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Active vibration control of seismic excitation

Marco Barbieri · Sinniah Ilanko · Francesco Pellicano

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Abstract Seismic wave control is very important both in civil and mechanical engineering. Common passive methods for isolating a building or a device include base isolators and tuned mass dampers. In the present paper, a time-varying controllable spring is considered as a vibration isolator for a linear mechanical system. The controller works as follows: When the seismic movement is active, the velocity of the moving mass is monitored as the reference velocity. When such reference velocity is positive, the stiffness is reduced; when it is negative, the stiffness is increased. Numerical investigations show that the controller is capable of filtering seismic excitation close to the natural frequency of the controlled system and reducing the total seismic energy transfer up to 5 times. The role played by the gravity in the active vibration filtering is pointed out by showing that no filtering action can be observed in gravity-free simulations. Moreover, control effectiveness has been proven for a measured seismic signal, showing its robustness in presence of noise.

M. Barbieri (✉) · F. Pellicano
Department of Engineering "Enzo Ferrari", University of Modena and Reggio Emilia, Via Pietro Vivarelli 10, 41125 Modena, Italy
e-mail: mark@unimore.it

F. Pellicano
e-mail: francesco.pellicano@unimore.it

S. Ilanko
Department of Engineering, School of Science and Engineering, The University of Waikato, Hamilton, New Zealand
e-mail: ilanko@waikato.ac.nz

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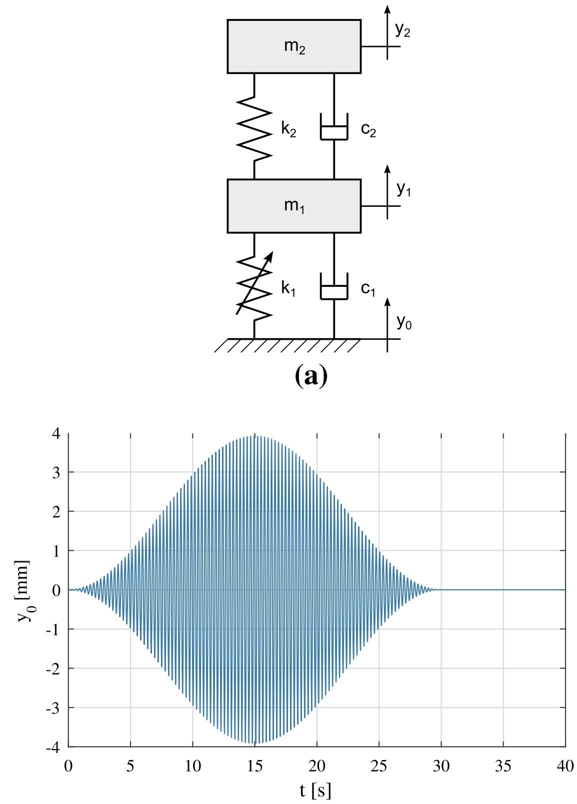
Introduction

The main motivation for starting this research is the powerful earthquake that severely damaged the city of Christchurch (NZ) on February 2011 and its peculiarity. The hypocenter was at a depth of 5 and 10 km away from the center of the city. It caused 185 deaths, 2000 injuries and severe damages to the city. In addition to direct damage to civil structures, the liquefaction phenomenon caused by the earthquake caused further destruction and about 400 tonnes of silt in the city suburbs. Even though the initial quake lasted about 10s, its catastrophic effects were due to several reasons, such us aftershocks and preexisting damages due to previous earthquake. In addition, due to the vicinity of the epicenter, strong vertical peak ground acceleration (PGA) was registered in the center of Christchurch, up to 1.9 g in the city and 2.2 g in the epicenter. The PGA registered during the Christchurch quake was one of the greatest ever ground accelerations recorded in the world and the biggest vertical PGA ever recorded in the world; this level is surprisingly high for an magnitude 6.3 quake; there are many examples of earthquakes with magnitude 7 or higher but with PGA lower than 1 g. The vertical oscillation of the ground was non-symmetric, i.e., the maximum upward acceleration was 1.9 g and the maximum downward acceleration was 0.9 g. Seismic waves act on a building as a transient external force, so that they can be very dangerous if the harmonic content of the seismic force matches one of the system natural frequencies [1]. In order to complete the analysis of the motivations of the present work, a short and elementary description of the methods used for protecting civil structures from the earthquakes is quite useful. For new civil structures, codes recommend standards of design and construction as well as materials. Very recent codes outline how a building must perform to withstand the forces expected during an earthquake. This means that both dynamic forces and the dynamic response of the building need to be evaluated; in this way, designers have more freedom in using new design concepts and new materials. Different solutions are in use for improving the resistance of civil structures to earthquake: the isolation, using flexible connectors, generally structural elastomeric bearings or sliding devices, which have the role of reducing the natural frequency and the response to seismic acceleration; the connections or bracings act as internal dampers but also play a role in terms of building strength providing a rigid link between the superstructure and its supports. Passive isolation methods include base isolators (BI) [2], which are low-pass filters designed in order to cut out the frequencies containing most of the seismic energy. Other more sophisticated solutions for reducing the effect of seismic excitation are dynamic absorbers (tuned mass dampers, TMD); such devices are quite common in mechanics and have a recent application in civil engineering [3,4]; the goal in this case is to transfer the vibration energy from the structure to the device, which dissipates the energy. As this topic has been the subject of an intense research activity recently, a short literature overview is useful. The archetype of TMD has been described by [5]. It is the first study on linear TMDs applied to loading. Den Hartog proved that one can find the optimal linear spring and viscous damper coefficients in order to minimize structural deflection. These devices are capable of canceling a resonance of the system. The drawbacks are mainly: difficulties in tuning, introduction of an additional (possibly dangerous) resonance and the narrow frequency band of effectiveness. In order to circumvent the limitations of the traditional TMDs, nonlinear energy sinks (NES) [6] and tuned liquid dampers (TLD) [7] have been proposed as passive seismic energy absorbers. Samani and Pellicano [8] proved that, in the case of transient moving loads on beams, the optimal stiffness and damper coefficients are generally different from those obtained by the classical approach [5] that was developed for periodic excitations; however, they proved the effectiveness of such devices also for transient loads in bridges [9,10]. Other interesting studies about TMDs applied to bridges are found in [11–13]. All these studies considered linear TMDs showing the great interest in these traditional devices. Nonlinear TMDs were studied in [6,14–16], where the possibility of improving the dissipation of the TMDs by inducing irreversible energy transfer has been proven thanks to the nonlinearity due to a cubic type spring. Avramov et al. proved the efficiency of a nonlinear absorber based upon a snap-through truss [17,18]. In references [19,20], it has been proven that, under certain conditions, a local nonlinear attachment, having essential nonlinear stiffness, can passively absorb energy from a linear non-conservative (damped) structure, in essence, acting as nonlinear energy sink (NES). The efficiency of TMDs (linear or nonlinear) is controversial, as can be seen from a series of papers and rebuttals. For example in [21], the capability of a nonlinear TMD of absorbing steady state vibration energy from a linear oscillator over a relatively broad frequency range has been shown. This is achieved through a one-way irreversible transfer of energy from a linear main system to the nonlinear attachment; Malatkar and Nayfeh [22] commented the previous work, concluding that they did not find any occurrence of energy transfer via modulation, as indicated in [21]; Vakakis and Bergman [23] replied, claiming that steady state energy pumping occurs in certain frequency ranges of the coupled system; Malatkar and Nayfeh [24] published additional results to disprove what was claimed by [23], stating that the presence of the nonlinear TMD magnifies the amplitude of vibration of the linear subsystem, i.e., it is not suitable for applications. From the literature available, it is clear that the use of TMD cannot yet be considered a generalizable solution for protecting civil structures. Limitations of linear TMDs are well known and the effectiveness of nonlinear TMDs is still controversial. Many of the aforementioned passive devices such as TMDs or base bearings (rubber or sliding) act mainly on horizontal ground seismic movements. However, the Christchurch example proves that vertical accelerations can reach destructive levels. For this reason, the development of new methods for protecting civil structures is needed. The use of active or semi-active devices has the main disadvantage consisting in the increment of technological complexity; on the other hand, they enormously increase the potential effectiveness. Active vibration control is not a new research topic, but it has gained increasing attention with the availability of efficient piezo-electric actuators [25,26]. Despite that, real-world applications have been seen seldom, in particular in the case of seismic excitations. Mohtat et al. [27] developed an active tuned mass damper for controlling a seismically excited beam. The problem of seismic wave isolation has been faced by many authors, both using passive and active control methods [28]. Henonen et al. [29] introduced a semi-active device for seismic isolation. The device was able to self-adapt its stiffness thanks to the properties of shape memory alloys. Fujita et al. [30] proposed a method for activating an air bearing isolating support upon earthquake occurrence. Recently, some works [31,32] have shown, by numerical simulations, the effectiveness of an active switch of the stiffness of the base in seismic isolation. In the present paper, the active stiffness control of a system under seismic excitation is investigated.

In the present paper, an active vibration control is proposed for improving the isolation from the base of civil structures or mechanical systems. The main idea is to act on a traditional elastic isolation foundation by suitably varying the stiffness; this idea came out from physical considerations after analyzing earthquake waves. The Christchurch earthquake has shown that the ground can experience very high vertical and upward accelerations, causing short-term transient loads. Such sudden vertical loads can be attenuated if the elastic connection (foundation) changes its stiffness in an appropriate way. Therefore, the controller must monitor the ground and the building acceleration, including the sign (up or down), and apply a fast stiffness decrement that reduces the dynamic load transmitted. On the other hand, a sharp stiffness variation can introduce broad band excitations and the control could loose stability. In order to overcome such undesirable effect, an additional control on the base velocity is added. The goal of the present work is to understand if a stiffness foundation control is capable of reducing the effects of a base excitation and estimate the characteristics required for developing a real control system for future experimentations.



(b)

Fig. 1 **a** Model of the two dof system; **b** external forcing y_0

1 Dynamic model

In the present work, a simple 2-dof model is considered, see Fig. 1a. The model consists of a mass m_1, which represents the base of the building, and of a suspended mass m_2, connected to the base by a spring having constant stiffness k_2, and by a viscous damper c_2. The base is connected to the ground by means of a spring having time-varying stiffness k_1 and a viscous damper c_1. The maximum value of the varying stiffness is $\bar{k}_1$. The system is under the effect of the weight force, and of the seismic base force due to the ground displacement y_0. The equations of motion are:

$$\begin{cases} m_1\ddot{y}_1 + k_1(t)(y_1 - y_0) + k_2(y_1 - y_2) + c_1(\dot{y}_1 \\ \quad - \dot{y}_0) + c_2(\dot{y}_1 - \dot{y}_2) = -m_1 g \\ m_2\ddot{y}_2 + k_2(y_2 - y_1) + c_2(\dot{y}_2 - \dot{y}_1) = -m_2 g \end{cases} \tag{1}$$

Note that the reference position (*i.e.,* where $y_1 = y_2 = 0$) is the un-loaded position, without the weight force exerted on m_1, m_2. Since the stiffness is time varying, the presence of the constant gravity force will affect the solution. Time dependency of k_1 relies on the control strategy, and it will be clarified in the following.

The forcing displacement y_0 is initially taken as a sine function of frequency f and maximum acceleration amplitude ag enveloped by a half sine wave having duration T, given by Eq. (2).

$$y_0(t) = \frac{a \sin(2\pi f t) \sin^2\left(\frac{\pi t}{T}\right)}{(2\pi f)^2} \quad (2)$$

The simple model proposed can simulate the dynamic behavior of a building or an equipment or a shipping container. In these three cases, the model parameters and the exciting base vibration are different.

k_1 is time varying due to the control activation; it changes during the simulation according to the following control strategy:

1. the control is activated if the overall base vibration (*i.e.,* maximum base acceleration within a period of the exciting oscillation) exceeds a certain value ψ
2. when the control is activated, base velocity is checked at control frequency f_c; if the system base has positive velocity at the kth control instant $t_{c,k} = k/f_c$, then the stiffness $\bar{k}_1$ is reduced to a fraction φ.

Provided that the first condition is matched, at the kth control instant, k_1 is switched as follows:

$$\text{for} \quad t_{c,k} < t \leq t \quad k_1 = \begin{cases} \varphi \bar{k}_1 & \text{if} \quad \dot{y}_1(t_{c,k}) > 0 \\ \bar{k}_1 & \text{otherwise} \end{cases} \quad (3)$$

The control strategy described above is simple and does not involve many parameters, so that it is used in the preliminary investigations described in the present paper. Nonetheless, the major drawback is that it is not practical to introduce a device capable of a sudden stiffness variation, which would require an infinite power to be actuated. In order to take into account for a realistic delay in control response, it can be assumed that the device used to change the stiffness is a first-order system under a step activation. In this case, the response is as follows:

$$k_1(t) = k_1|_{t \to t_0^-} + k_r \left(1 - e^{-\frac{t - t_0}{\tau}}\right), \quad t > t_0 \quad (4)$$

where k_r is the required value ($\bar{k}_1$ or $\varphi \bar{k}_1$), τ is the characteristic time. It is worthwhile noting that after 3τ the response is 95% of the required value; therefore, an activation time $T_a = 3\tau$ can be defined. This strategy is considered in the second part of the present work, where the control strategy is applied to a measured earthquake signal.

Solution of system (1) is found by direct integration as follows:

1. For $t < t_{c,1}, k_1 = \bar{k}_1$, the system is smooth and integration is performed using explicit Runge–Kutta (4,5);
2. At $t = t_{c,k}$ with $k = 1, 2, \ldots$ integration is stopped, k_1 is set accordingly to the aforementioned condition, and integration is started again for $t_{c,k} < t <= t_{c,k+1}$ using the same solver.

2 Results and discussion

2.1 Control effectiveness for a simulated seismic signal

In order to show how the proposed method can be effective in controlling a seismic signal, first let us consider a simulated signal defined as in Fig. 1b. In the present paper, simulations are performed referring to a very simple oscillating system. The system is the simplest possible description of a two-story building on a seismic isolator, modeled as a two degrees of freedom system: Table 1 presents the parameters used in numerical computations. These parameters represent a two-story building composed of two concrete floors supported by four reinforced concrete columns. Damping is chosen in order to have a damping ratio close to 10%.

Figure 2a displays the results of a run without control (case A) along with a run having velocity control activated (case B). In both cases, the external forcing frequency f matches the fundamental frequency of the system $f_1 = 3.56$ Hz. The control parameters are $\varphi = 0.5$ and $\psi = 0.01$ g, *i.e.*, stiffness is reduced by one half for positive base velocity and the control works only if the overall vibration exceeds 0.01 g. The control is capable of reducing the maximum acceleration of the suspended mass m_2 by 88%: from 1.9 g to 0.2 g. In the same picture, case D represents the solution obtained using the same control parameters, but for a system which is not loaded by any weight force ($g = 0$ in Eq. (1)). For case D, the maximum acceleration is

Table 1 Parameters used in numerical simulations

	Case A	Case B	Case C	Case D
m_1 [kg]	8.0×10^3	8.0×10^3	8.0×10^3	8.0×10^3
m_2 [kg]	8.0×10^3	8.0×10^3	8.0×10^3	8.0×10^3
$\bar{k}_1 \left[\frac{\text{N}}{\text{m}}\right]$	1.05×10^9	1.05×10^9	1.05×10^9	1.05×10^9
$k_2 \left[\frac{\text{N}}{\text{m}}\right]$	1.05×10^9	1.05×10^9	1.05×10^9	1.05×10^9
$c_1 \left[\frac{\text{N}}{\text{m/s}}\right]$	5.7966×10^4	5.7966×10^4	5.7966×10^4	5.7966×10^4
$c_2 \left[\frac{\text{N}}{\text{m/s}}\right]$	5.7966×10^4	5.7966×10^4	5.7966×10^4	5.7966×10^4
T [s]	30	30	30	30
a [g]	0.2	0.2	0.2	0.2
f_c [Hz]	No control	100	100	100
φ	//	0.5	0.5	0.5
ψ [g]	//	0.01	0	0.01
$g \left[\frac{\text{m}}{\text{s}^2}\right]$	9.81	9.81	9.81	0

cut by 44% only, thus suggesting that an important role in the proposed active control method is played by the weight force. Indeed, reducing the stiffness when the base is going upwards (positive $\dot{y}_1$) means having a longer stroke for the weight force, when it is doing negative work over the system.

Figure 2b shows what happens if no check of the overall vibration is performed (case C, $\psi = 0$ g). $\widetilde{y}_1$ and $\widetilde{y}_2$ are defined subtracting the static equilibrium solution from y_1 and y_2. The static equilibrium position is unstable, and the controlled system presents a limit cycle in the aftershock, oscillating around a new equilibrium position. In order to overcome such limit cycle arising, numerical simulations have proven that $\psi = 0.01$ g is sufficient; moreover, an higher value of ψ would introduce higher vibrations when the control activates, due to the abrupt change in the system when it is already oscillating.

Figures 2 and 3 clarify the behavior of the system with/without control. Control activation changes the center around which the system oscillates: This is due to the reduced average stiffness. In terms of acceleration, when the control is active, the top mass acceleration is much lower than in the no control case; nonetheless, the base presents a significant acceleration for all the seismic duration. Figure 3b clarifies this feature: Each time the velocity $\dot{y}_1$ reaches a zero, the corresponding acceleration $\ddot{y}_1$ has a jump, which is due to the sudden stiffness variation. The energy for this change, which cannot be instantaneous in the real application, must be provided by the control actuator. Figure 4b shows the isolation effect due to the control: The total energy of the system has a maximum of 3849 J without control, 1072 J with optimal control.

In terms of transmitted force (Fig. 5), it is possible to observe that the proposed control strategy reduces both the force exerted by the soil on m_1, namely F_1, and the force exerted by m_1 on m_2, *i.e.,* F_2. For the proposed test case, the control algorithm is able to ensure that all forces remain compressive for the overall seismic duration.

2.2 Optimal parameters

In this section, a parametric analysis is performed: The maximum acceleration of the top mass a_2 is chosen as the objective function, and its relationship with the forcing frequency f and the stiffness parameter φ is investigated (Fig. 6). If the stiffness k_1 is reduced by a small amount, the acceleration is still high; if k_1 is reduced a lot, then the varying stiffness excites the system more than the seismic load itself. Among the test values used, the best value for φ is 0.5: For such value, the proposed control strategy is effective broadband, both below and over the fundamental frequency of the system.

2.3 Control effectiveness for a real seismic signal

In the previous section, the effectiveness of the proposed control method has been pointed out for a sim-

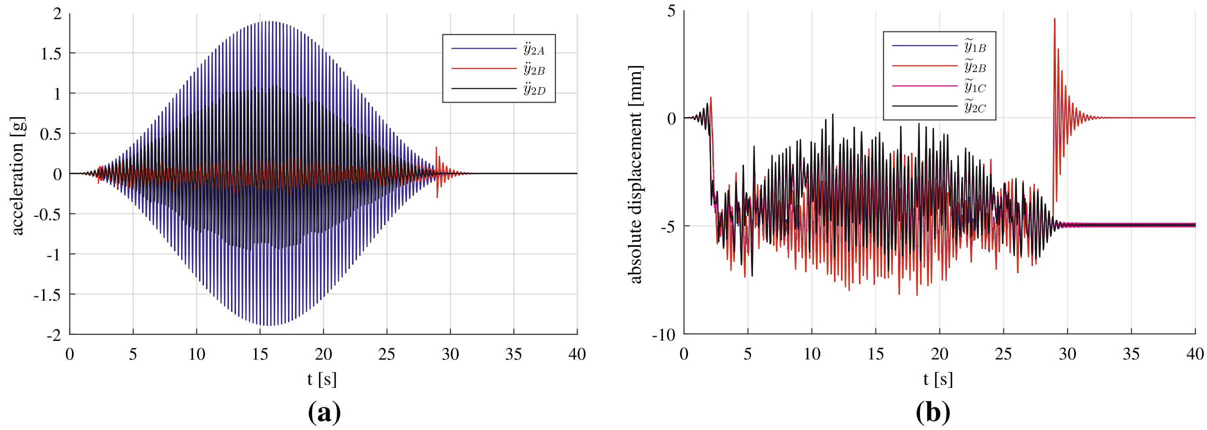


Fig. 2 Effectiveness of the control: **a** A—no control, B—controlled, D—controlled without gravity; **b** B— controlled; C—controlled with $\psi = 0g$ (displacements $\tilde{y}$ are shown from the static equilibrium)

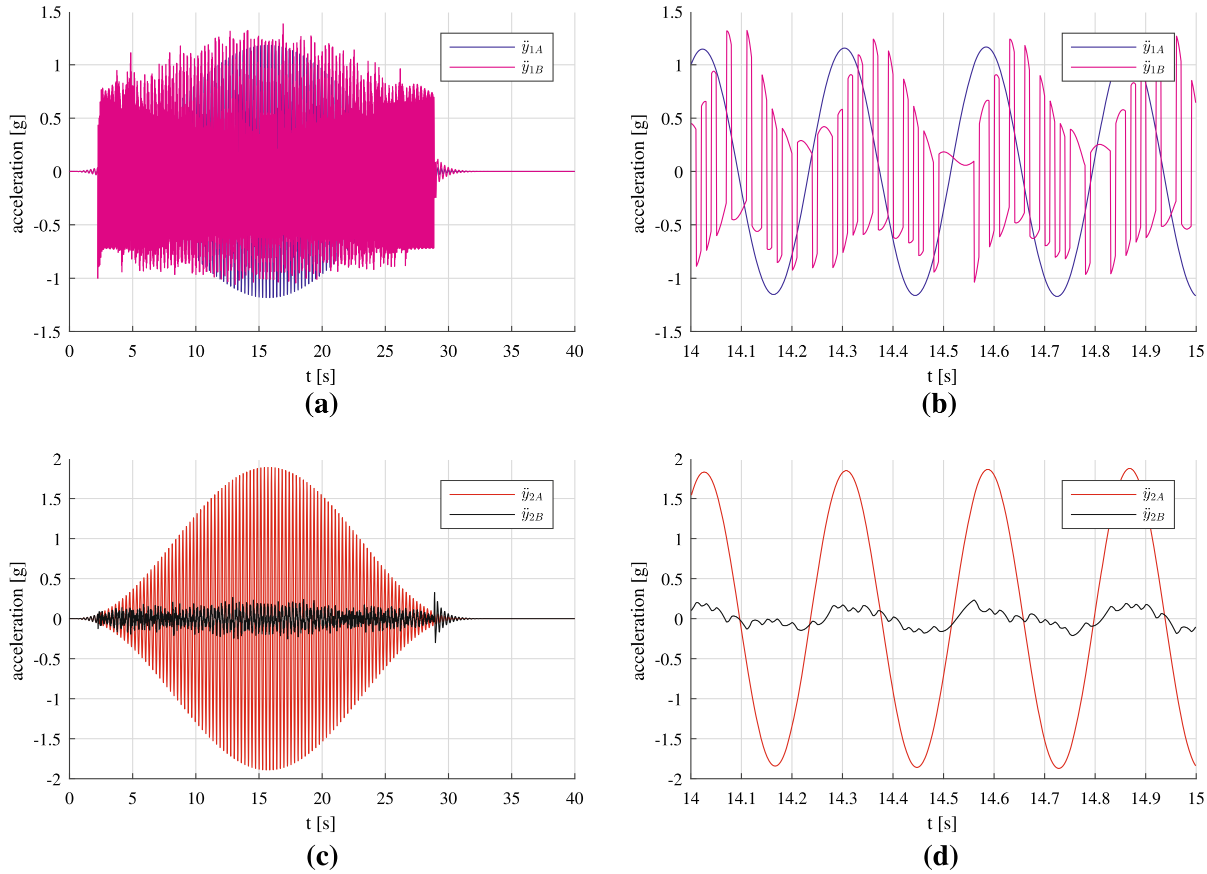


Fig. 3 Accelerations of the oscillating masses 1 and 2: case A—without control, case B—with $\varphi = 0.5$

ulated signal. Furthermore, it has been shown that a sudden reduction in the support stiffness is capable of reducing vibration in the top mass if the system is subject to the gravity force; therefore, in a real seismic isolation device, the proposed method would be effective for reducing vertical seismic vibrations, while it

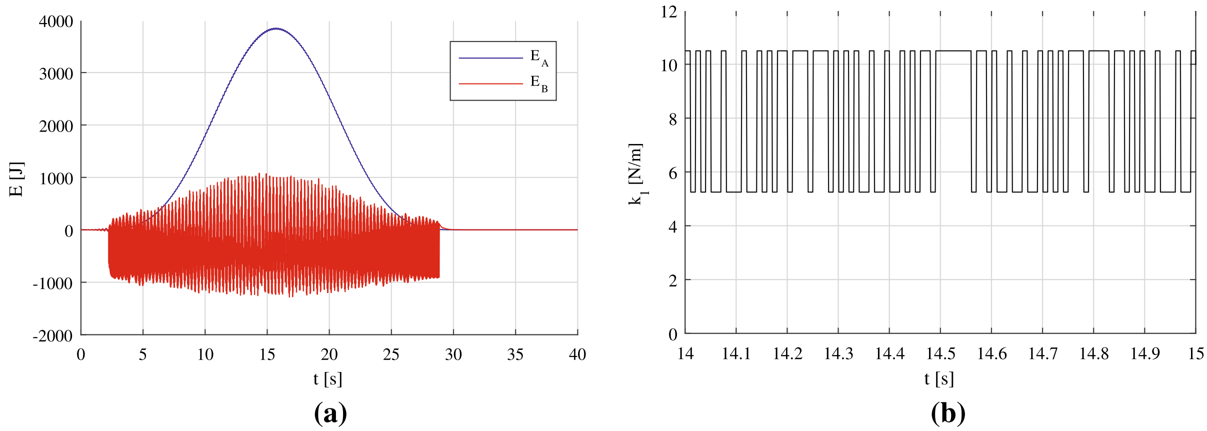


Fig. 4 **a** Total energy: case A—no control, case B— with $\varphi = 0.5$; **b** stiffness fluctuation during seismic control: case A—no control, case B—with $\varphi = 0.5$

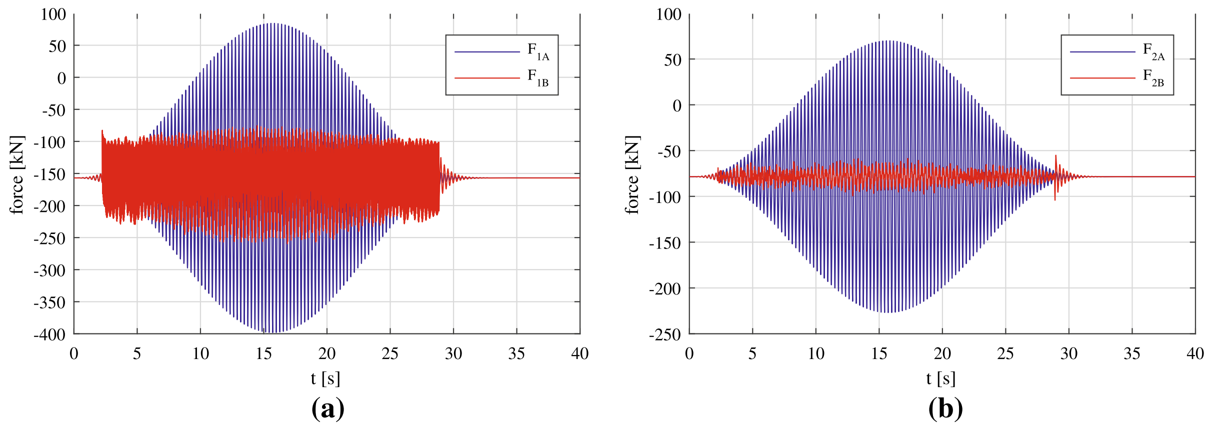


Fig. 5 Transmitted forces: case A—no control, case B—with $\varphi = 0.5$: **a** base mass force **b** top mass force

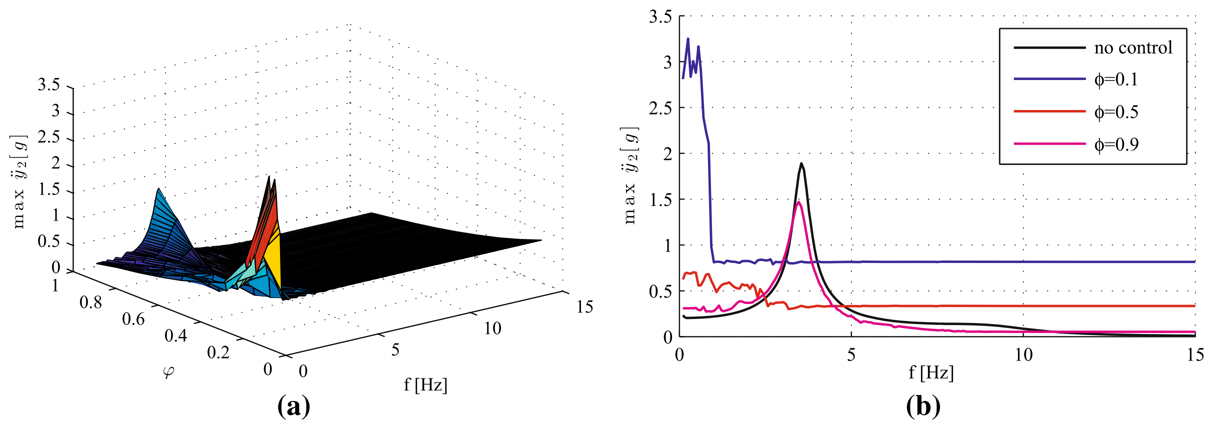


Fig. 6 Maximum top mass acceleration for varying control parameters: **a** varying forcing frequency and φ; **b** varying forcing frequency

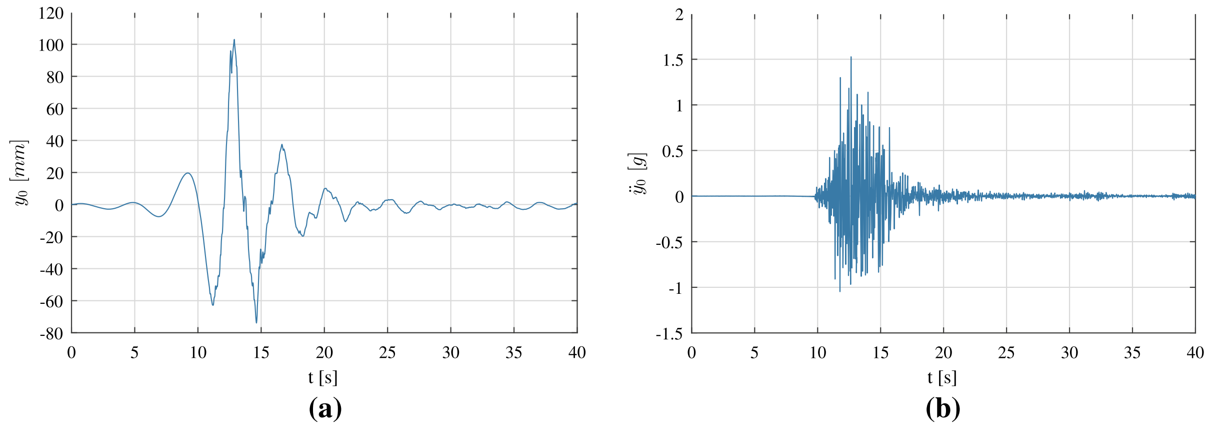


Fig. 7 Real seismic data (Heathcote Valley Primary School station): **a** vertical displacement **b** vertical acceleration

Table 2 Simulations with real seismic data

	Case E	Case F	Case G
m_1 [kg]	8.0×10^3	8.0×10^3	8.0×10^3
m_2 [kg]	8.0×10^3	8.0×10^3	8.0×10^3
$\bar{k}_1$ $\left[\frac{\text{N}}{\text{m}}\right]$	1.05×10^9	1.05×10^9	1.05×10^9
k_2 $\left[\frac{\text{N}}{\text{m}}\right]$	1.05×10^9	1.05×10^9	1.05×10^9
c_1 $\left[\frac{\text{N}}{\text{m/s}}\right]$	5.7966×10^4	5.7966×10^4	5.7966×10^4
c_2 $\left[\frac{\text{N}}{\text{m/s}}\right]$	5.7966×10^4	5.7966×10^4	5.7966×10^4
f_c [Hz]	No control	100	100
φ	//	0.5	0.5
ψ [g]	//	0.1	0.1
g $\left[\frac{\text{m}}{\text{s}^2}\right]$	9.81	9.81	9.81
T_a [s]	//	0	0.1

is not useful for tangential vibrations. It is well known that tangential vibrations due to earthquake are usually stronger than vertical vibrations; nonetheless, it should be noted that passive seismic isolators are most effective in filtering tangential vibration, rather than vertical. Furthermore, it is worthwhile noting that for some earthquakes the presence of large cities straight over the hypocenter can produce larger vertical oscillations. This is the case of the strong earthquake that occurred in the New Zealand city of Christchurch on February 21, 2011, at 23:51:42UT. In the following, data measured at the Heathcote Valley Primary School station will be considered (station code HVSC): For this station, the maximum vertical acceleration was 1.47 g, while the maximum horizontal component was 1.45 g, so that common seismic isolators were not sufficient to filter the overall seismic vibration. Data are owned by the Institute of Geological and Nuclear Sciences New Zealand, and they are made available online by the Strong Motion Virtual Data Center (VDC) in the form of raw acceleration data sampled at 200 Hz; here these data are integrated twice to get the corresponding displacement. As usual in seismic data treatment, at each integration data are filtered using a Ormsby filter (transition bands are at 0.10–0.25 Hz and at 24.50–25.50 Hz). The corresponding displacement and acceleration are shown in Fig. 7.

In Table 2, data of the simulations performed using real seismic data are shown. Note that ψ is now set at 0.1 g, in order to avoid the control system staying

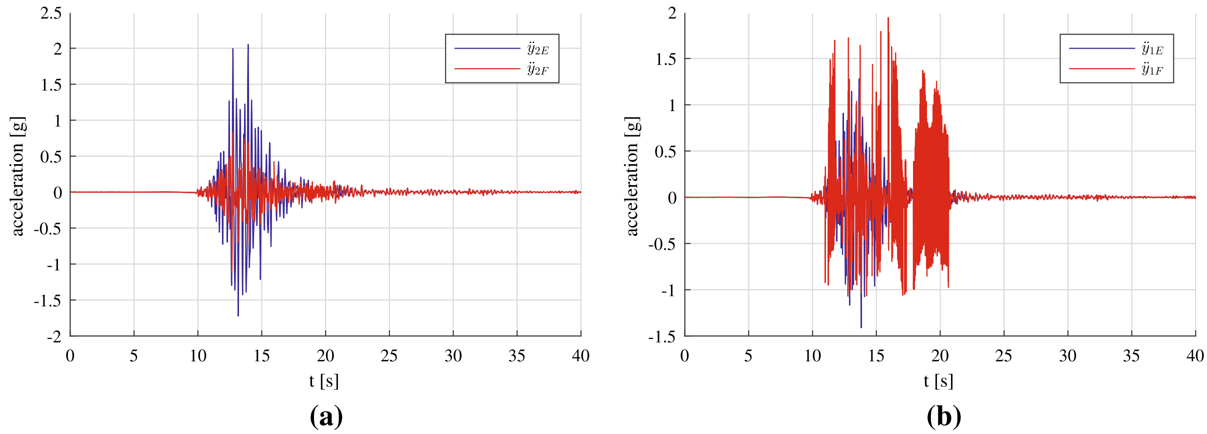


Fig. 8 Control of a real seismic signal E—no control, F—controlled: **a** Top mass acceleration; **b** Base acceleration

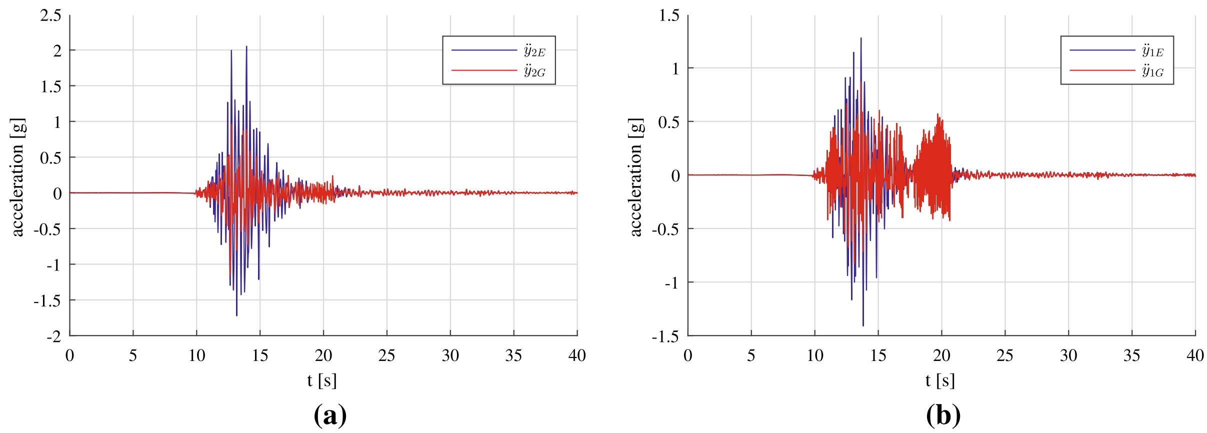


Fig. 9 Control of a real seismic signal E—no control, G—controlled with gradual actuation: **a** Top mass acceleration; **b** base acceleration

active for a long while in the aftershock, which would produce larger vibrations than in the case of no control.

Figure 8 shows how the vibration of the top mass and of the base is affected by the stiffness control. It can be seen that the control strategy is less effective with a real signal, since there is a good reduction in the top mass vibration, but the base undergoes larger vibrations. A possible reason of such behavior is that the real signal contains a significant amount of energy at higher frequency, so that the control is activated much more frequently due to the change of sign of the base velocity, see Eq. (3). Obviously, each time the control is activated the system receives a sudden impulse, so that it is reasonable that base vibration can be reduced if the actuation is modeled as gradual by means of Eq. (4).

Figure 9 shows that with an actuation time $T_a = 0.1$ the top mass vibration is reduced as with the sudden control, but the base vibration is largely reduced. Note that T_a is larger than $1/f_c$, *i.e.,* the actuation time is 10 times the time step between two control instants: This can be easily observed in Fig. 10b where the time-varying stiffness of the support is shown. It is to be stressed that the curve is continuous and the value of stiffness is usually intermediate between the two extreme values: This kind of control law is more effective and much more likely to be feasible in a real control device.

In Fig. 10a, the total energy of the system with/without control is shown: even with the real forcing function and with a more realistic actuation, the control strategy is successful in filtering seismic vibrations and avoiding the transfer of force and energy to the controlled structure.

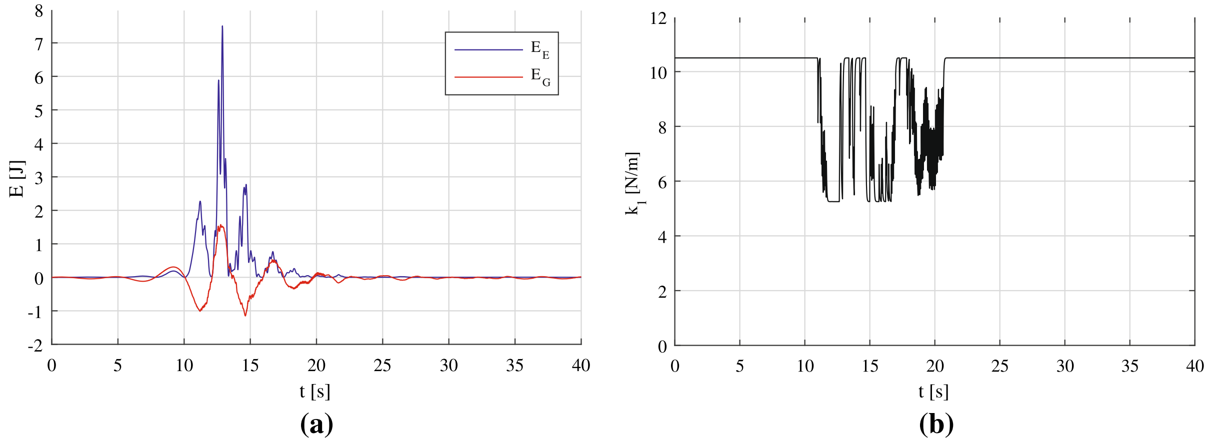


Fig. 10 **a** Total energy: case E—no control, case G— controlled with gradual actuation; **b** stiffness fluctuation during seismic control, case G—controlled with gradual actuation

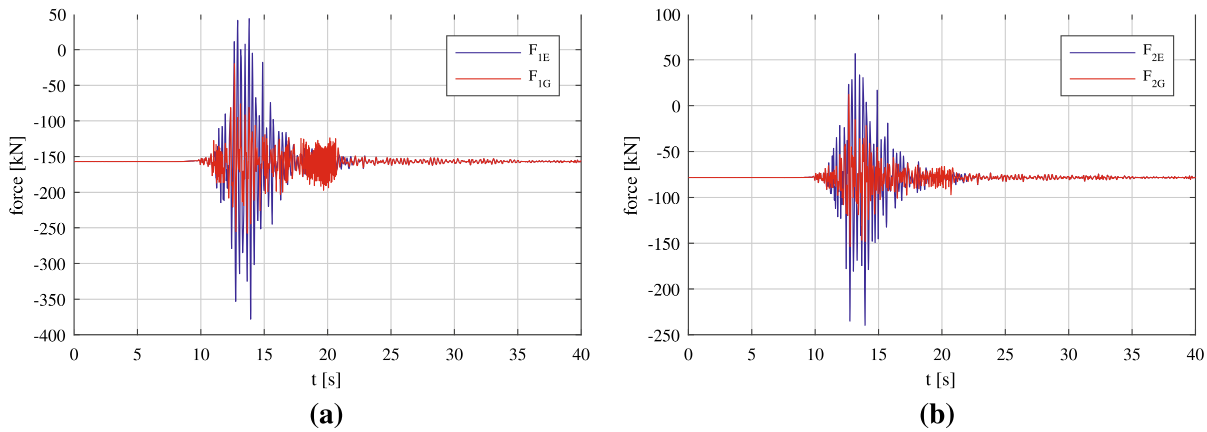


Fig. 11 Transmitted forces: case E—no control, case G—controlled with gradual actuation: **a** base mass force **b** top mass force

The transmitted force under a real seismic signal is shown in Fig. 11. The control strategy is effecting in preventing strong oscillations of the forces. In the uncontrolled case, both F_1 and F_2 reach positive values in the core part of the seismic movement; with the control activated, only F_2 has a single positive spike. This behavior is expected, since the minimum acceleration $\ddot{y}_{2G}$ in Fig. 10a is less than -1 g.

3 Conclusions

A control method for seismic isolation of buildings or equipments has been theoretically investigated. The control consists in changing the stiffness of the building base when its velocity has opposite sign with respect to the weight force. The role of the weight force has been pointed out by means of numerical simulations; this confirms that the proposed control strategy is effective in filtering vertical vibrations rather than horizontal vibrations. It is worthwhile noting that passive seismic isolators are effective in filtering horizontal vibrations, so that the proposed strategy can be considered to be complementary to friction isolators.

A parametric study on a test problem has shown that the best control for all the forcing frequencies can be obtained for a base stiffness reduction of one half. For such value, the top mass acceleration is cut by 88% with respect to the uncontrolled case; nonetheless, the base vibrates at constant amplitude for a longer time, due to effect of the actuator.

The control strategy has been checked using a real seismic signal; in particular, an earthquake having a stronger vertical component has been chosen as a benchmark. Simulations performed with a theoretical infinitely fast control show that the proposed method is effective in reducing top mass vibration, but it can introduce undesired base vibrations. This behavior was not observed in a simulated seismic signal, and it is mainly due to the higher harmonic content of a real signal. In order to overcome this issue and to keep into account for a more realistic actuation, the stiffness change has been modeled as a first-order system, and a proper actuation time has been defined in terms of the characteristic time. The proposed method reduces the maximum acceleration of the top mass by 55% without introducing larger vibrations at the base; the effectiveness of the control strategy is proven by maximum value of the total energy of the system, which is reduced by 81%. Although the results presented were on a specific idealized structural model, the results show that the stiffness control strategy used is an efficient filter for vertical seismic vibration isolation.

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