The Effect of the Friction Coefficient and the Pendulum Radius on the Behavior of Structures Isolated with Simple Friction Pendulums

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Abstract: - The study presented in this paper shows the results of simulation made on a rigid structure isolated with four simple friction pendulums. We created a model in *SolidWorks* that was used to find out how the pendulums radii and friction coefficients respectively the frequency of the excitation influences the structural response. It has also been found that the frequency of the structure does not increase with the frequency of excitation if the latter exceeds the natural frequency of the pendulum, but in the post-resonance domain it remains constant taking the value of the natural frequency of the system.

Keywords: - Friction pendulum, Structural response, Friction coefficient, Pendulum Radius, Simulation

1. INTRODUCTION

Earthquakes happen if there is a relative shift along fractures in the crust of the Earth. There are soil trepidations on a large surface around the epicenter of the earthquake, causing damage to the built environment and possibly resulting in human losses. Some Romania regions present a higher risk because of the seismic activity that originates from the Vrancea source [1]-[2] and the Banat source [3]. Important ground excitation can be produced also by human activity, such as blast, heavy traffic, construction works and so on [4]. Progresses in seismic isolation have been made over the last decades, and now there are available advanced solutions to reduce the effect of ground movement [5]-[7]. Insertion between the ground and the protected structure of elastomeric elements is a popular solution [8]. Description of devices involving elastic elements consisting of natural rubber or neoprene is largely presented in the literature [9]. A lead core can be added to such devices to increase the hysteretic effect [10]. A highly nonlinear effect is obtained if an elastomeric bearing is combined with a lead-rubber bearing resulting in the so-called hybrid lead rubber bearing [11]. Models of such rubber bearings describing their specific behavior are available [12]-[14]. A type of seismic isolation devices based on the energy dissipation by friction was introduced in 1985. These are known as the friction pendulums (FP), which can have one, two or three sliding surfaces [15]-[18] respectively a polynomial sliding surface [19].

In the study presented herein we describe the research conducted to discover the influence of the sliding surface radius and that of the friction coefficient on the response to excitations with various frequencies.

2. PROBLEM FORMULATION

A rigid structure isolated with simple friction pendulums (SFP) behave in respect to the radius of the sliding surface. The friction coefficient of the involved materials has a limited, but clear influence. The frequency of the ground trepidation has also to be considered.

For calculating the natural frequency f_n of the isolated system one can involve the relation:

$$f_n = 2\pi\sqrt{\frac{R}{g}}, \qquad (1)$$

which is deduced from the free damped system oscillation. Here, the pendulum radius is denoted with R and the gravitational acceleration is g=9.80665 m/s^2. One can observe that the friction coefficient μ and the weight of the structure G do not influence the natural frequency.

The frequency and the amplitude resulted for a given excitation depends on the excitation parameters, which are the amplitude A_e and the frequency f_e. The task of the SFP is to maintain the amplitude of the displacement $A_{\max}$ achieved in the transitory regime as well as the amplitude in the stabilized regime A_{stab} as small as possible, in order to avoid dangerous acceleration.

During ground shacking, the inertial forces belonging to the structure push it in horizontal direction. The force caused by friction opposes to this action, being a reaction force. Note that the friction coefficient μ varies with the speed. If the inertia exceeds the friction force, a relative displacement between the structure and the friction pendulum takes place and the structure attains another frequency f_{struc} as the excitation. This is lower as f_e and supplementary contribute to the reduction of the structure's acceleration.

3. MATERIALS AND METHODS

In this section we present the study on the behavior of the isolated structure made with help of the *SolidWorks* program, particularly involving the *Motion* module described in [20],[21]. The 3D model of the perfectly rigid structure was built with steel bars and wood plates after a laboratory-size structure available in our university. The structure, as the part denoted with 1, has the geometry and essential dimensions described in Figure 1.

The ground is conceived as an assembly consisting of two parts. One of them is a base plate that is fixed, indicated as part 2 in the Figure 1, which is used as a reference. The second part is the shaking plate 3 that can shift along the base plate without friction. It reproduces the ground motion. The dimensions of the two plates are given also in Figure 1.

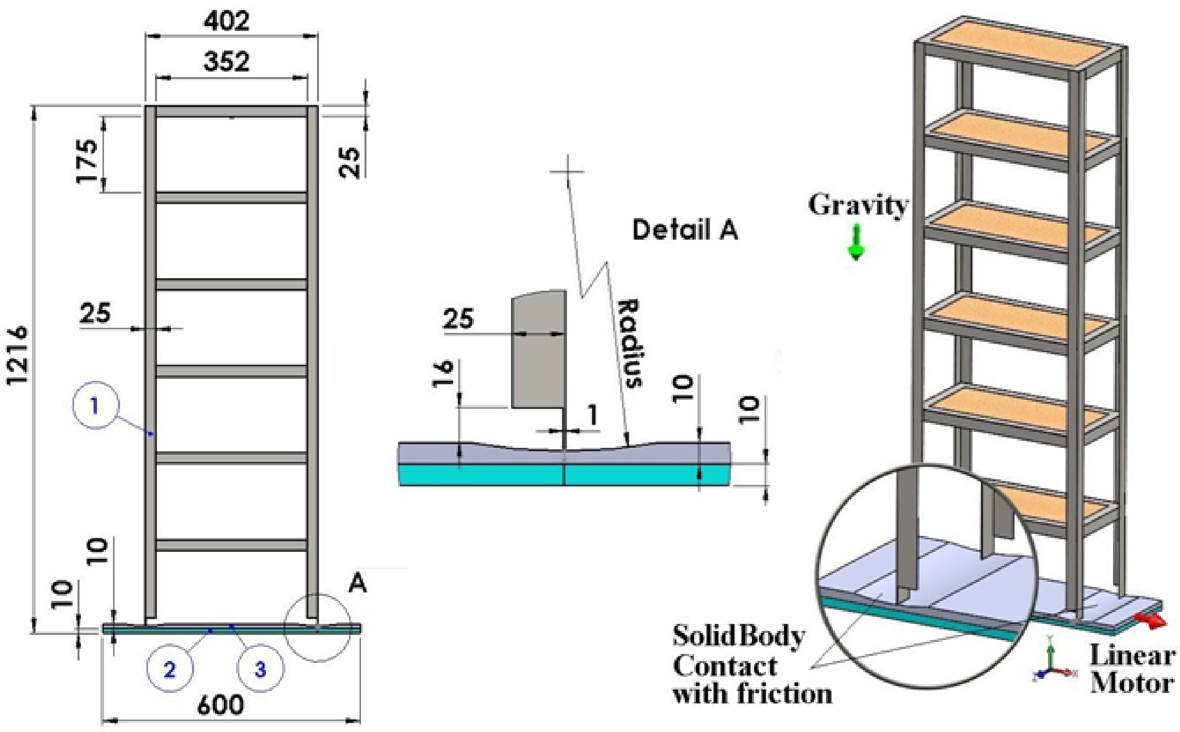

Figure 1. Description of the system composed by the structure and the friction pendulum

Table 1. Contact condition based on friction coefficients

Contact case	Components	Contact type	μ_D [-]	ν_D [mm/s^2]	μ_S [-]	ν_S [mm/s^2]
1	Structure	Steel (dry)	0.25	10.16	0.3	0.1
	Shaking plate	Steel (dry)				
2	Structure	Acrylic	0.05	10.16	0.08	0.1
	Shaking plate	Steel (greasy)				
3	Structure	Custom	0.03	10.16	0.05	0.1
	Shaking plate					

The shaking plate is moved in the X direction with a feature of the *SolidWorks* program called *Linear Motor*. It can impose a displacement after a harmonic function. For the first simulations we used following parameters: A_{e1}=5 mm ensured by the command *Max Displacement* and eight frequencies f_{e1}=0.75 Hz; f_{e2}=1 Hz; f_{e3}=1.5 Hz; f_{e4}=2 Hz; f_{e5}=2.5 Hz; f_{e6}=3 Hz; f_{e7}=3.5 Hz; f_{e8}=4.5 Hz and f_{e9}=6 Hz, ensured by the command *Frequency*.

The pendulum's sliding surface is realized as a cylindrical material extrusion applied to the shaking plate. In this stage of the research the radius R=260 mm was selected and the analysis time was set for 10 seconds. The contact between the structure and the shaking plate was simulated considering the static and dynamic friction coefficients μ_D and μ_S presented in Table 1.

The analyses in the second stage are made for a time length of 30 seconds and an excitation with A_{e2}= 10 mm and f_{e2}=1 Hz. Several radii of the sliding surface were selected for this stage of the study.

The initial radius was R_{1}=110 mm and afterwards it was step-by-step modified by increasing it with 50 mm until the radius value R_{18}=960 mm was achieved. The three considered contact conditions are indicated in Table 1.

3. RESULTS AND DISCUSSIONS

The simulation results for the first study are presented in Figure 2, were the acrylic/steel contact is considered. The FP has $f_{n4}=2\pi\sqrt{R_4/g}=0.9774\,\text{Hz}$, determining the occurrence of resonance at this excitation frequency. The largest displacement is expected at this excitation and it is really achieved, Figure 3 confirming it. Estimating the response frequencies f_{struc} from Figure 2, one can observe that this frequency increases until the natural frequency f_n of the system is achieved and stop increasing if f_e>f_n. In the post-resonance domain f_{struc}= f_n.

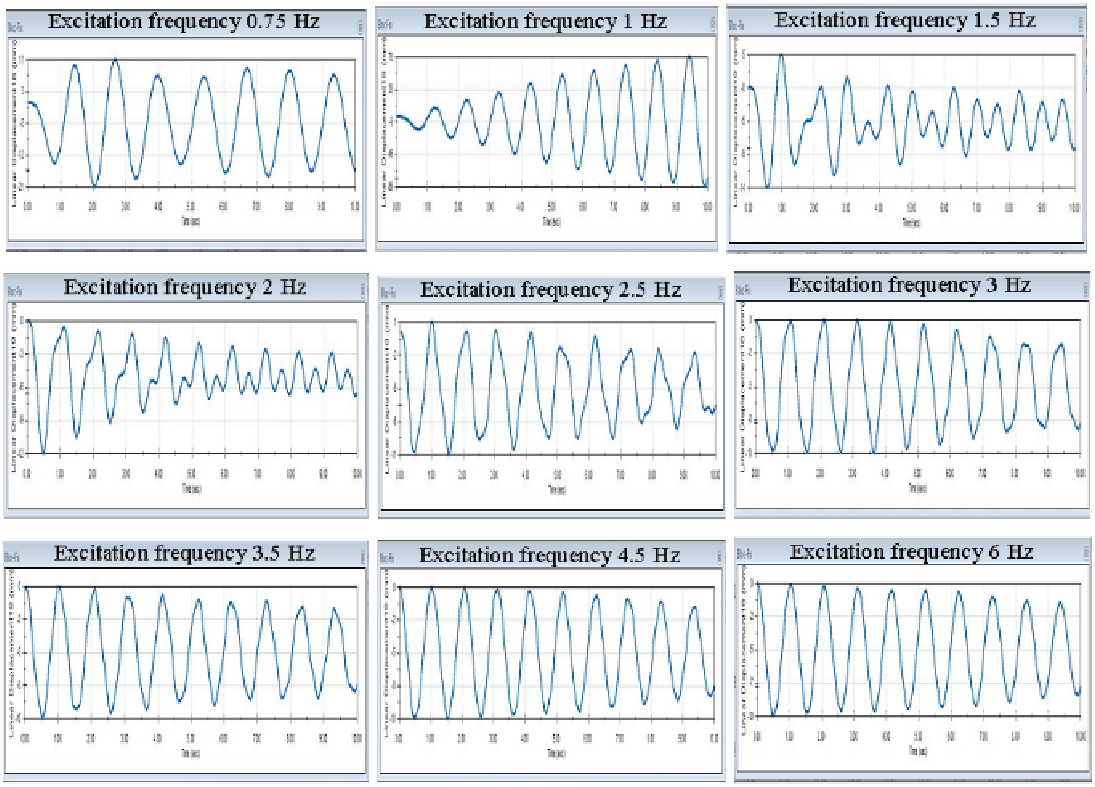

Figure 2. Elongation achieved in X direction for the structure isolated by SFPs with acrylic pivots and stainless steel sliding surfaces

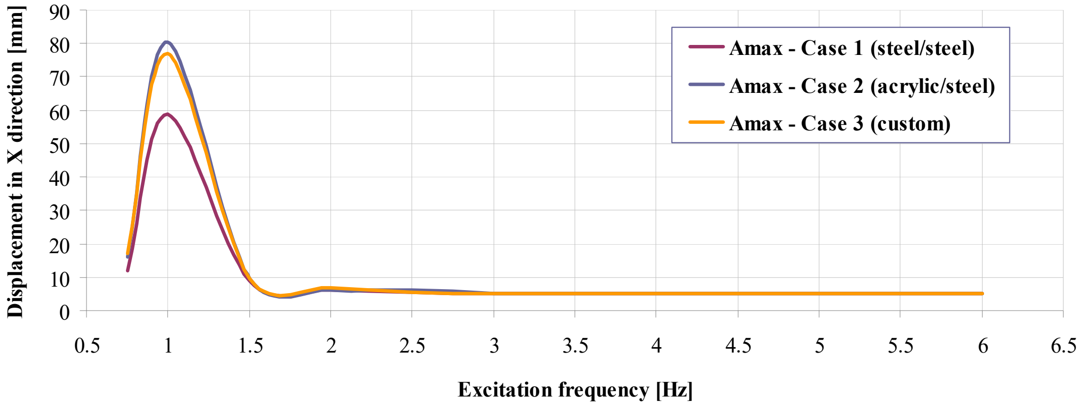

Figure 3. Elongation achieved in X direction for different frequencies of the excitation

If $f_e > \sqrt{2} f_n$, the displacement of the structure A_{max} is smaller as the ground motion A_e and so a good isolation is accomplished. Moreover, because the frequency of the isolated structure does not increase if f_e exceeds f_n clearly results that the acceleration amplitude do not change. In consequence, the best seismic isolation is ensured by the analyzed SFP for excitation frequencies above 3 Hz, but an acceptable level of isolation is ensured also if f_e is in the range 1-3 Hz.

Next results reflect the research made by considering different friction coefficients and pendulum radii in the condition that the excitation frequency is maintained unchanged. The responses of the structure in terms of displacements in the horizontal direction X are given in Figure 4 for the resonance was passed, while the Figure 5 shows the behavior in the post-resonance domain.

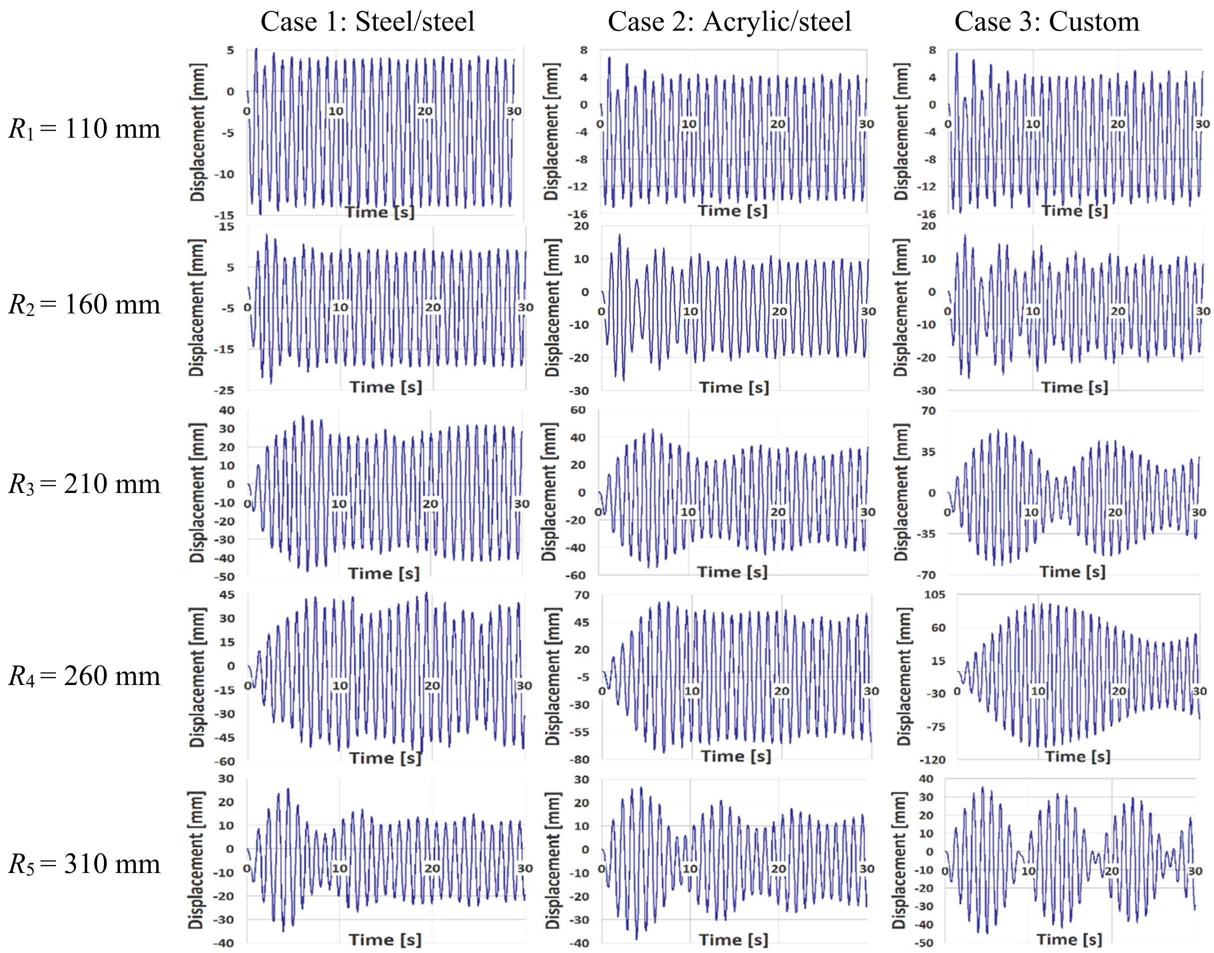

Figure 4. Structural displacement evolution with the pendulum radii increase until the resonance is passed

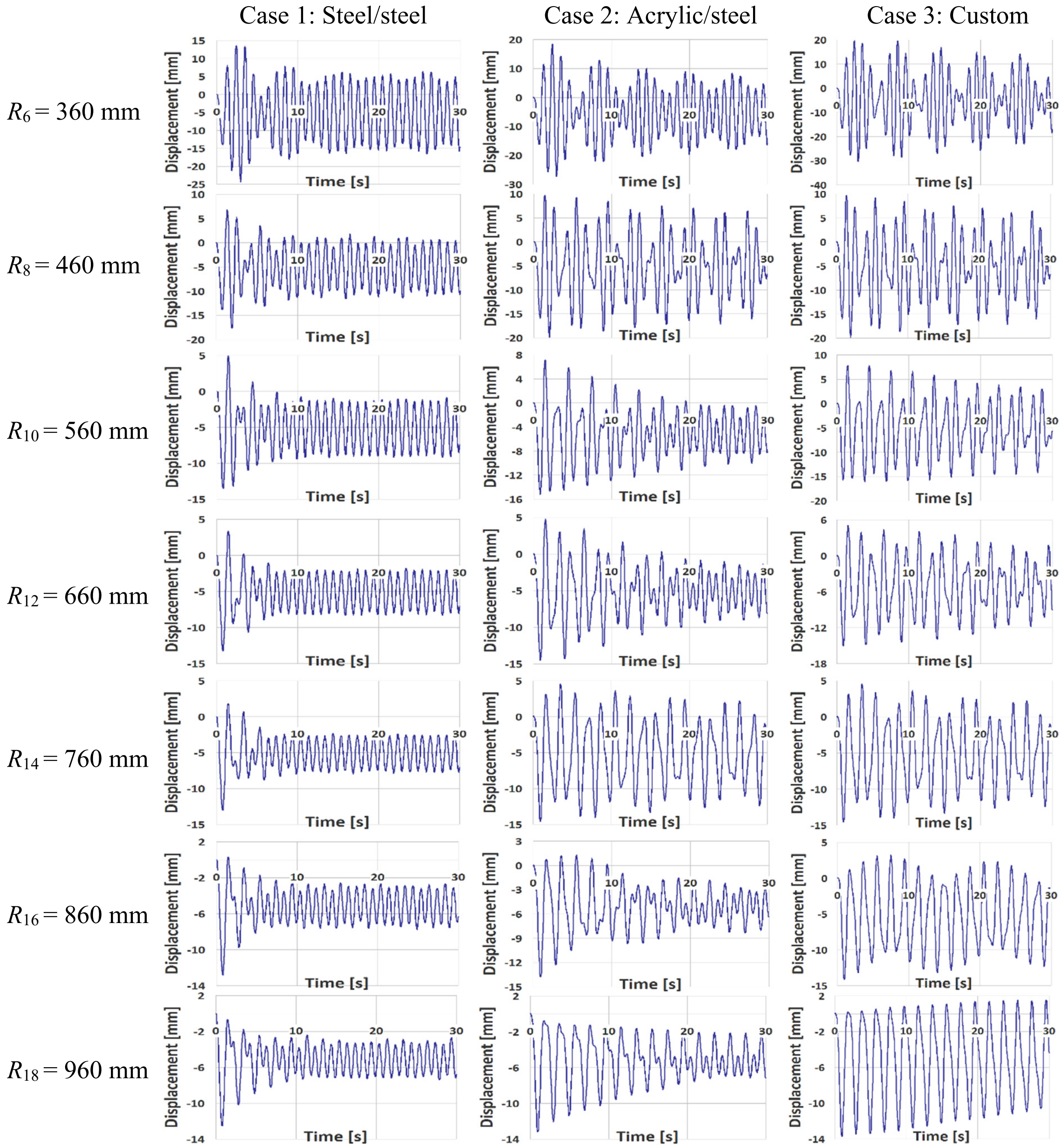

Figure 5. Structural displacement evolution with the pendulum radii increase in the post-resonance domain

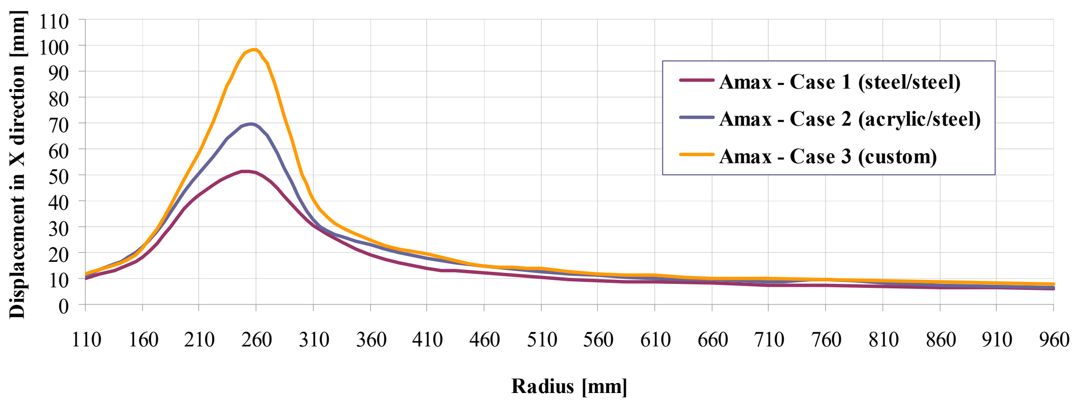

Figure 6. Maximum amplitudes for the different pendulum radii and the three friction coefficients

From Figure 6 it can be observed that the effective isolation is assured for radii bigger then 610 mm for all the three friction coefficients. In consequence, for the excitation frequency f_{e2}=1 Hz considered in the second stage of the study, the friction pendulum should fulfill this condition. Evidently, for friction pendulums working in real conditions, their design must consider the significant earthquake period T that is expected in the region of the isolated structure. Another conclusion rising from Figure 6 refers to the amplitude achieved in resonance; the higher the friction coefficient, the lower the amplitude is. Also, it ca be observed here that the friction coefficient does not affect the resonance frequency.

4. CONCLUSIONS

The paper presents a research regarding the identification of the response of a structure isolated by friction pendulums. It was found that the best isolation is achieved if the excitation frequency exceeds 1.5 times the natural frequency of the friction pendulum. This natural frequency is not influenced by the weight of the structure and the friction coefficient has also a low influence, but if it has higher values the amplitude of the oscillation decades. Hence, these two parameters have low influence on the dynamic behavior of the isolated structure. On the other hand, the pendulum radius has a significant influence on this behavior, since it is the parameter controlling the natural frequency of the pendulum. It was finally concluded that isolation can be made either by dissipating energy by ensuring a certain significant friction coefficient or by permitting a large relative displacement between the ground and the structure and avoiding in this way significant acceleration of the structure. The two constructive parameters, namely the friction coefficient and the pendulum radius, must be carefully adapted in both design cases.

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