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Influence of time delay and saturation capacity to the response of controlled structures under earthquake excitations

Nikos G. Pnevmatikos*[1,2] and Charis J. Gantes[1,2]

[1]Department of Civil Infrastructure Works, Faculty of Technological Application, Technological Educational Institution of Athens, Ag. Spyridonos Str., P.O. 12210 Egaleo-Athens, Greece
[2]Metal Structures Laboratory, School of Civil Engineering, National Technical University of Athens, 9 Heroon Polytechneiou, GR-15780 Zografou, Greece

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Abstract. During the last thirty years many structural control concepts have been proposed for the reduction of the structural response caused by earthquake excitations. Their research and implementation in practice have shown that seismic control of structures has a lot of potential but also many limitations. In this paper the importance of two practical issues, time delay and saturation effect, on the performance of controlled structures, is discussed. Their influence, both separately and in interaction, on the response of structures controlled by a modified pole placement algorithm is investigated. Characteristic buildings controlled by this algorithm and subjected to dynamic loads, such as harmonic signals and actual seismic events, are analyzed for a range of levels of time delay and saturation capacity of the control devices. The response reduction surfaces for the combined influence of time delay and force saturation of the controlled buildings are obtained. Conclusions regarding the choice of the control system and the desired properties of the control devices are drawn.

Keywords: structural control; time delay; saturation control; pole placement; structural dynamics; earthquake engineering.

1. Introduction

Structural control has received wide-spread attention in recent years. A strong trend in structural technology is to shift from conventional earthquake resistant structures, to structurally controlled buildings, which are designed to suppress the vibration itself. The research and application of control to civil engineering structures include analytical studies and experimental verifications. Over the past few decades various control algorithms and control devices have been developed, modified and investigated by various groups of researchers. Several well-established algorithms in control engineering have been introduced to control structures. While many of these structural control strategies have been successfully applied, technological problems and challenges relating to time delay, saturation capacity effects, cost, reliance on external power, and mechanical intricacy during the life of the structure have delayed their widespread use and relatively few actual structures are

*Corresponding Author, Dr., E-mail: nikos_pnevmatikos@hotmail.com

equipped with control systems.

Since the entire control process involves measuring response data, computing control forces by means of an appropriate algorithm, transmitting data and signals to actuators and activating the actuators to a specified level of force, time delays arise and cannot be avoided. The problem of time delay in the active control of structural systems has been investigated by many scientists and engineers. Chu *et al*. (2008) developed an optimal discrete-time direct output-feedback control algorithm with consideration of sampling period and appropriate time delay in its control force action. In the work of Abdel-Rohman (1987), it is shown how the stability of the structure could be lost due to time delay, and two ways of time-delay compensation are suggested. In the first the gain matrix is redesigned considering the presence of time delay, while in the second low-pass filters are used to filter the velocity measurements from the frequency components of the high order modes. In the first case, the structure could remain unstable when using control moments as control actions, while in the second a number of vibration modes can be controlled and compensated for time delay but the higher order modes remain uncontrolled. Sain *et al*. (1992), compensate time delay with Pade approximations, while in the work of Agrawal *et al*. (2000) the allowable time delay is related with natural period and feedback gain for a single degree of freedom system. The maximum allowable time delay is found to decrease with decrease in natural period of the structure as well as with increase in active damping, and a compensation of time delay by modeling it as transportation lag is suggested. Under earthquake excitations, simulation results for the response of multi degree of freedom structures indicate that the degradation of the control performance due to fixed time delay is significant when time delay is close to a critical value. It is further demonstrated that the time-delay problem is more serious for structures with closely spaced vibrational modes.

In the work of Cai (2003), an optimal control method for linear systems with time delay is developed. Time delay is considered at the very beginning of the control design, and no approximation and estimation are made in the control system. Thus, the system performance and stability can be guaranteed. Instability in the response might occur only if a system with time delay is controlled by an optimal controller that was designed with no consideration of time delay. Furthermore, Pu (1998), studied the influence of time delay to controlled base isolated structures. Through varied allocation of the controlled poles, the control system shows variable performance. However, the locations of the controlled pole pairs should be carefully specified and checked according to the characteristics of the system. Analytical expressions of limiting values of time delay for single degree of freedom systems are derived in the work of Connor (2003), however such expressions are very difficult to obtain for multi degree of freedom systems. In the work of Undwadia (2007), proportional control with positive feedback that uses intentional time delays, which may not necessarily be small compared to the natural periods of the structural system, is presented. Casciati *et al.* (2006), take into consideration the time delay effect solving numerically delayed deferential equations. All of these studies demonstrate how important the issue of time delay is in structural control, and how it may result in a degradation of the control performance and may even render the controlled structure to become unstable. Most studies show that time delays influence negatively the control system, therefore they should be kept small compared to the fundamental period of vibration of the system, and should, if possible, be eliminated and/or compensated.

Another important practical problem is the saturation of the control force. Actuator saturation occurs when the actuator is given by the control algorithm a demand requiring an output that is larger than its designed peak output. Failure to account for this nonlinear effect can decrease the efficiency of the control system and possibly drive the structure to become unstable. Most control algorithms are linear, assuming that there is no limit in the magnitude of the control force. However, maximum capacity of the control devices is limited. Therefore, designing controllers to account for the bounded nature of the devices is desirable. Many researchers have considered bounded controllers for control of civil engineering structures. Some algorithms and techniques which have been investigated are the followings: Clipped optimal control derived from H_2/LQG, Dyke *et al.* (1996), a polynomial controller to represent the bounded controller Tomasula *et al.* (1996), modified bang bang controller by Wu and Soong (1996), saturation control based on matrix inequalities by Nguyen *et al.* (1997), continuous and robust bounded controllers for active control in structures by Arfiadi and Hadi (2006) and saturation control of hysteretic structures by Asano and Nakagawa (1998). Lin *et al.* (2007) use fuzzy controllers to sent the comant voltage to Mr damper with saturated capasity.

From the above studies it is concluded that the two issues of time delay and saturation of the control device are, in most cases, considered and studied separately. However, in the application of real control systems these two issues act simultaneously. With this fact in mind, in this paper the combined effect of the non linear phenomena of bounded capacity of the actuators and time delay of the system, acting simultaneously during the control process, on the systems response is investigated. Their influence to the structural response is evaluated and limits for time delay and saturation capacity are proposed, that can be used in the design process of controlled structures. The controlled algorithm that is used in the numerical simulations is a modified pole placement algorithm, developed by the authors Pnevmatikos and Gantes (2007).

2. Control of structures accounting for time delay and limited saturation capacity

2.1 Time delay

The equation of motion of a structural system with *n* degrees of freedom controlled by m forces and subjected to an earthquake excitation a_g, without considering time delay and limited saturation control capacity, is

$$\mathbf{M}\ddot{\mathbf{U}}(t) + \mathbf{C}\dot{\mathbf{U}}(t) + \mathbf{K}\mathbf{U}(t) = -\mathbf{M}\mathbf{E}a_g(t) + \mathbf{E}_f\mathbf{F}(t) \tag{1}$$

where **M**, **C, K** denote the mass, damping and stiffness matrices of the structure, respectively, **F** is the control force matrix and $\mathbf{E}_f$**,** **E** are the location matrices for the earthquake and the control forces on the structure, respectively. In the state space approach the above equation can be written as follows.

$$\dot{\mathbf{X}}(t) = \mathbf{A}\mathbf{X}(t) + \mathbf{B}_g a_g(t) + \mathbf{B}_f\mathbf{F}(t) \tag{2}$$

where the matrixes **X**, **A,** $\mathbf{B}_g$, $\mathbf{B}_f$ are given by

$$\mathbf{X} = \begin{bmatrix}\mathbf{U}\\ \dot{\mathbf{U}}\end{bmatrix}_{2n\times 1},\ \mathbf{A} = \begin{bmatrix}\mathbf{O} & \mathbf{I}\\ -\mathbf{M}^{-1}\mathbf{K} & -\mathbf{M}^{-1}\mathbf{C}\end{bmatrix}_{2n\times 2n},\ \mathbf{B}_g = \begin{bmatrix}\mathbf{O}\\ -\mathbf{E}\end{bmatrix}_{2n\times 1},\ \mathbf{B}_f = \begin{bmatrix}\mathbf{O}\\ \mathbf{M}^{-1}\mathbf{E}_f\end{bmatrix}_{2n\times 1} \tag{3}$$

Using a linear state feedback, the control force **F** is given by

$$\mathbf{F}(t) = -[\mathbf{k}_{f1}\ \mathbf{k}_{f2}]\begin{bmatrix}\mathbf{U}(t)\\ \dot{\mathbf{U}}(t)\end{bmatrix} = -\mathbf{K}_f\mathbf{X}(t) \tag{4}$$

$\mathbf{K}_f$ is the feedback gain matrix, which is calculated according to a control algorithm, while $\mathbf{k}_{f1}$ and $\mathbf{k}_{f2}$ are the sub-matrixes of $\mathbf{K}_f$ related to the displacement and velocity of the system, respectively. The control force, **F**, should be applied to the structure in a direct or indirect way, depending on the control device that is used.

Since the above control process involves measuring response data, $\mathbf{X}(t)$, computing the feedback matrix, $\mathbf{K}_f$, and control forces from the algorithm, transmitting data and signals to the actuators and activating the actuators to a specified level of force, a time delay, t_d, arises, which cannot be avoided. Accounting for time delay the control force **F**, instead of equation , is now given by

$$F(t) = -\mathbf{K}_f\mathbf{X}(t-t_d) \tag{5}$$

Then the equation that governs the control system becomes

$$\mathbf{M}\ddot{\mathbf{U}}(t) + \mathbf{C}\dot{\mathbf{U}}(t) + \mathbf{K}\mathbf{U}(t) = \mathbf{M}\mathbf{E}a_g(t) + \mathbf{E}_f\mathbf{F}(t-t_d) \tag{6}$$

From a structural point of view, the influence of time delay is to change the response of the controlled structure. From a mathematical point of view, time delay brings in additional terms in the eigenvalues of matrix **A**. This may cause the real part of an eigenvalue to become positive, consequently the system will be unstable. It is pointed out that the mechanics of the actuator and its dynamic characteristics, which may be frequency dependent, are not modeled and thus phase delay is not examined in this study.

For single degree of freedom systems analytical expressions for time delay, beyond which the system becomes unstable, can be obtained, Connor (2003). For multi degree of freedom systems numerical simulations are needed in order to quantify the influence of time delay on the response of the controlled structure.

If u_{max} is the maximum response of the uncontrolled system and $u_{max,td}$ is the maximum response

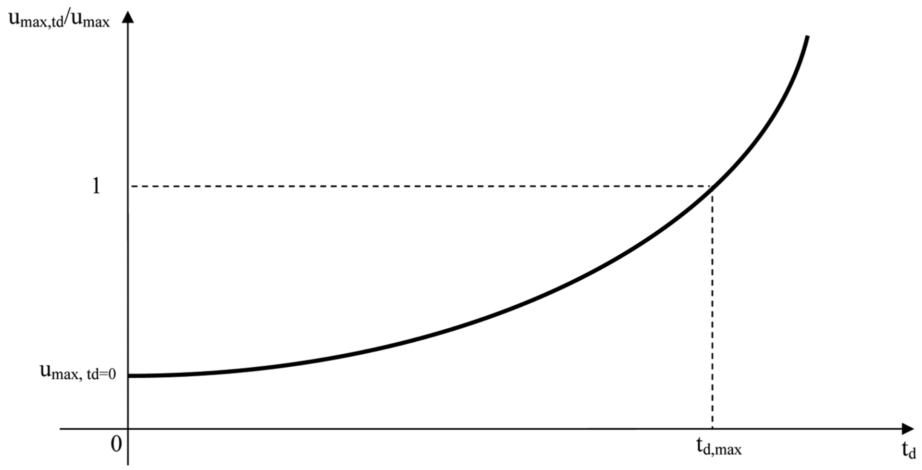


Fig. 1 The qualitative influence of time delay to the response of a controlled structure

of the controlled structure accounting for time delay, it is well known that the variation of the ratio $u_{max,td}/u_{max}$ with respect to time delay t_d is qualitatively described by a curve like the one shown in Fig. 1. In that figure it is shown that when an ideally controlled system is analyzed without considering time delay, the maximum response is $u_{max,td=0}$, which is the lowest response that can be achieved. As time delay increases $u_{max,td}$ also increases. There is an upper bound of time delay, $t_{d,max}$, for which the response of the controlled system becomes equal to the response of the uncontrolled system. In order for the control to be meaningful, time delay should be considerably lower than $t_{d,max}$.

The influence of time delay depends also on the dynamic characteristics of the structure to be controlled. In the literature it is stated that, the larger the eigenperiod is, the higher margin of time delay exists in order to achieve the same reduction in the response of the structure. In this paper, the upper bound of time delay with respect to the fundamental period, so that a system has at least the same response as the corresponding uncontrolled system subjected to sinusoidal and earthquake excitation, is going to be determined.

2.2 Saturation capacity of control force

Another parameter that also influences the response of the controlled structure is the maximum capacity of the control devices, F_{sat}. It may very often be the case that the control algorithm calculates a control force that is higher than the maximum capacity of the control device. In that case the control force that will finally be applied to the structure will be the maximum capacity of the control device, $\mathbf{F}_{sat}$. This phenomenon should be considered in the numerical simulation. Accounting for the maximum capacity of the device, the saturated control force, $sat\mathbf{F}(t)$, is given by

$$sat\mathbf{F}(t) = \begin{cases} \mathbf{F}(t), & \mathbf{F}(t) < \mathbf{F}_{sat} \\ \mathbf{F}_{sat}, & \mathbf{F}(t) \geq \mathbf{F}_{sat} \end{cases} \tag{7}$$

Replacing the above expression for the control force into Eq. (2) the following equation is obtained

$$\dot{\mathbf{X}}(t) = \mathbf{A}\mathbf{X}(t) + \mathbf{B}_g a_g(t) + \mathbf{B}_f \,\mathrm{sat}\mathbf{F}(t) \tag{8}$$

Solving the above equations numerically for different levels of saturation capacity, $\mathbf{F}_{sat}$, it is found that, if $u_{max,sat}$ is the maximum response of the controlled structure accounting for force saturation, then the variation of the ratio $u_{max,sat}/u_{max}$ with respect to the level of saturation capacity, $\mathbf{F}_{sat}$, is described qualitatively by a curve like the one of Fig. 2. The lower the saturation capacity level $\mathbf{F}_{sat}$ is, the larger the response of the controlled system becomes. There is an upper bound in saturation capacity of the device, $\mathbf{F}_{sat,max}$, beyond which the performance of the system does not improve any more. The response of the controlled system, $u_{max,sat,min}$, in this case is the lower response value that can be achieved. Thus, there is no need for the control devices to have the ability to provide more force than the limit value $\mathbf{F}_{sat,max}$.

2.3 Coupling of time delay and saturation capacity of control force

If the above two parameters, time delay and saturation capacity, are considered simultaneously, then Eq. (2) becomes

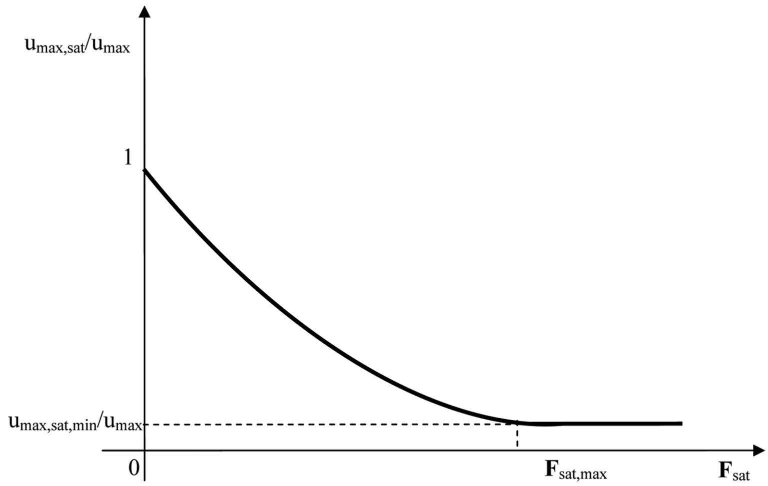


Fig. 2 The qualitative influence of the maximum capacity of the control devises, $\mathbf{F}_{sat}$, on the response of a controlled structure

$$\dot{\mathbf{X}}(t) = \mathbf{A}\mathbf{X}(t) + \mathbf{B}_g a_g(t) + \mathbf{B}_f \, \mathrm{sat}\mathbf{F}(t - t_d) \tag{9}$$

The above Eq. (9) is highly nonlinear and the influence of time delay and saturation capacity on the response of the controlled structure cannot be consider as linear superposition of each one acting separately. The coupling of time delay with saturation effect for structures subjected to earthquake action cannot be studied by means of analytical expressions for the solution of Eq. (9). To solve this non linear system an averaging method can be used. In this paper, in order to study the influence of those two parameters acting together, Eq. (9) is solved numerically, by means of a software program developed in MATLAB environment. Pole placement algorithm ιs chosen as control algorithm for the analysis. The estimation of the new locations of poles of the controlled structure is based on the frequency content of the signal excitation. The control algorithm and the associated numerical procedure are as follows (Fig. 3):

a. Initially the parameters of the system, mass, stiffness and damping matrixes, time delay, maximum saturation control capacity, initial conditions, the state space formulation and parameters related to the excitation signal are defined (Control on line.m file).

b. The strategy for the selection of the poles of the controlled system is to transform the structure into the complex plane, then transform the loading into the complex plane and there, depending on their relationship, take appropriate decisions. As the initial part of the signal arrives, it is analyzed for every small time interval by FFT process or wavelet analysis, and its spectrum and main frequencies are obtained. These main frequencies that should be avoided are chosen based on their participation to the spectrum and to the power of the corresponding part of the incoming signal. Then, cycles with radii equal to those frequencies are drawn in the complex plane. All points on or near those cycles should be avoided as possible pole locations, in order to avoid resonance. Next, unsafe zones with semi-bandwidth ω_s are defined around each of those cycles, where near-resonance conditions are expected, therefore, poles should preferably not be located there. Then, the positions of poles of the uncontrolled structure are compared to the unsafe zones and a decision whether to move the poles of the controlled system and where to put them is taken. If the poles are outside of the unsafe zones, then they are left provisionally at the same position, as is the case with

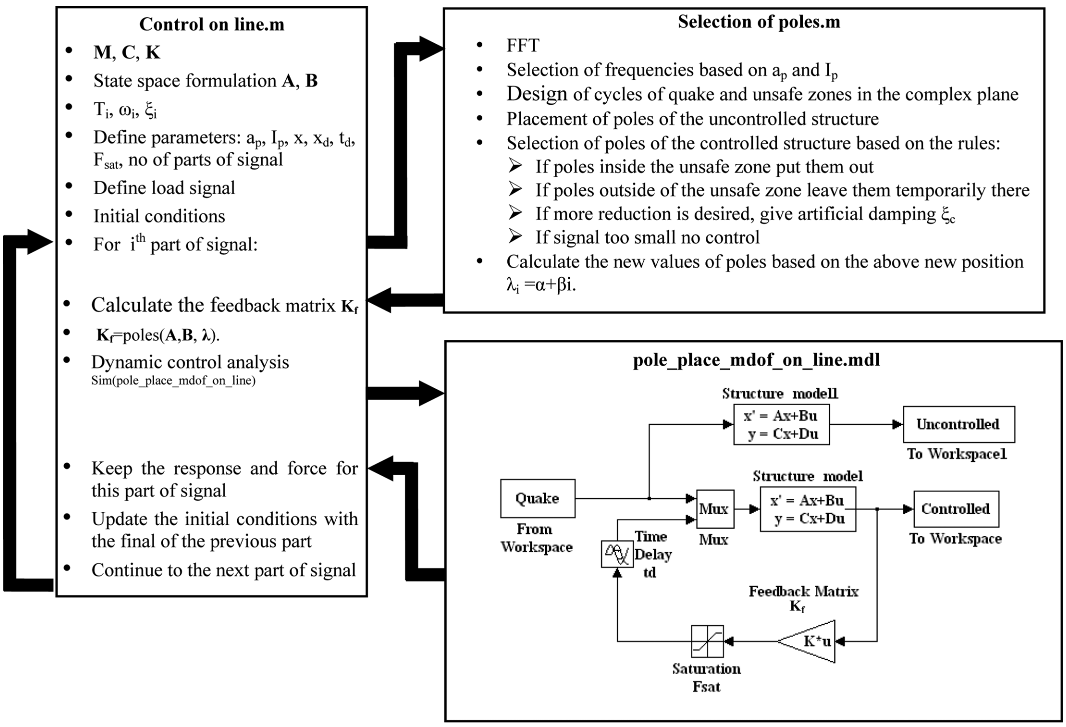


Fig. 3 The main files, their function and the simulink model of the software accounting for time delay and saturation effects

pole $\lambda_{o,1}$ in Fig. 4, otherwise, they are moved outside of the zone, along the radius between the initial pole and the origin of axes. The direction of movement will be outwards if the pole is outside of the cycle zone or inwards if the pole is inside the cycle zone (movement AB of pole $\lambda_{o,2}$, or movement A 'B' of pole $\lambda_{o,3}$, in Fig. 4). After that, based on the desired equivalent percentage of damping, the poles can be moved along a cycle, with centre the axes origin and radius defined by the new position, with direction towards the real axis, (movement BC, B 'C' or A "C" in Fig. 4). A transformation of the signal to the complex plane and the choice of the new location of poles are performed in the Selection of poles.m Matlab file. Details about the above dynamic control analysis and the choice of the location of poles of the controlled structure can be found in previous work of the authors Pnevmatikos and Gantes (2007), where, however, time delay and saturation capacity of control force had not been taken into account.

c. Based on the new position of the poles the feedback matrix is estimated with the help of the pole placement algorithm, and then the control forces are obtained, (Control on line.m file). These forces should be applied to the structure, in a direct or indirect way, so that the integrated controlled system will have a behavior like an uncontrolled system with the above location of poles, and thus will avoid resonance, have sufficient equivalent damping and consequently reduce its response.

d. A dynamic time history control analysis is performed and the response of the system for this time interval is calculated, the results are stored and the final state of the system is used as initial conditions for the next time period of the earthquake signal. This procedure is implemented in the simulink file pole_place_mdof_on_line.mdl,

e. The above procedure is repeated for each new part of the incoming signal.

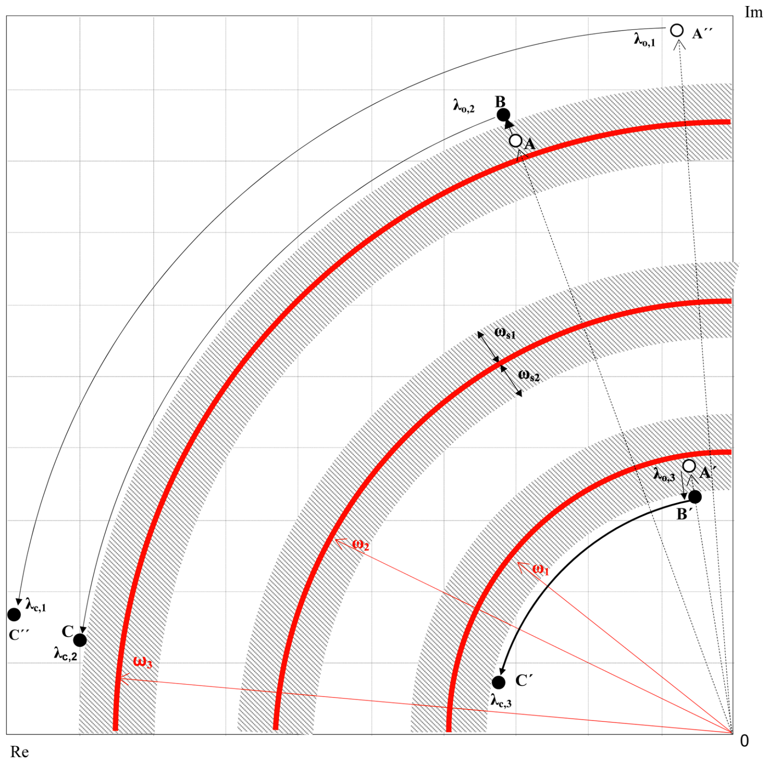
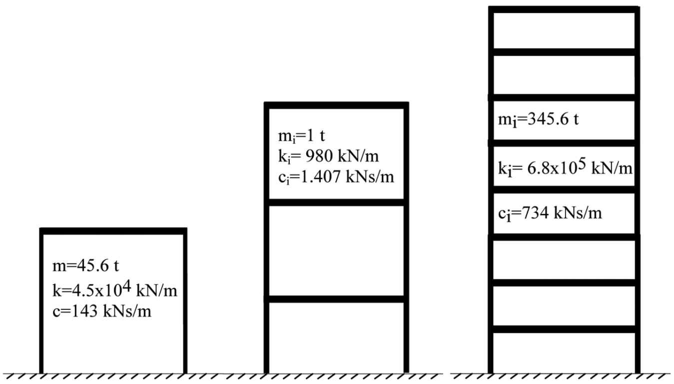


Fig. 4 The graphical representation of selection of poles of the controlled structure (●) from poles of the uncontrolled structure (○), based on the cycles of frequency of the incoming earthquake



Eigenperiods (sec)	0.2	{0.45, 0.16, 0.12}	{ 0. 77, 0.26, 0.15, 0.12, 0.09, 0.08, 0.075, 0.07 }
Eigenfrequencies (sec^{-1})	5	{2.217, 6.212, 8.977}	{1.29, 3.86, 6.29, 8.50, 10.43, 12.00, 13.16, 13.87 }
Damping ratio	0.05	{0.01, 0.028, 0.04}	{0.004, 0.013, 0.021, 0.028, 0.035, 0.04, 0.044, 0.047}
Poles	-2±31.35i	{-2.48 ± 56.36 i, -1.093 ± 39.0 i, -0.13 ± 13.93 i}	{-4.10±87.10 i, -3.69 ± 82.64i, -3.07 ± 75.36i, -2.31 ± 65.32i, -1.54 ± 53.44i, -0.84 ± 39.53i, -0.31 ± 24.27i, -0.03 ± 8.18i}

Fig. 5 The simulation models and their dynamic characteristics

In order to study the influence of time delay, saturation capacity and their coupling, a number of numerical simulations were performed using the above software for a wide range of values of these parameters, and the results are described in the next session.

3. Examples and numerical experiments

The above dynamic control strategy has been applied to one single, one three and one eight degree-of-freedom system, modeling buildings with the properties shown in Fig. 5, subjected first to sinusoidal and then to seismic actions.

3.1 Time delay

The single degree of freedom system is investigated first, subjected to a sinusoidal loading with period equal to the eigenperiod of the system, and to the Athens 1999 earthquake record, shown in Fig. 6. The response of the controlled system is first calculated for a wide range of values of time delay, neglecting initially the issue of saturation. Calculating the ratio of the maximum response of the controlled system, $u_{max,td}$, to the maximum response of the uncontrolled one, u_{max}, with respect to the ratio of time delay, t_d, over the fundamental period of the structure, T, Fig. 7 is obtained, verifying the negative influence of time delay.

For low values of time delay the controlled response is also at low levels compared to the uncontrolled response. As time delay increases the response of the controlled system is also increasing, until becoming equal or even larger than the response of the uncontrolled system. The maximum response of the controlled system without considering time delay, $u_{max,td=0}$, is at 2% of the response of the uncontrolled one (98% reduction) for the sinusoidal loading. For the ratio of time delay over period of structure ranging between 0.005 (t_d=1 ms) and 0.08 ($t_{d,min}$=16 ms), the response is always at the minimum level (98% reduction). For values of this ratio larger than 0.08 (t_d larger

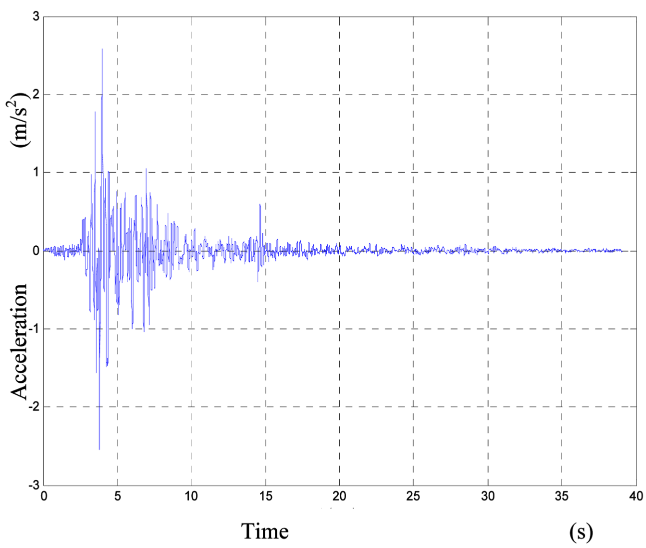


Fig. 6 Athens 1999 earthquake excitation

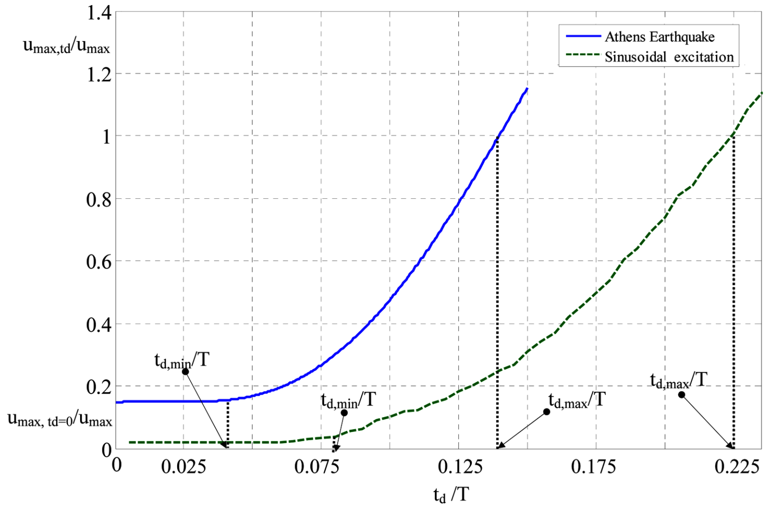


Fig. 7 The ratio of maximum response of the one-story controlled building subjected to sinusoidal and Athens earthquake excitation to the corresponding maximum response of the uncontrolled building, with respect to the ratio of time delay over the period of the structure

than 16 ms) the response starts increasing rapidly, up to a value of 0.225 ($t_{d,max}$=45 ms), where the response of the controlled system becomes equal to the response of the uncontrolled one. Beyond that value of time delay, $t_{d,max}$, the influence of control to the response is detrimental.

In the case of excitation with the Athens 1999 earthquake record, the initial reduction in the response without considering time delay is 85%. The maximum value of ratio $t_{d,min}/T$, for which the response is kept at a minimum level equal to the initial one (85% reduction) is 0.04, ($t_{d,min}$=8 ms). The value of $t_{d,max}/T$, beyond which the response of the controlled system becomes higher than the response of the uncontrolled one, is 0.14, ($t_{d,max}$=28 ms).

By applying control forces at each story of the three-story building and applying a sinusoidal excitation which is in resonance with the first frequency, (0.12 sec), of the building, Fig. 8 is obtained. In Fig. 8 it is shown that the initial reduction at third floor is 97.8% and this reduction is kept up to $t_{d,min3}/T$ equal to 0.31, ($t_{d,min3}$=38 ms). Beyond this limit the response starts increasing until $t_{d,min3}/T$ becomes equal to 0.65 ($t_{d,min3}$=79 ms), for which the response of the third floor exceeds the corresponding one of the uncontrolled system. Regarding the second and first floor the parameter $t_{d,min}$ and the corresponding ratio is the same, while the values $t_{d,min2}/T$ and $t_{d,min1}/T$ are 0.67 and 1.06 respectively, ($t_{d,max2}$=81 ms, $t_{d,max1}$=128 ms). The response of the third floor governs the value of time delay that should be considered in the design of the control system. It is also observed that there is a region near to $t_{d,i}/T$ equal to one (time delay, from 90 ms to 115 ms,) where the response ratio decreases again. This is due to the fact the time delay equals to the period of the structure and the influence of the time delay on control performance decreases. For this region there is a low confidence level, because a small exceedance will cause high response of the controlled system. This phenomenon is also observed at higher levels of time delay. A region of time delay exists, where the response ratio decreases again, but it is still higher than one. Results of the simulation of the system subjected to earthquake excitation are presented in Fig. 9.

Sinusoidal and earthquake excitation are also applied to the eight-story building. The sinusoidal excitation is now in resonance with the first frequency of the eight-story building. The results of the

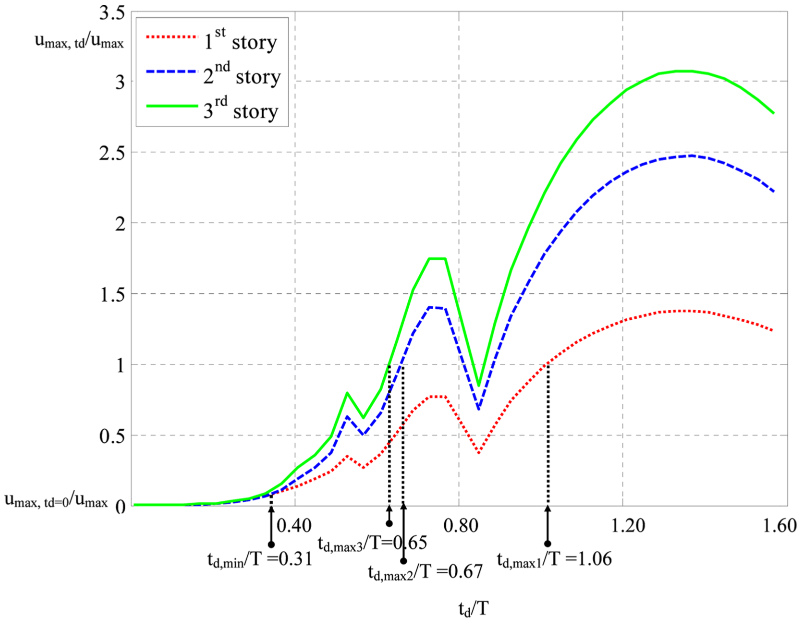


Fig. 8 The ratio of the maximum response of the three story controlled building to the maximum response of the uncontrolled building subjected to sinusoidal excitation with respect to the ratio of time delay over the period of the structure

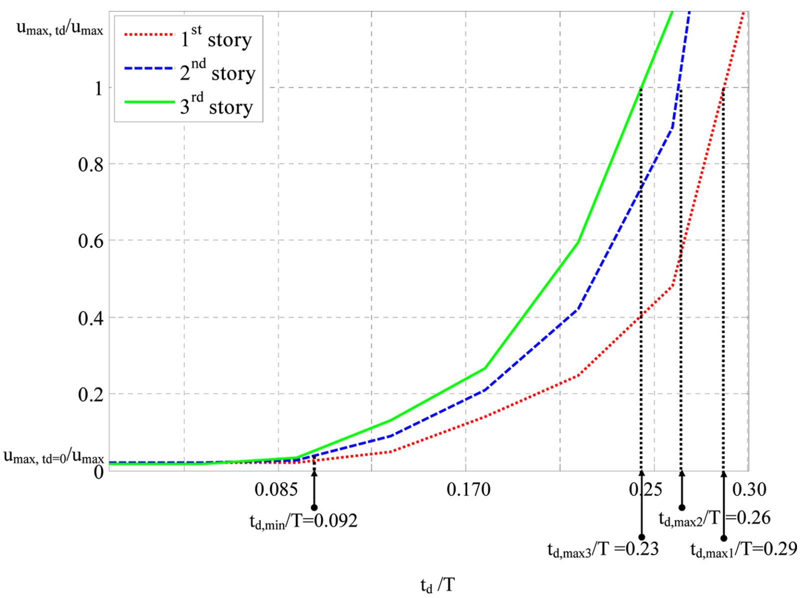


Fig. 9 The ratio of the maximum response of the three story controlled building to the maximum response of the uncontrolled building subjected to Athens 1999 earthquake excitation with respect to the ratio of time delay over the period of the structure

simulations are shown in Figs. 10 and 11, respectively.

In Table 1, all results of initial reduction, $u_{max,td=0}/u_{max}$, the limit of ratio of time delay for which

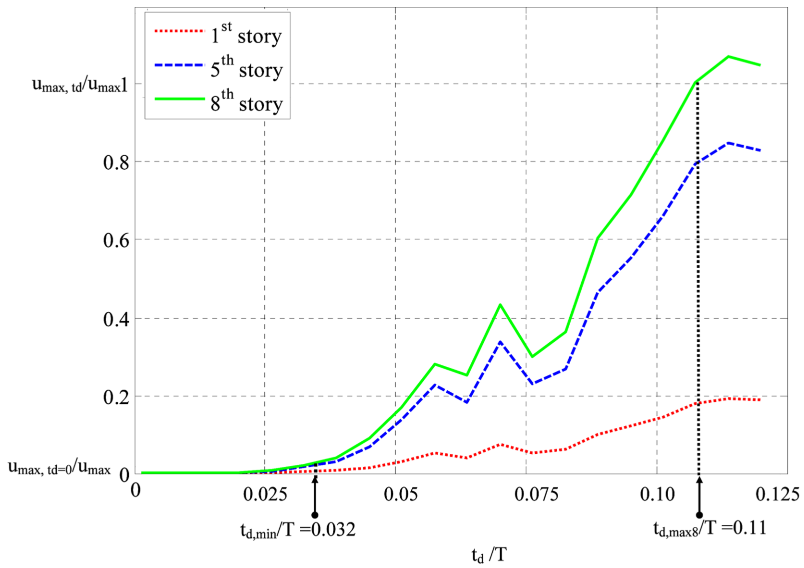


Fig. 10 The ratio of the maximum response of the eight story control building to the maximum response of the uncontrolled building with respect to the ratio of time delay over the period of the structure, subjected to sinusoidal excitation

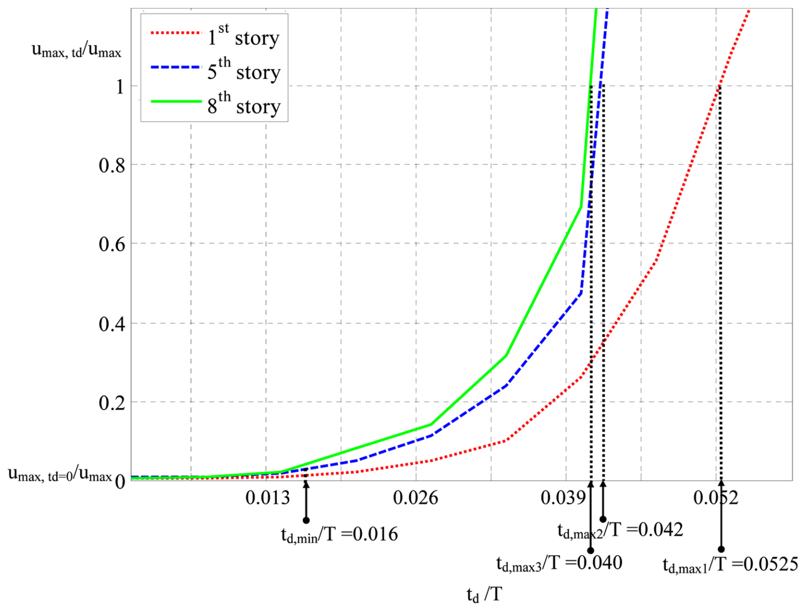


Fig. 11 The ratio of the maximum response of the eight-story control building to the maximum response of the uncontrolled building with respect to the ratio of time delay over the period of the structure subjected to Athens 1999 earthquake excitation

the response of the system is at low levels, $t_{d,min}$, as well as the limit of time delay for which the response of the system becomes higher than the uncontrolled one, $t_{d,max}$, are summarized for every system and excitation.

Table 1 The values of parameters, $t_{d,max}$, $t_{d,min}$ and $u_{max,td=0}/u_{max}$ for different systems and excitations

	One story building		Three story building		Eight story building	
	Sinusoidal	Athens 1999	Sinusoidal	Athens 1999	Sinusoidal	Athens 1999
$u_{max,td=0}/u_{max}$	0.019	0.15	0.023	0.02	0.001	0.007
$t_{d,max}/T$	0.225 ($t_{d,max}$=45 ms)	0.14 ($t_{d,max}$=28 ms)	0.65 ($t_{d,max3}$=79 ms)	0.23 ($t_{d,max3}$=23 ms)	0.11 ($t_{d,max8}$=86 ms)	0.040 ($t_{d,max8}$=31 ms)
$t_{d,min}/T$	0.08 ($t_{d,min}$=16 ms)	0.04 ($t_{d,min}$=8 ms)	0.31 ($t_{d,min3}$=38 ms)	0.09 ($t_{d,min3}$=0.011 ms)	0.032 ($t_{d,min8}$=25 ms)	0.015 ($t_{d,min8}$=12 ms)

From this table it is seen that the time delay which is required to keep the response at low levels, $t_{d,min}$, is higher for sinusoidal than for earthquake excitation or, in other words, the earthquake excitation gives lower limits for allowable time delay than the sinusoidal one.

Another observation is that for all three buildings subjected to earthquake excitation the minimum time delay, $t_{d,min}$, is almost the same, which is not the case for sinusoidal excitation. This is due to the fact that the earthquake excites similar frequencies of the three and eight story building (periods near to 0.2 sec) which leads to similar values of minimum time delay, as time delay depends on the dynamic characteristics of building, as shown below.

During the design of a control system the value of actual time delay of the system poses a crucial requirement for the overall performance and should be checked accordingly. This value should be at least lower than the maximum value, $t_{d,max}$, so that the controlled system has lower response than the uncontrolled one. Depending on the desired level of performance of the controlled building, $u_{max,td}/u_{max}$, the actual time delay should not exceed a specific level of time delay, t_d, which can be obtained by numerical simulation like the ones described in Figs. 7 to 11. The maximum performance of the controlled building can be achieved when the actual time delay, t_d, is less than the value of $t_{d,min}$.

In order to study the influence of time delay depending on the dynamic characteristics of the system,

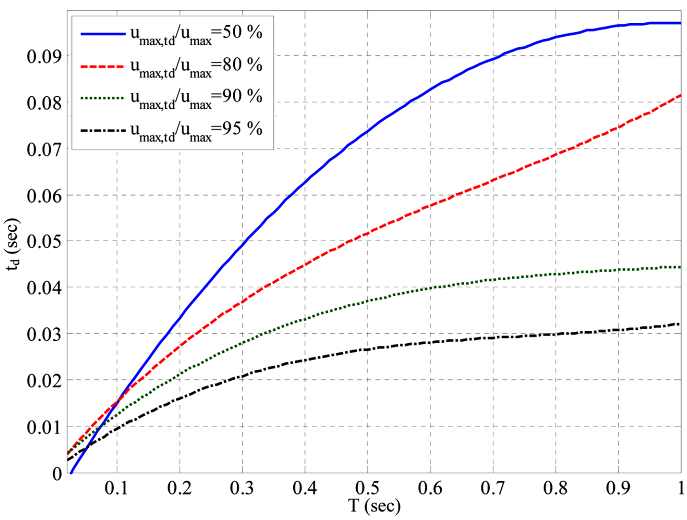


Fig. 12 The acceptable time delay, t_d, with respect to eigenperiod, T, for specific values of the response reduction ratio $u_{max,td}/u_{max}$, for the one-story building subjected to a sinusoidal excitation in resonance with its eigenperiod

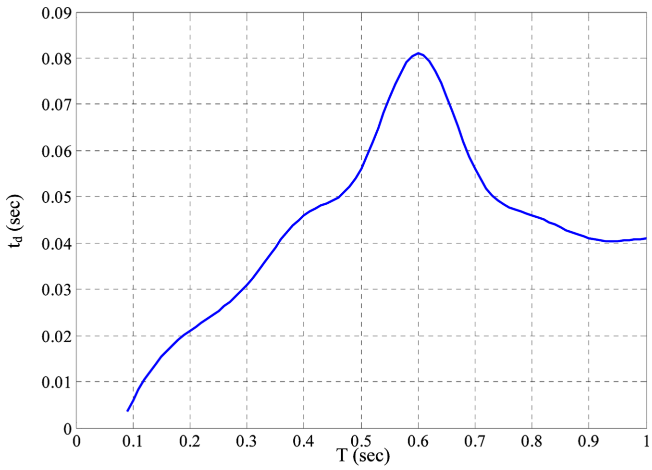


Fig. 13 The acceptable time delay, t_d, with respect to eigenperiod, T, so that the one-story building has 50% response reduction ratio $u_{max,td}/u_{max}$, when subjected to a sinusoidal excitation not in resonance with its eigenperiod

a sinusoidal excitation is applied on the one degree of freedom system, which is always in resonance with the system. The results of these simulations are shown in Fig. 12, where the required time delay, t_d, is plotted with respect to the eigenperiod, T, for specific values of the response reduction ratio $u_{max,td}/u_{max}$, varying between 50% and 95%. It is concluded that the higher the eigenperiod is, the longer the acceptable time delay becomes for the same level of performance. In other words, the acceptable time delay in tall buildings, which are in resonance with the excitation, is larger than in low buildings which are also in resonance with the excitation, for the same desired reduction of the response. It is also observed that as the desired response reduction ratio $u_{max,td}/u_{max}$ decreases, the acceptable time delay decreases as well.

If the excitation is not in resonance with the system, then Fig. 13 is obtained. In that case a sinusoidal signal with a period of 0.6 sec is applied on a system with period ranging from 0.1 sec to 1 sec. It is observed that the higher value of the acceptable time delay, for the same response reduction ratio, is when the system is in resonance, while when the system is out of resonance the acceptable time delay is lower. Applying the Athens 1999 earthquake a similar behavior is observed in Fig. 14, but now the values of acceptable time delay are approximately one half of those for the case of sinusoidal excitation. In Fig. 13, when the system comes to resonance the time delay does not influence the performance and the limit value becomes very high. In regions that are out of resonance the time delay that influences the performance becomes small enough. In Fig. 14 local maxima are observed because the earthquake contains several important frequencies that come to resonance with the system.

3.2 Saturation effect

In the above examples the force capacity was considered to be unlimited. By performing simulations with very small and constant value of time delay, thus neglecting its influence, but changing the level of control force capacity, Fig. 15 through 19 are obtained. In these figures the influence of saturation capacity limit $\mathbf{F}_{sat,max}$ on the ratio of maximum response in the presence of saturation to

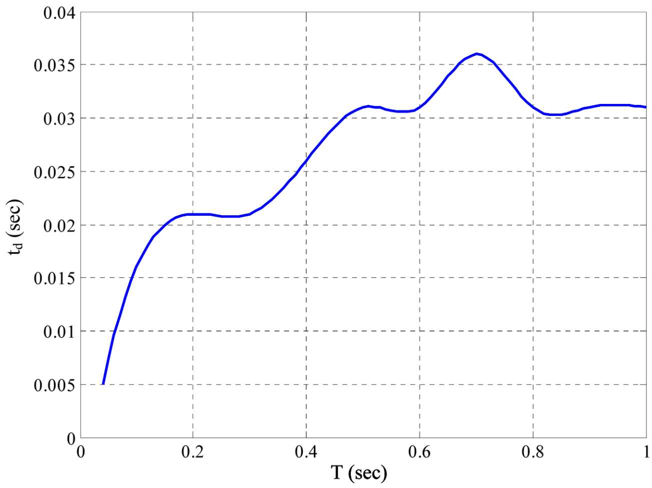


Fig. 14 The acceptable time delay, t_d, with respect to eigenperiod, T, so that the one-story building has 50% response reduction ratio $u_{max,td}/u_{max}$, subjected to Athens earthquake excitation

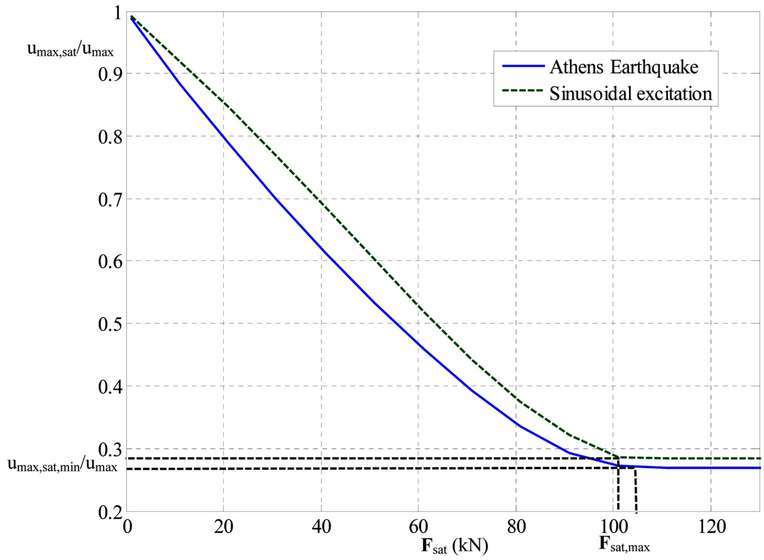


Fig. 15 The response reduction ratio, $u_{max,Fsat}/u_{max}$, with respect to saturation capacity, $\mathbf{F}_{sat}$, for the one-story building subjected to sinusoidal and earthquake excitation

the maximum response without saturation are plotted. Observing these figures it is clear that the response ratio becomes higher as the saturation limit decreases.

The saturation effect is taken into account only when the control algorithm demands a control force which is higher than the capacity of the control device. Thus, during control process, it may be once or several times to reach the saturation control force. The system is stable during the control process, thus the saturation is not caused due to instability of the system.

The values of the parameters $\mathbf{F}_{sat,max}$, normalized to the weight of the building W, and the ratio $u_{max,sat,min}/u_{max}$ are summarized in Table 2, for every building and excitation. From these simulations it is concluded that the lower the force capacity is the higher the response becomes. Furthermore,

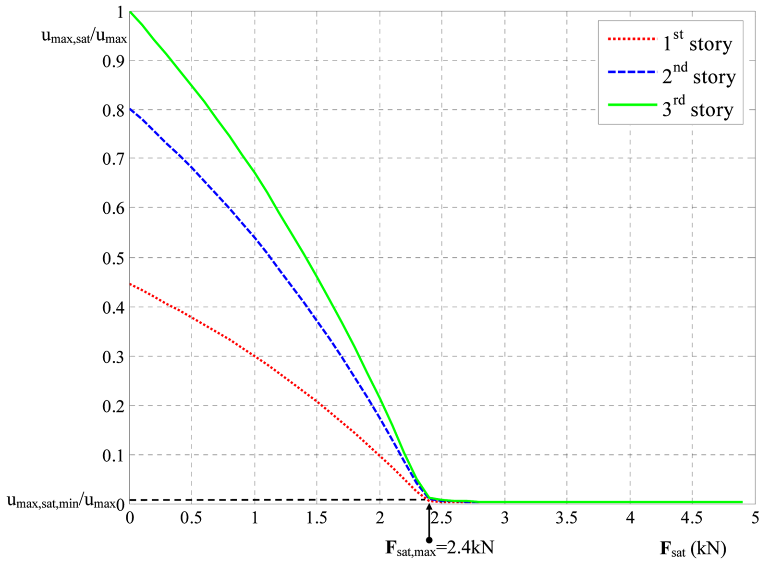


Fig. 16 The response reduction ratio, $u_{max,Fsat}/u_{max}$, with respect to saturation capacity, $\mathbf{F}_{sat}$, for the three-story building subjected to sinusoidal excitation

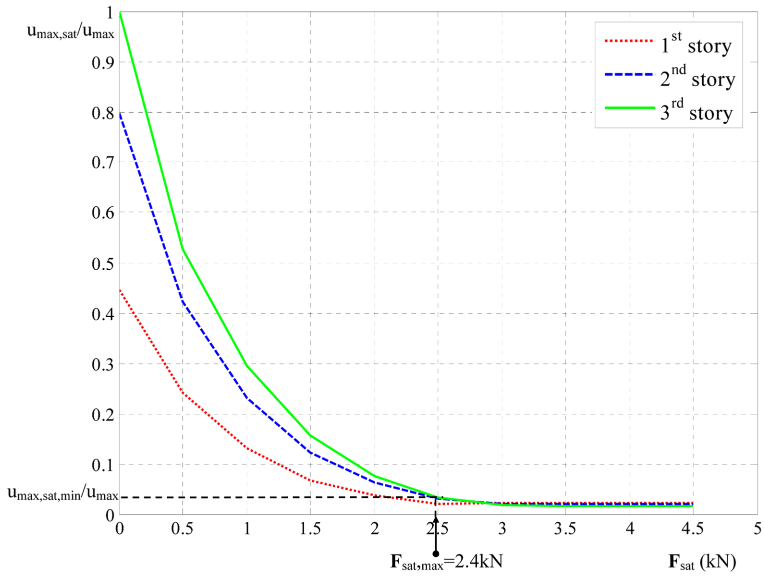


Fig. 17 The response reduction ratio, $u_{max,Fsat}/u_{max}$, with respect to saturation capacity, $\mathbf{F}_{sat}$, for the three story building, subjected to Athens earthquake excitation

there is a limit of the saturation capacity, $\mathbf{F}_{sat,max}$, beyond which the response is not further decreased. The value of the parameter $\mathbf{F}_{sat,max}$ varies from 3% to 20% of the weight of the building, and the corresponding maximum performance of the controlled building varies from 0.1% up to 30% of the response of the uncontrolled building, depending on the building and the excitation.

From Tables 1 and 2 it is seen that it is more effective to control a structure against a sinusoidal loading than an earthquake, since higher reduction in the response is succeeded. This is because a

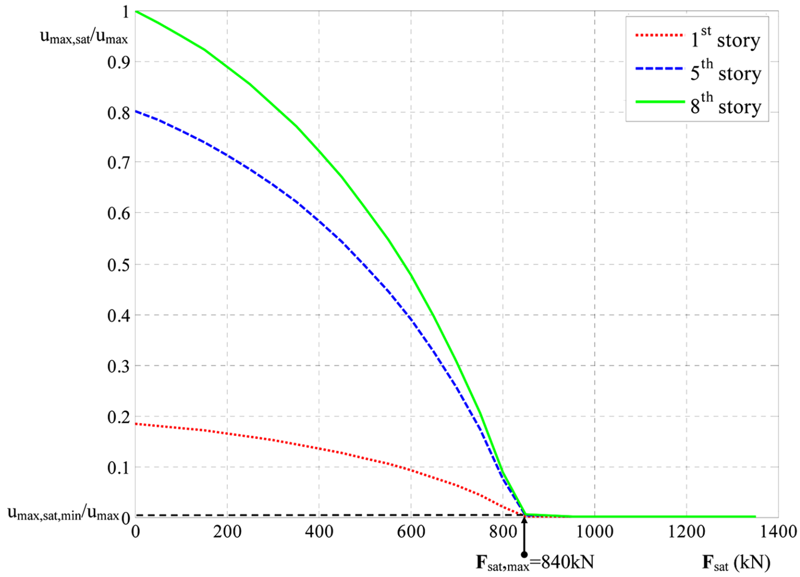


Fig. 18 The response reduction ratio, $u_{max,Fsat}/u_{max}$, with respect to saturation capacity, $\mathbf{F}_{sat}$, for the eight story building, subjected to sinusoidal excitation

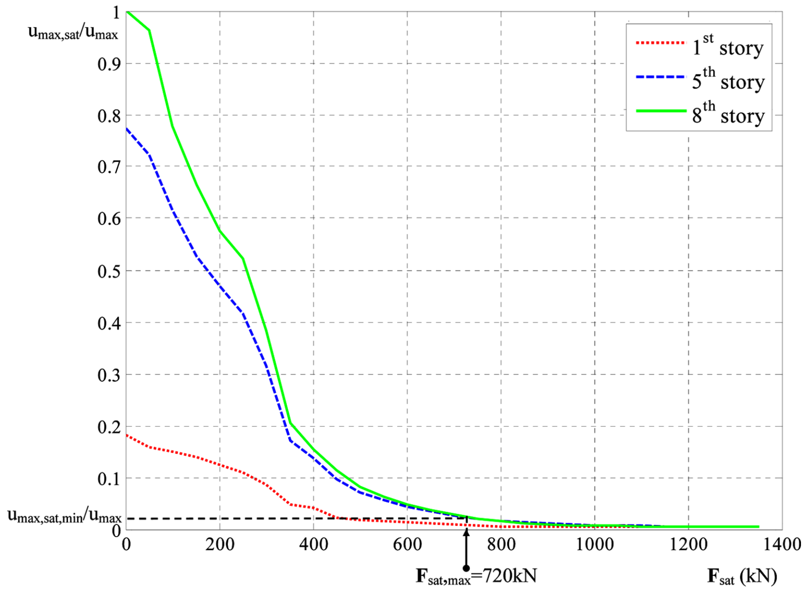


Fig. 19 The response reduction ratio, $u_{max,Fsat}/u_{max}$, with respect to saturation capacity, $\mathbf{F}_{sat}$, for the eight story building, subjected to Athens earthquake excitation

Table 2 The values of parameters, $\mathbf{F}_{sat,max}/W$, and the ratio $u_{max,sat,min}/u_{max}$ for different systems and excitations

	One story building		Three story building		Eight story building	
	Sinusoidal	Athens 1999	Sinusoidal	Athens 1999	Sinusoidal	Athens 1999
$u_{max,sat,min}/u_{max}$	0.28	0.28	0.01(3rd floor)	0.04(3rd floor)	0.001(8th floor)	0.02(8th floor)
$\mathbf{F}_{sat,max}$/W	0.220	0.230	0.080(3rd floor)	0.080(3rd floor)	0.030(8th floor)	0.026(8th floor)

sinusoidal excitation contains only one constant frequency which is recognized by the algorithm and avoided rapidly, while an earthquake contains more frequencies which are changing during its application and it is more difficult for the algorithm to identify and avoid them.

3.3 Coupling of time delay and saturation effect

In real control systems, time delay and saturation of control force capacity exist simultaneously and influence each other. Simulations have been performed for a wide range of values of those two parameters and the ratio of the maximum response of the controlled system, $u_{max,con}$, to the maximum response of the uncontrolled one, u_{max}, was obtained. The results of those simulations for the three systems of Fig. 5 subjected to Athens 1999 earthquake excitation are shown in Fig. 20 through 23. In these figures the influence on the response of coupling of the two parameters is shown.

The numerical results show that as time delay increases and saturation limit decreases the system becomes unstable. It is also verified that as time delay decreases and the saturation limit capacity increases, the control is more effective and the response is reduced drastically. Furthermore, it is observed that even though for high saturation capacity limit of the device low response is expected, the simultaneous existence of high time delay causes instability. Comparing the results obtained considering the time delay or the saturation effect individually to those that refer to the simultaneous influence of the two parameters it is concluded that the simultaneous effect is substantially more critical for the same earthquake and for the same building.

Based on the percentage of response reduction that the designer aims at achieving with the control system, a region Ω, where the response ratio is below the desired percentage, can be determined. The Ω region contains pairs of time delay values and saturation capacity limits for which the response is lower than the predefined response ratio. Values of response ratio and the corresponding limits of the Ω regions are shown in the contour plots of Figs. 20 to 23. The border of this region depends on the desired performance level of the controlled structure.

It should be noted that the Ω region depends also on the specific earthquake record considered. In Fig. 23 this region is shown for a 0.5 response ratio and for four different earthquakes. With dashed line is the minimum envelope curve of the four above individual curves. The values of time delay

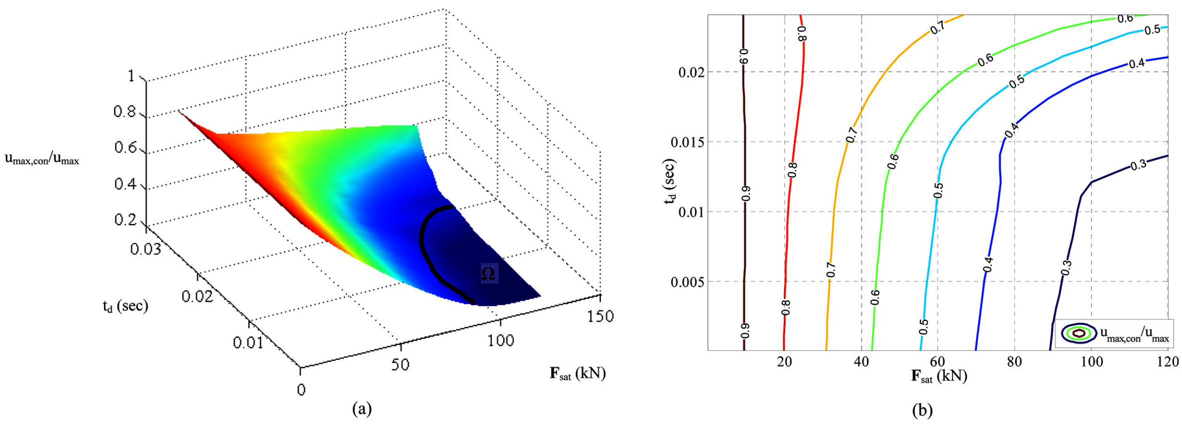
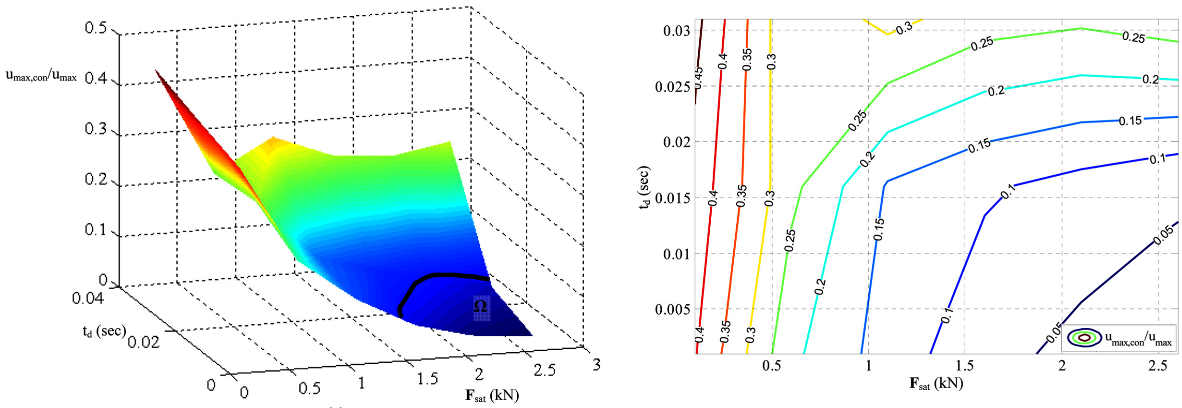
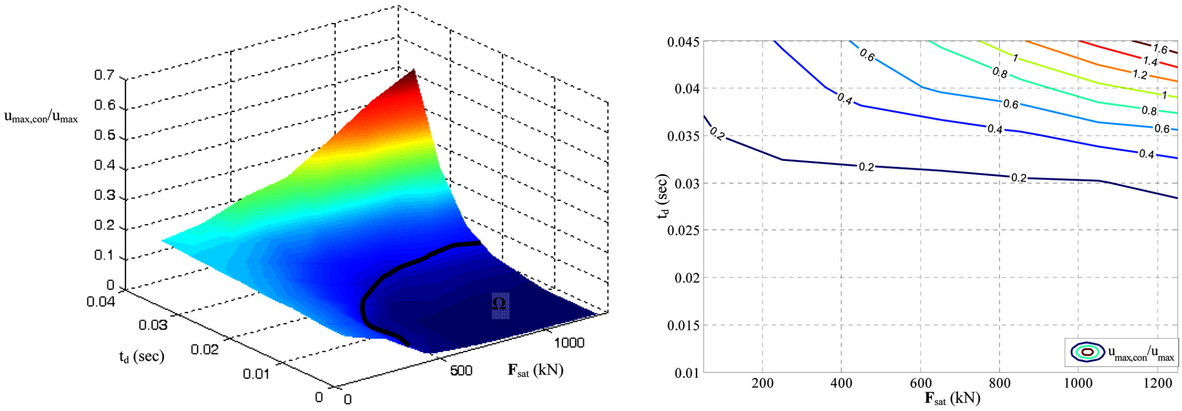


Fig. 20 Combined influence of time delay and force saturation on the response of the controlled one-story building, subjected to Athens earthquake excitation, (a) 3D plot and (b) contour plot



(a) (b)

Fig. 21 Combined influence of time delay and force saturation on the response of the controlled three-story building, subjected to Athens earthquake excitation, (a) 3D plot and (b) contour plot



(a) (b)

Fig. 22 Combined influence of time delay and force saturation on the response of the controlled eight-story building, subjected to Athens earthquake excitation, (a) 3D plot and (b) contour plot

and saturation capacity in this region can be considered as design specifications for the control devices and system that is going to be used.

All examples that were analyzed show the negative influence of time delay and saturation capacity acting either separately or simultaneously. This negative influence is a general trend for structures equipped with control systems. These examples show the need of performing numerical simulations, accounting for the coupling of time delay and saturation capacity, before installing the control system in the building. Such simulations will help to identify the limits of time delay and saturation capacity of the control devices that will keep the building stable and in reduced response compared to the uncontrolled one.

Since all the above results are dependent on the excitation and it is not easy to predict the earthquake ground motion thus conclusions of general validity for upper bound of time delay or lower limits of saturation capacity are not possible, as these phenomena are highly non linear and depend on the earthquake excitation as well as the dynamic characteristics of the specific building.

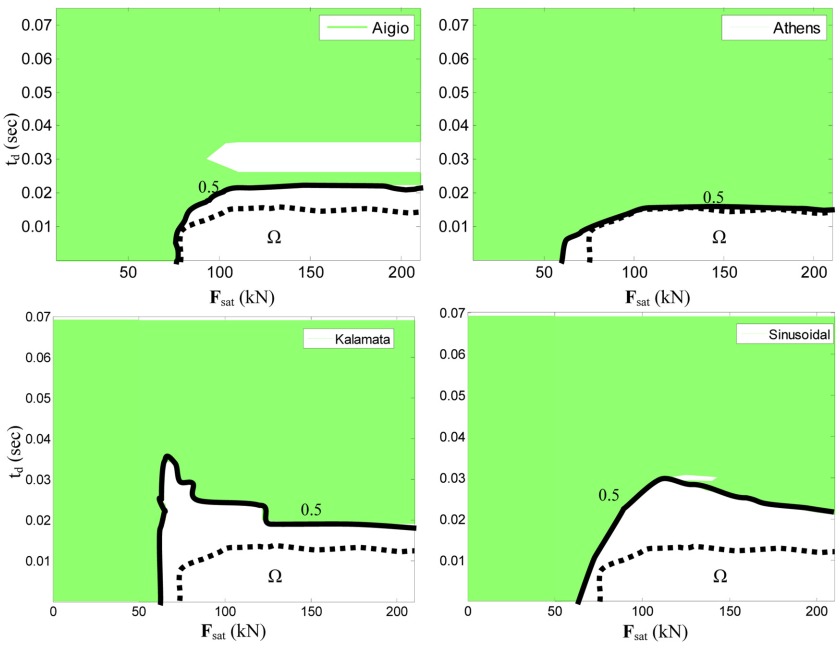


Fig. 23 The Ω region corresponding to response ratio 0.5 for four different earthquakes and the envelope curve (dashed line)

It is therefore suggested that before finalizing the control system response surfaces like the ones in Figs. 22 and 23 should be obtained and used as a design tool, assisting the designer to decide about the appropriate values of time delay and saturation capacity that the proposed system should satisfy. In other word, during design, simulations of the structure's response for a wide range of earthquakes (near fault, far fault) should be performed, and acceptable values of time delay should be obtained for each signal. Then, an envelope of minimum time delay should be obtained and this should be used as a limit for the design of the control system.

4. Conclusions

The influence of time delay and saturation capacity on the response of controlled building structures subjected to seismic actions has been investigated. As it is impossible to obtain closed form solutions for the response of multi degree of freedom systems, accounting for time delay and saturation capacity, thus, numerical simulations should be carried out before the installation of any control system, considering the combined effect of these two important parameters. Such numerical simulations will provide limits of time delay and saturation capacity that should not be exceeded, so that the response of the controlled system will be lower than that of the uncontrolled one. From the numerical examples presented here, it was concluded that there is interaction between time delay and saturation capacity leading to a combined influence on the response. This influence depends both on the dynamic characteristic of the building and on the characteristic of the excitation. It is suggested that before the installation of a control system to the structure, diagrams like those in Fig.

23 should be obtained for a wide range of earthquakes, which identify the safe region of values of time delay and saturation capacity. Based on such diagrams the engineers will specify values of time delay and saturation capacity of the control devices provided by the manufacture so that they are within the safe region (inside of dashed line in Fig. 23). A "safe region" of values of time delay and saturation capacity can be defined that should be used as design specification for the control devices that are going to be installed in the building. Then, the controlled system will indeed have reduced response.

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