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PASSIVE, ACTIVE AND SEMI-ACTIVE CONTROL SYSTEMS IN CIVIL ENGINEERING

BY
SEPTIMIU-GEORGE LUCA, FLORENTINA CHIRA
and VICTOR- OCTAVIAN ROŞCA

In the recent years many techniques has been developed to reduce the vibration response in civil structure, such as tall buildings and long bridges. Attention of this paper is focused on the difference among passive, active and semi-active control systems. If passive control systems are used for enhancing structural damping, stiffness or strength, the other control techniques employ controllable forces to add or dissipate, or both, energy in a structure due to the specific devices integrated with sensors, controllers and real-time processes to operating. Some applications will be proposed and applied to single degree of freedom systems in vertical working conditions.

1. Introduction

The traditional approach to mitigate vibrations due to the earthquake and wind loads is to design structures with sufficient strength and deformation capacity in a ductile manner. This approach, based on the ensuring of strength – ductility combination, provides the strong wind or seismic action as ultimate load, accepting a certain number of structural or non-structural degradations. Usually, for a steel structure, the dissipation of the energy introduced in structure by dynamic action occurs only in the plastic hinges. For this reason, taking into account the way in which the load bearing structural elements of a steel system functions together, a global plastic mechanism is generated.

The modifications of the structural systems carried out in order to reduce vibrations, have conducted towards the concept of *Structural Control*. This concept was first time introduced by Y a o [5]. This means that the structure is regarded as a dynamic system whose response variables (displacement, velocity and acceleration) are functions of time and in which some mechanical properties, typically the stiffness and the damping, may be adjusted to minimize the dynamic effects of load under an acceptable level.

During the decades many techniques have been proven to develop successful physical, analytical, numerical and experimental models in predicting the dynamic behaviour of the civil engineering systems that are subjected to excitations. According to the natural complex mode shapes of a structure and their corresponding damping values, we must find a good way to reduce the magnitudes of frequency response with respect to the excitation input. Frequency response analysis and transient problems became common design criteria for the community engineering. During the first half of the XXth century the research directions have included the knowledge of a large number of diverse disciplines as follows: computer science, system theory, material science, sensing technology, stochastic processes, etc., some of which are not within the domain of traditional civil engineering [4]. Therefore, in recent years, it has been paid a considerable attention to new concepts of structural control including a large variety of techniques: passive, active and semi-active.

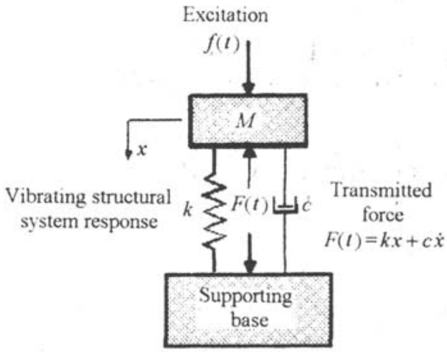

Fig. 1.- Passive viscous damper to control either the transmitted force or the vibrating system response.

To understand the necessity and opportunity to choose the best one among the passive, active and semi-active control systems a single degree of system, in which a vibratory machine is supported on a rigid base through a spring and a dashpot (the classical mass-spring-dashpot model), will be further considered (Fig. 1).

2. Semi-active *versus* Passive

A passive control system consists of one or more devices, attached or embedded to a structure, designed to modify the stiffness or the damping of the structure in an appropriate manner without requiring an external power source to operate, developing the control forces opposite to the motion of controlled structural system.

From historical point of view, passive control techniques, such that base isolation and passive control devices, are the first of them implemented. A lot of researches have studied structures equipped with these passive techniques and a lot of practical realisations have already implemented in many countries.

The isolation or reducing vibrations, which are produced, for instance, by industrial machines, or other vibrators are accomplished in order to reduce the force transmitted by these to the foundations or other structures. This reason has been applied in the field of civil engineering coming from other fields, particularly automotive and mechanical engineering. Usually, a damping system is introduced between the vibratory machine and its supporting base or, if it's possible, an inertial mass attached by the vibratory machine. Considering the system model from Fig. 1, the equation of motion in time domain is given by

$$M\ddot{x} + c\dot{x} + kx = f(t), \tag{1}$$

and also the force transmitted to the supporting base, f_s, is given by the relation

$$c\ddot{x} + kx = f_s(t). \tag{2}$$

The receptance transfer functions of the elements of the system (mass M, spring k, damper c) in frequency domain are: $R_m = 1/Ms^2$, $R_k = 1/k$, respectively $R_c = 1/cs$, where $s = \mathrm{j}\Omega = \mathrm{j}2\pi f$ (s is Laplace operator). Because the elements are connected in parallel we can write the receptance frequency transfer function between the excitation, f, and the vibrating system response, x, as follows

$$\frac{1}{R_x} = \frac{1}{R_m} + \frac{1}{R_c} + \frac{1}{R_k}. \tag{3}$$

Hence,

$$\frac{x}{f} = \frac{1}{Ms^2 + cs + k} = \left.\frac{1}{-M\Omega^2 + \mathrm{j}c\Omega + k}\right|_{s=\mathrm{j}\,\Omega}. \tag{4}$$

Also the receptance transfer function between the force transmitted to the supporting base and vibrating system response is

$$\frac{1}{R_f} = \frac{1}{R_c} + \frac{1}{R_k}. \tag{5}$$

Consequently, the dynamic stiffness transfer function of Eq. (5) becomes

$$\frac{f_s}{x} = cs + k = \left.\mathrm{j}c\Omega + k\right|_{s=\mathrm{j}\,\Omega}. \tag{6}$$

The force transmissibility is given by the ratio between the force transmitted to the support and the excitation force applied to the mass namely

$$\frac{f_s}{f} = \frac{\mathrm{j}c\Omega + k}{-M\Omega^2 + \mathrm{j}c\Omega + k}. \tag{7}$$

Introducing the non-dimensional frequency ratio $\beta = \Omega/\omega$, where Ω is the excitation frequency, $\omega = \sqrt{k/M}$ – undamped natural frequency and the damping ratio $\zeta = c/2\sqrt{kM}$, the Eqs. (4) and (7) can be written

$$G_d(\mathrm{j}\,\Omega) = \frac{kx}{f} = \frac{1}{1 - \beta^2 + \mathrm{j}2\zeta\beta} \tag{8}$$

and, respectively,

$$G_{\mathrm{tr}}(\mathrm{j}\,\Omega) = \frac{f_s}{f} = \frac{1 + \mathrm{j}2\zeta\beta}{1 - \beta^2 + \mathrm{j}2\zeta\beta}. \tag{9}$$

When we want to control the vibrating system response, the Eq. (8) is used; when we want to control the force transmissibility, the Eq. (9) is used. The magnitude of the transfer function, $|G_d|$, or the dynamic magnification factor, D, is

$$D = |G_d| = \frac{|kx|}{|f|} = \frac{1}{|1 - \beta^2 + \mathrm{j}2\zeta\beta|}. \tag{10}$$

Also, the form of dynamic magnification factor, D, can be written as

$$D = |G_d| = \frac{1}{\sqrt{(1-\beta^2)^2 + (2\zeta\beta)^2}}. \tag{11}$$

The force transmissibility magnitude, $|G_{\mathrm{tr}}|$, or transmissibility ratio, Tr, is

$$\mathrm{Tr} = |G_{\mathrm{tr}}| = \frac{|f_s|}{|f|} = \frac{|1 + \mathrm{j}2\zeta\beta|}{|(1 - \beta^2 + \mathrm{j}2\zeta\beta)|}. \tag{12}$$

Finally, the transmissibility can be expressed in an alternative form:

$$\mathrm{Tr} = |G_{\mathrm{tr}}| = \frac{\sqrt{1 + (2\zeta\beta)^2}}{\sqrt{(1-\beta^2)^2 + (2\zeta\beta)^2}}. \tag{13}$$

The dynamic magnification factor and the transmissibility are plotted in Fig. 2, respectively Fig. 3, as a function of β and damping ratio, ζ.

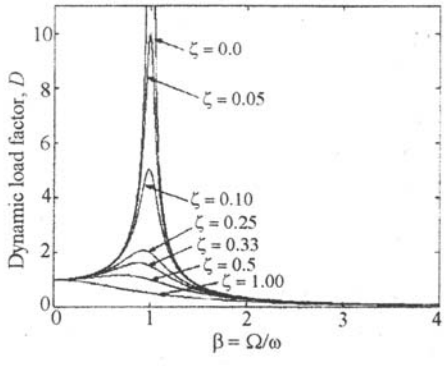

Fig. 2.- Dynamic magnification factor of a SDOF model for several values of damping ratio.

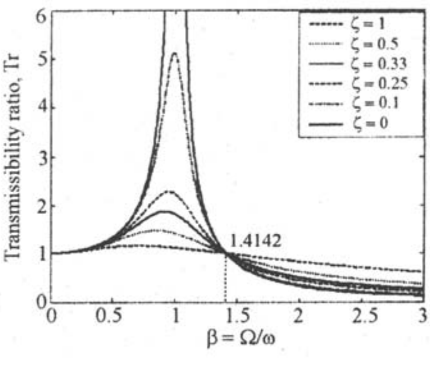

Fig. 3.- Transmissibility of a SDOF model for several values of damping ratio.

The selection of the value of damping is crucial to use a damper in vibration control. It's well known that the higher values of damping are suitable when the nondimensional frequency ratio is comprised within the interval $\beta \in [0.7, 1.3]$ in order to control either the vibrating system response or the force transmissibility. Analysing the graph of Fig. 3, we can see that for $\beta > \sqrt{2}$ the transmissibility is less than 1, therefore a lower value of damping is desired. But for the values comprised within the interval $\beta \in [0, \sqrt{2}]$, a higher damping is preferable. In the last case the force transmitted to the foundation is higher than the excitation one.

According to above explanations, the implementation of passive dissipating devices into the structure can lead to undesired situations, especially during the transient response. Damping for passive control system can be dependent on the time, frequency or environment, as well as to be non-linear. With a semi-active control the damping characteristic of devices can be changed in a desired manner, continually or chosen within a range with pre-established values, with respect to the functioning conditions. Implementation of semi-active control law is very simple, as is show in Fig. 4, taking into account the model with a vibratory machine supported on a foundation. Examples of such common semi-active devices known in literature, that could be implemented, are: semi-active hydraulic devices, variable stiffness devices, controllable friction dampers, or controllable fluid dampers and so on.

Let's consider now a semi-active hydraulic damper with on–off behaviour. A high value for damping is used when the machine starts or stops, having a low speed (during the acceleration or deceleration). For high speed the value of damping is low. This type of control is very useful only if the dynamics characteristics and the excitation condition are very well known.

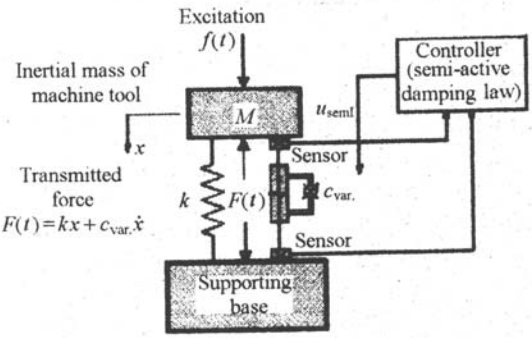

Fig. 4.– Semi-active damping control either the transmitted force or the vibrating system response.

3. Semi-active *versus* Active

An active control system is defined as one in which a large external power source or many, from tens kilowatts to several megawatts, control actuators that apply forces to the structure in a prescribed manner. These forces can be used to both add and dissipate energy in the structure. For these reasons, active control strategies were adopted in the field of civil engineering coming from electrical and mechanical engineering. The real problem of active system is that their energy requirement is large.

Semi-active control systems are a class of active control systems for which the external energy requirements are smaller amounts than those of typical active control. A battery power, for instance, is sufficient to make them operative. Semi-active devices cannot add or remove energy to the structural system, but can control in real time parameters of the structure such as spring stiffness or coefficient of viscous damping. The stability is guaranteed, in the sense that no instability can occur, because semi-active devices utilize the motion of the structure to develop the control forces.

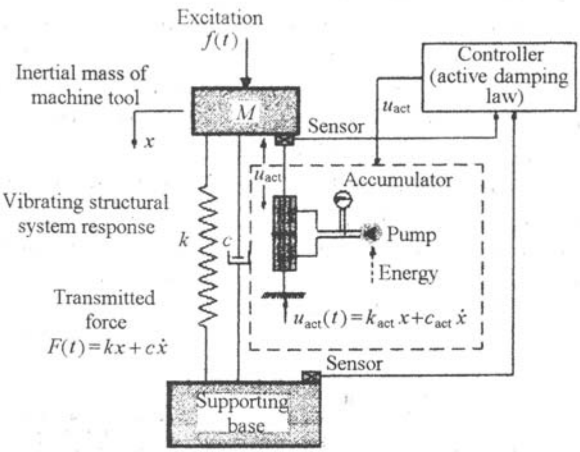

Fig. 5.- Active control system to reduce dynamic response of the structural system (negative feedback).

A schematic diagram of active control system is represented in Fig. 5. The control forces within the framework of an active control system are generated by a wide variety of actuators that can act hydraulic, pneumatic, electromagnetic, piezoelectric or motor driven ball-screw actuation. The controller (*e.g.* a computer) is a device that receives signals from the response of the structure measured by physical sensors (within active control using feedback) and that on basis of a pre-determined control algorithm compares the received signals with a desired response and uses the error to generate a proper control signal [1]. The control signal is then sent to actuator. In feed-forward control, the disturbance (input signal), not the response (output signal), is measured and used to generate the control signals. Both feedback and feed-forward principles can be used together in the same active control system.

3.1. State-Space Model

It's convenient to represent the vibrating structural system response by a state space model in order to apply passive, semi-active or active techniques. Let's consider now a single degree of freedom system with the following dynamic characteristics: $M = 7,949$ kg; $k = 2,859333$ N/m; $c = 2,413$ Ns/m; $\omega = 18.96$ rad/s; $T = 0.33$ s; $f = 3.0185$ Hz; $\zeta = 0.008$. The equation of motion (1), where the substitutions

$x_1 = x$, $x_2 = \dot{x}$ and $u = f(t)$ are introduced, can be written in the following state space description

$$\begin{cases} \dot{x}_1 = x_2, \\ \dot{x}_2 = -M^{-1}kx_1 - M^{-1}cx_2 + M^{-1}u. \end{cases} \tag{14}$$

Hence, the description can be modified to

$$\begin{bmatrix} \dot{x}_1 \\ \dot{x}_2 \end{bmatrix} = \begin{bmatrix} 0 & 1 \\ -M^{-1}k & -M^{-1}c \end{bmatrix} \begin{bmatrix} x_1 \\ x_2 \end{bmatrix} + \begin{bmatrix} 0 \\ M^{-1} \end{bmatrix} u, \tag{15}$$

resulting finally:

$$\begin{cases} \dot{x}_(t) = \mathbf{A}x(t) + \mathbf{B}u(t), t \in R, x \in R^n, u \in R^m, \\ y(t) = \mathbf{C}x(t) + \mathbf{D}u(t), y \in R^p, \end{cases} \tag{16}$$

where: $x(t)$ is the vector of the state variables ($1 \times n$ dimension), $y(t)$ – the vector of the measurable variables ($p \times 1$ dimension), $u(t)$ – the vector of the controllable and forcing variables, $\mathbf{A}$ – the system matrix ($n \times n$ dimension), $\mathbf{B}$ – the input matrix ($n \times m$ dimension), $\mathbf{C}$ – the output matrix ($p \times n$ dimension), $\mathbf{D}$ – the connection matrix between input $u(t)$ and output $y(t)$ ($p \times m$ dimension). The matrix $\mathbf{D}$ is null in practical applications because the input $u(t)$ is not fed forward into the response, $y(t)$.

The transfer function matrix, $\mathbf{G(s)}$, is given by

$$\mathbf{G(s)} = \mathbf{C}(s\mathbf{I} - \mathbf{A})^{-1}\mathbf{B} + \mathbf{D}, \tag{17}$$

where $\mathbf{I}$ is identity matrix ($n \times n$ dimension).

Assume that the vector $u(t)$, for an active control law, is given by

$$u(t) = -k_{\text{act}}x_1 - c_{\text{act}}x_2. \tag{18}$$

In this case the displacement and velocity of the mass, M, are measured and a negative feedback is achieved in system through the multiplication of $x(t)$, in real time, with the state feedback gain matrix, $\mathbf{K}$, in order to implement the control signal, $u(t) = -\mathbf{K}x(t)$. The Eq. (19) describes a closed-loop control system, because the state $x(t)$ is fed back to the control signal, $u(t)$. On contrary, when the state $x(t)$ is not fed back to the control signal, $u(t)$, the description is a open-loop control system

$$\begin{cases} \dot{x}_(t) = (\mathbf{A} - \mathbf{BK})x(t), \\ y(t) = \mathbf{C}x(t), \end{cases} \tag{19}$$

where

$$\mathbf{K} = \begin{bmatrix} 0 & 0 \\ k_{\text{act}} & c_{\text{act}} \end{bmatrix}. \tag{20}$$

The difference among passive, semi-active and active systems is shown in a simple way in Fig. 6, taking into account that only the damping is inserted with active control law and also the graphs represent the magnitude and phase angle curves of the receptance transfer function of the considered SDOF between the excitation and displacement response. The results have been obtained using quadratic optimal control. The aria between the active and passive response curves can offer theoretical possibilities for a semi-active control system.

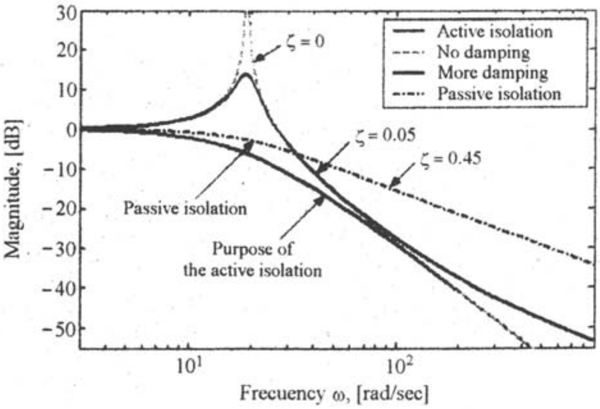

Fig. 6.– Purpose of an active system from transmissibility point of view.

In another way said, semi-active control techniques make the rehabilitation of passive control systems, while they can occur similar performances of active control systems.

4. Conclusion

A comparison among passive, semi-active and active control techniques have been discussed. Some schemes of these ones, for a single degree of freedom, have been illustrated. In real application, we can compare both the transient response and more responses of the transfer functions (receptance, impedance, mobility, accelerance, etc). Not only the damping is considered, but also the accelerations, the velocities or the forces that act the structure. Therefore, it's customarily to make a balance among all this constrains regarding the desired control degree that is different from a system to another.

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"Gh.Asachi" Technical University, Jassy,
Department of Structural Mechanics

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SISTEME DE CONTROL PASIV, ACTIV ŞI SEMI-ACTIV ÎN CONSTRUCŢII CIVILE

(Rezumat)

In ultimii ani numeroase tehnici au fost dezvoltate cu scopul de a reduce răspunsul structural la vibraţii in construcţii civile, mai precis clădiri înalte şi poduri de mari deschideri. Scopul acestei lucrări este de a studia diferenţa dintre sistemele de control pasiv, activ şi semi-activ. Dacă sistemele de control semi-activ sunt folosite la creşterea amortizării, rigidităţii şi rezistenţei structurale, celelalte tehnici de control, prin forţe controlabile, introduc sau disipează (sau introduc şi disipează) energie într-o structură prin dispozitive specifice, suplimentate de senzori, controleri şi procese de informare în timp real. Câteva aplicaţii sunt propuse şi aplicate pentru un sistem structural cu un singur grad de libertate dinamic în condiţii de lucru verticale.