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# Influential Structural Parameters of Pounding between Buildings during Earthquakes

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## Abstract

This article studies the sensitivity of the response of pounding buildings with respect to structural and earthquake excitation parameters. A comprehensive sensitivity analysis is carried out by means of Monte Carlo simulations of adjacent single degree of freedom impacting oscillators. This sensitivity analysis, performed with Sobol'’s method, computes sensitivity indexes which provide a consistent measure of the relative importance of parameters such as the dimensionless main excitation frequency, the mass and frequency ratios of the structures and the coefficient of restitution. Moreover, the influence of nonlinear behaviour of the impacting structures is also considered. The consequences of pounding, on the structures themselves, are analyzed in terms of maximum force and nonlinear demand amplification compared to the case without pounding.

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*Keywords:* buildings pounding, sensitivity analysis, floor response spectra

## 1. Introduction

The interaction between adjacent structures during earthquakes became of interest as researchers gathered evidence of its occurrence over last decades [1]. This phenomenon was source of local damages on buildings as well as on bridges, and in some cases it may be thought that it lead even to failure initiation [2]. Acceleration records of instrumented interacting structures showed high amplitude and short duration spikes [3, 4]. In the case of industrial

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and power generation facilities, these acceleration spikes may influence the floor response spectra and thus the response of equipment mounted on them.

Nevertheless, despite rather considerable research in this field, the potential damaging effect of pounding remains difficult to estimate. In fact, conflictual results, conclusions and statements can be found in analytical and experimental works [5] as well as in reports on feedback from past earthquakes [1]. As a result, there is no consensus regarding the consequences of pounding for the general case of two adjacent structures. Consequently, in some studies an effort is made to understand the physics of pounding by means of simple model. For instance, Davis [6] focuses on two adjacent impacting oscillators or an oscillator impacting with a rigid barrier (fixed or following the ground motion) subject to harmonic excitation. This study highlights the well-known fact that, for some excitation frequencies, periodic impacts do not occur and the oscillators do not exhibit a steady state despite the periodicity of the excitation. Dimitrakopoulos et al. [7, 8] used dimensionless analysis for two single degree of freedom (SDOF) oscillators interacting with each other while they are subject to pulse like excitation. These studies drew meaningful conclusions on the dimensionless displacement response of impacting structures depending on the dimensionless excitation frequency, the SDOF oscillators' characteristics in terms of frequency and mass ratios as well as on the impacting oscillators' constitutive laws. It is also observed that pounding structures may be vulnerable to excitations with predominant frequencies quite different from their resonant frequency.

Nevertheless the above studies do not apply a systematic method to determine the importance of each parameter. In an effort to extend the results of these studies, a comprehensive sensitivity analysis of the earthquake induced pounding of two SDOF impacting oscillators is carried out. The performed global sensitivity analysis, based on Sobol's method [9], determines the contribution of the variations of the input parameters to the variance of the model output. In addition to linear elastic oscillators, some other nonlinear constitutive laws, representative of the behaviour of common structural systems are, also, considered. The consequences of pounding on the structures themselves are analyzed in terms of maximum force and nonlinear displacement demand amplification compared to the case without pounding. In addition, unlike most of the previous studies, this work investigates also the influence of pounding on floor response spectra. To this end, the relevant output quantity of interest is the observed maximum impact impulse.

## 2. Model

In order to perform the sensitivity analysis, the simplest model of two impacting oscillators is considered here (Figure 1). To model impact, a penalty method is employed considering a gap element with stiffness  $K_{impact}$  and damping coefficient  $C_{impact}$ . The impact stiffness is assigned a value, significantly higher than of the oscillators' stiffness values and the damping coefficient is related to the coefficient of restitution. Regarding the excitation, the variability of the frequency content (which may influence considerably pounding) is handled with the use of artificially generated signals compatible with a Kanai-Tajimi filtered white noise. These signals are characterized by a filter frequency parameter  $\omega_e$  and a filter critical damping ratio  $\xi_e$ .

To provide a further insight into the consequences of pounding on buildings, in addition to linear elastic behaviour three nonlinear constitutive laws which are rough approximations of the nonlinear behaviour of some, commonly met, structural systems are considered (Figure 1b). An elastoplastic law with kinematic hardening is used to model the performance of ductile steel structure, whereas, an origin oriented law is applied to model the behaviour of high stiffness degrading structure. Finally a nonlinear elastic behaviour is used as an approximation of the response of walls that exhibit uplift at their base because of foundation uplift or because of a full depth crack. It may also be used to approximate the behaviour of prestressed unbonded precast joints [10]. To reduce the number of varying parameters, the stiffness after the nonlinear onset is reached (slope  $K_2$  in Figure 1b) is fixed to 5% the initial stiffness. Moreover, for the results of the sensitivity analysis to be meaningful, all nonlinear oscillators exhibit the same amount of nonlinear demand when pounding does not occur. This is achieved through a reduction force coefficient to determine the nonlinear displacement onset. To avoid excessive nonlinear demand when the oscillator frequency is much higher than the excitation frequency  $\omega_e$ , the reduction force coefficient decreases for low values of the dimensionless excitation frequency. In the case of linear oscillators, the effect of pounding on the structures themselves is quantified by the ratio of the maximum elastic force (or, equivalently, maximum displacement) with

pounding to that without pounding. For the nonlinear oscillators, the relevant quantity of interest is the ratio of maximum nonlinear displacement demands.

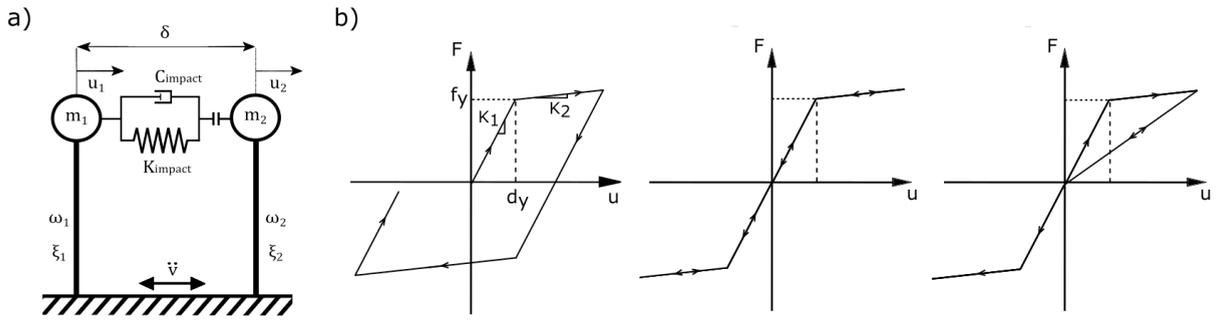


Figure 1. a) Model of two interacting oscillators b) considered nonlinear constitutive laws

**3. Dimensionless variables**

To carry out a sensitivity analysis of general validity, it is important to employ dimensionless input and output variables. Furthermore, to take into account the frequency variability of the excitation, several simulations are performed for each value of Kanai-Tajimi filter frequency parameter  $\omega_e$ . Therefore, the output quantities of interest are the mean values of these simulations. In the case of linear oscillators, forces are proportional to displacements and thus the ratio of the mean maximum displacement of oscillator  $i$  ( $i = 1, 2$ ) when pounding occurs  $\bar{U}_i^{\max}$  to that without pounding  $\bar{u}_i^{\max}$  is considered as a relevant index of the pounding effect on the structure’s response. This ratio is a function of ten dimensionless parameters:

$$\frac{\bar{U}_i^{\max}}{\bar{u}_i^{\max}} = \Phi \left( \frac{\omega_1}{\omega_2}, \xi_1, \xi_2, \frac{m_1}{m_2}, \frac{K_{impact}}{\omega_i^2 m_i}, \varepsilon, \frac{\delta \omega_i^2}{A}, \frac{\omega_e}{\omega_1}, \xi_e, \omega_e T \right) \tag{1}$$

where  $\omega_1, \omega_2$  are to the oscillators’ frequencies,  $\xi_1, \xi_2$  their critical damping ratios,  $m_1, m_2$  their masses,  $\varepsilon$  the coefficient of restitution,  $\delta$  the initial gap between the oscillators and  $A$  and  $T$  are the earthquake acceleration maximum amplitude and duration. Due to the computational cost of the sensitivity analysis, some of the dimensionless parameters are fixed. Therefore, the critical damping ratio of both oscillators is fixed to 5%, the impact element stiffness is fixed to 100 times the maximum stiffness of the oscillators, the dimensionless duration of the excitation signals is fixed to  $80 \times 2\pi$ . The Kanai-Tajimi filter damping ratio is fixed to 0.6 which is a commonly met value to model wide band signals. In addition, to focus on the consequences of pounding, only the cases for which pounding occur are of interest here. Hence, the initial gap between buildings is considered null. In the case of linear interacting oscillators, the following parameters are chosen as dimensionless varying inputs of the sensitivity analysis study:

$$\Pi_{\omega_e} = \frac{\omega_e}{\omega_1}, \Pi_{\omega} = \frac{\omega_2}{\omega_1}, \Pi_m = \frac{m_2}{m_1}, \varepsilon \tag{2}$$

As already mentioned, the output variable will be  $\Pi_U = \bar{U}_i^{\max} / \bar{u}_i^{\max}$  as an index of the maximum displacement (or, equivalently, force) amplification. In the case of nonlinear behaviour of the oscillators, as already mentioned, the additional variables (i.e. the nonlinear displacement onset and the stiffness after the nonlinear onset is reached) have been fixed and therefore the same input variables will be considered for the sensitivity analysis. In this case, the

output variable is the mean nonlinear displacement demand amplification:

$$\Pi_{\mu} = \frac{\overline{\mu_i^p}}{\overline{\mu_i^{np}}} \tag{3}$$

Where  $\overline{\mu_i^p}$  and  $\overline{\mu_i^{np}}$  are the mean nonlinear displacement demands with and without pounding. For both linear and nonlinear oscillators cases, the dimensionless maximum impact impulse is considered as a relevant output index of the influence of pounding on the floor response spectra. Actually, it is observed that the floor response spectra of impacting oscillators exhibit a characteristic shape strongly influenced by the maximum impulse of the impact force.

$$\Pi_{Imp} = \frac{\overline{Impulse}^{max}}{m_i \omega_i u_i^{max}} \tag{4}$$

#### 4. Statistical approach to pounding consequences

Sobol’'s method of sensitivity analysis is based on the decomposition of the variance of a model as a sum of elementary variances. In a probabilistic framework, considering a model  $Y = f(X)$ , where  $X = \{X_1, X_2, \dots, X_d\} \in [0;1]^d$  is a vector of  $d$  random variables, this decomposition, named functional ANOVA (ANalysis Of VAriance), reads:

$$Var(Y) = \sum_{i=1}^d Var(f_i) + \sum_{i=1}^d \sum_{i>j}^d Var(f_{ij}) + \dots + Var(f_{ij\dots d}) \tag{5}$$

where  $f_u$  ( $u \subseteq \{1, 2, \dots, d\}$ ) are  $2^d - 1$  functions depending only on those variables in  $X$  whose indexes belong to the subset  $u$ . Sobol’ defined a first order index  $S_u$  and a total sensitivity index  $S_{Tu}$  to measure the contribution of an input variable or a group of variables  $X_u$  to the output variance:

$$S_u = \frac{\sum_{v \subseteq u} Var(f_v)}{Var(Y)} = \frac{Var(E(Y|X_u))}{Var(Y)} \tag{6}$$

$$S_{Tu} = S_u + \sum_{v \subseteq \{1..d\} | u \subset v} S_v \tag{7}$$

The first order sensitivity index gives a measure of the contribution of the variable  $X_u$  alone while the total sensitivity index considers both the individual contribution of the variable  $X_u$  and also the contribution of its interactions with the remaining variables. Nevertheless for the above described ANOVA to be valid, the input variables are supposed to be independent. This is not the case here since  $\Pi_{\omega_e}$  and  $\Pi_{\omega}$  depend, both, on  $\omega_1$ . To eliminate this dependency between variables, the oscillator 1 frequency is fixed and several sensitivity analyses are done for each value of  $\omega_1$ . The six following values (in Hz) of oscillator 1 frequency are considered: 0.5, 1, 2, 3, 4, 5. For the sensitivity analysis corresponding to each value of  $\omega_1$ ,  $\omega_e$  and  $\omega_2$  are assumed to be uniformly distributed in [0.5 Hz, 5 Hz].

As for the mass ratio, values of  $m_2/m_1$  varying between 1/6 and 6 are considered. To ensure that the mass ratio of the adjacent structures takes reciprocal values with the same probability (e.g. same probability that oscillator 2 is three times heavier or three times lighter than oscillator 1), we do not consider a uniform distribution in [1/6, 6].

Instead, we consider a uniform distribution of  $m_2/m_1$  in  $[1, 6]$  and also, a uniform distribution of  $m_1/m_2$  in  $[1, 6]$  (i.e. for  $1/6 < m_2/m_1 < 1$ ). For the coefficient of restitution a uniform distribution is considered between 0 for plastic impact and 1 for elastic impact.

To keep a reasonable computational cost while obtaining accurate estimates of the sensitivity indexes, each Monte Carlo simulation consists of  $n = 1000$  runs, each run corresponding to a different set of the  $d = 4$  varying dimensionless variables. According to Sobol’'s method [11]  $(d+2) \times n$  runs of the model are required to evaluate both first order and total sensitivity indexes of all variables. In addition, as exposed earlier, the output dimensionless variables are mean values when several signals with the same excitation amplitude  $A$  and filter frequency  $\omega_e$  are considered. Therefore, five different excitation signals are generated for each sample of input data and the mean output is computed. Eventually, there are 35000 runs for each value of  $\omega_1$ .

### 5. Results

For the sake of conciseness, the results presented in this section focus on the linear elastic and elastoplastic interacting oscillators cases only. As several sensitivity analyses are performed for fixed values of oscillator 1 frequency, the sensitivity indexes for the maximum force and nonlinear demand (Figure 2) and for the dimensionless maximum impact impulse (Figure 3) are displayed as functions of oscillator 1 frequency. In addition, bounds of the 95% confidence intervals are depicted by cross markers. It may be observed that these bounds are quite narrow and thus it is concluded that the accuracy of the results is quite satisfactory.

When the maximum force or nonlinear demand amplification are of interest, as a general observation, significant difference is noticed between first order sensitivity indexes and total sensitivity indexes of all variable. Interactions between variables have an important contribution to the output variability. In general the frequency ratio of the two oscillators is the variable with the higher total sensitivity index for all constitutive laws, the mass ratio coming in second position. In the case oscillator 1 has a low frequency (in particular when  $f_1 = 0.5$  Hz) all input variable have comparable total sensitivity indexes. It is also observed that, the coefficient of restitution is the less influential parameter in all cases. Furthermore it influence diminishes with increasing frequency of oscillator 1 up to 3 Hz.

Regarding the dimensionless maximum impact impulse, both the mass and frequency ratios are influential parameters. In all cases, when the oscillator 1 frequency is less than 2 Hz the influence of the mass ratio is predominant. It is also observed that, in the case of elastoplastic oscillators, the influence of the dimensionless excitation frequency becomes considerable with increasing frequency of oscillator 1. This trend holds for both first order and total sensitivity indexes.

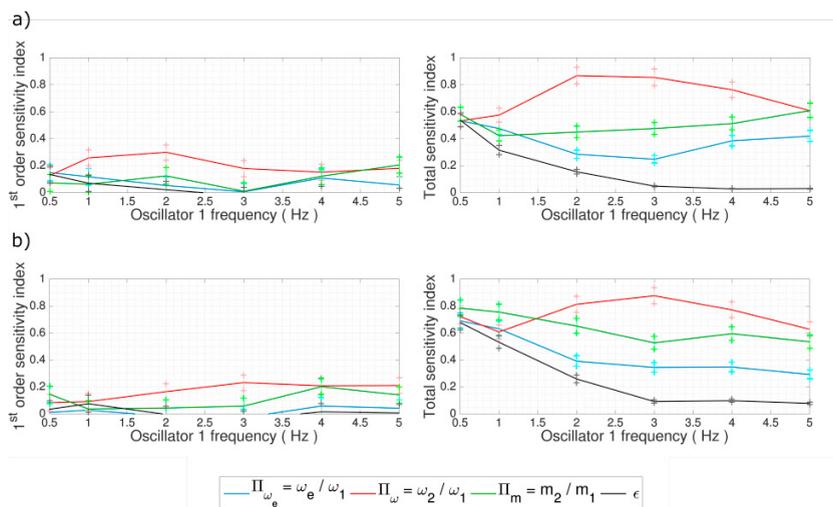


Figure 2. Sensitivity indexes and their 95% confidence intervals a) for the dimensionless force amplification of linear elastic oscillators b) for the nonlinear demand amplification of elastoplastic oscillators.

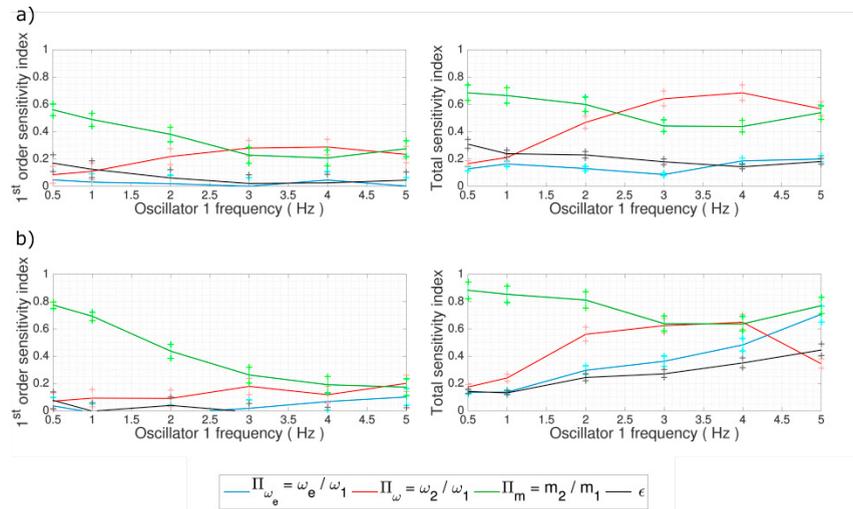


Figure 3. Sensitivity indexes and their 95% intervals for the dimensionless maximum impact impulse. a) linear elastic oscillators, b) elastoplastic oscillators.

## 6. Conclusions

This work deals with the sensitivity of the response of pounding buildings and determines the more influential structural and earthquake excitation parameters. A comprehensive sensitivity analysis of two single degree of freedom impacting oscillators was carried out using Sobol'’s method. The overall conclusions of this analysis are that the frequency ratio is, in general, the most important parameter as far as maximum force and ductility demand are concerned. Regarding the maximum impact impulse, the mass and frequency ratios are, in general, the most influential parameters, the mass ratio being predominant, for all constitutive laws, in the case of rather low frequencies (e.g. less than 2 Hz) of the oscillator of interest.

Because of the simple model considered here, this work does not cover all aspects of the sensitivity of pounding structures. In fact, the multi-degree of freedom nature of the impacting structures may have a considerable influence of the response leading to results which may differ, to some extent, from those based on SDOF models. Therefore, a future direction could be the extension of this work to 2DOF impacting structures.

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