a way that the performance index defined as

$$J = \int_0^{t_f} \left(\mathbf{z}^T(t)\mathbf{Q}\mathbf{z}(t) + \mathbf{u}^T(t)\mathbf{R}\mathbf{u}(t) \right) dt \ , \tag{8}$$

is minimized. Moreover, vectors $\mathbf{z}(t)$ and $\mathbf{u}(t)$ fulfill Eqn (6) together with the initial condition $\mathbf{z}(0) = \mathbf{z}_0$. $\mathbf{Q}$ and $\mathbf{R}$ are weighting matrices in which a compromise between the effects and cost of control is hidden.

It can be shown in [6], that the required control vector is given by

$$\mathbf{u}(t) = -\tfrac{1}{2}\mathbf{R}^{-1}\mathbf{B}^T\mathbf{P}(t)\mathbf{z}(t) \ . \tag{9}$$

The matrix $\mathbf{P}(t)$ appearing in Eqn (9) is the symmetric and positive definite matrix satisfying the following differential Riccati equation:

$$\dot{\mathbf{P}}(t) + \mathbf{P}(t)\mathbf{A} - \tfrac{1}{2}\mathbf{P}(t)\mathbf{B}\mathbf{R}^{-1}\mathbf{B}^T\mathbf{P}(t) + \mathbf{A}^T\mathbf{P}(t) + 2\mathbf{Q} = \mathbf{0} \ , \tag{10}$$

together with the condition $\mathbf{P}(t_f) = \mathbf{0}$. However, it has been shown in [8, 9] that in typical structural problems the elements of matrix $\mathbf{P}(t)$ remain constant for a large part of time interval $(0,\ t_f)$. In this case, the Riccati matrix $\mathbf{P}$ can be determined as a solution to the following algebraic Riccati equation

$$\mathbf{P}\mathbf{A} - \tfrac{1}{2}\mathbf{P}\mathbf{B}\mathbf{R}^{-1}\mathbf{B}^T\mathbf{P} + \mathbf{A}^T\mathbf{P} + 2\mathbf{Q} = \mathbf{0} \ . \tag{11}$$

Moreover, it has been pointed out that external excitation is neglected in derivation of Eqn (11). For this reason, the control force given in Eqn (9) is only suboptimal. Because all parameters in Eqn (11) are known, the matrix $\mathbf{P}$ can be computed off-line, and the on-line computation of $\mathbf{u}(t)$ require only multiplications of the matrices shown in Eqn (9).

The determination of a solution to Eqn (11) and to its linear version

$$\mathbf{PA} + \mathbf{A}^T\mathbf{P} + 2\mathbf{Q} = \mathbf{0} \ , \qquad (12)$$

known as the Lyapunov equation, is a serious numerical problem especially when dimensions of the matrices in Eqns (11) and (12) are large. The problem is important because both equations occur in many methods used in the active control (see [1, 9]). The Porter method, the Kleinman method and the Bartel-Stewart procedure (described in [8, 9, 44]) could be useful to solve these equations.

From the practical standpoint, a number of important questions must be solved before the active control system is constructed. Theoretical results are obtained based on idealized structure and control system description. Modeling errors may have significant influence, known as the control and observation spillover, which is able to destabilize the structure motion. Methods of spillover compensations are given, for example, in [6, 45]. In the ideal control system it is assumed that all operations needed to execute the control forces can be performed instantaneously. In reality, it takes time and in consequence some time delay exists. The time delay can make the control ineffective or, in the worst case, can destabilize the structure motion. The influence of time-delay on the effectiveness of structural control is discussed in [46 – 48]. Another problem is connected with a very limited number of sensors which are in the real control systems. This is accounted for in the above-mentioned direct output feedback or by using observers such as, for example, the Kalman filter. Experimental verification of the proposed control systems is very important in this context. Experimental results are described in [49 – 51].

Moreover, optimization of the locations of sensors and actuators is an important question because of the sensitivity of control results to the locations of sensors and sensitivity of the energy required by actuators to actuator locations. These questions are open but some results are given in [52 – 54].

4. Semi-active systems

The semi-active systems combine the best features of passive and active control systems. The main parts of semi-active control systems are the same as in the active systems, except some important differences concerning actuators. The semi-active actuators have the adaptability like the active devices but they can operate on very small (usually battery) power sources. Moreover, the semi-active control devices cannot destabilize the structural systems because they can only dissipate energy like the passive devices. In many cases, the semi-active devices can also act as the passive ones if the power source fails. The appropriately designed semi-active systems perform much better than passive devices and only slightly worse than active systems. However, the behavior of semi-active systems is non-linear.

Several types of semi-active dampers exist. The variable-orifice damper [55], variable-stiffness device [56], semi-active friction damper [57], resettable damper [58] and the semi-active hydraulic damper, which was installed in the Kajima Shizuoka Building in Shizuoka, Japan, have been constructed and tested. Other semi-active devices are the magnetorheological dampers [59] which are a particularly promising class because of their mechanical simplicity, low power requirements and high force capacity.

Semi-active fluid viscous dampers described in [60] consist of a cylinder containing a piston which separates the two sides of a cylinder filled with a fluid (usually oil). The damper has an external bypass loop containing an external control valve with orifice modulated by a small electric motor. If the piston is moved, the fluid within the damper is forced to pass through small orifices. The damping factor of the device can be changed on-line due to the orifice modulation ability. The time required to go from a fully open to fully-closed valve is about 10 ms.

If the semi-active control of vibration is realized by actuators of viscous type the control force generated in the actuator fulfils the relation:

$$u(t) = c(t)\dot{x}(t) \ , \tag{13}$$

where $c(t)$ is the time-varying damping factor which takes values from the range ($c_{\min}$, $c_{\max}$). The process to design a semi-active control system consists of two steps. In the first step, the desirable control forces $\tilde{u}$ are determined from Eqn (9). The execution of this force by the semi-active actuator is not always possible due to the limited range of variation of the damping factor. In the second step the desirable damping factor $\tilde{c}_i$ is calculated from the formula:

$$\tilde{c} = \tilde{u}(t) / \dot{x}(t) \ . \tag{14}$$

If $c_{\min} \le c \le c_{\max}$, then the real factor $c = \tilde{c}$, otherwise, c is equal to $c_{\min}$ or $c_{\max}$, respectively. The real semi-active force is calculated from Eqn (13).

5. Concluding remarks

In this paper, an attempt has been made to review the basic concepts of passive, active and semi-active structural control systems which are an exciting and fast expanding field of interest currently. The concepts, characteristic features and typical methods of analysis of all of the considered systems are briefly described. It is necessary to emphasize that all structural control systems are still evolving and important improvements in both technology and theory are expected in the coming years. Continuing efforts are needed to make this technology ready for wide implementation in practice.

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