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Passive Control Solutions Applied to Civil Constructions under Dynamic Load

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In the paper an overview of passive control solutions used for reduction of vibration of civil engineering structures is presented and the special attention is put on the friction pendulum bearings applications as the example of facility supporting the frame building. The experimental results of the frame building equipped with friction pendulum bearing located on the vibration table is studied. The analysis covers the acceleration response of the frame in time domain as well as power amplitude spectrum for eleven levels of shaking table's horizontal excitation movement. On the basis of analysis the clasification of vibrations of the frame according to earthquake Intensity Modified Mercalli scale is performed. Discussion on effectivennes of friction pendulum depending on concave radius of the friction pendulum bearing and its friction coefficient is performed.

Keywords: *friction pendulum bearing, vibration of building, control of vibrations*

1. Introduction

Civil engineering structures are subjected to loads of high level of variability in terms of load direction and values, such as earthquakes or wind loads. In order to minimize the effects of these loads, the passive dampers are used. The choice of passive dampers in the scope of their localization in the structure as well as their elastic and damping parameters are related to the dynamic characteristics of the vibrating object and the type of dynamic excitation. Passive bearings are one of the solution forms of vibration reduction. There are number of works that concern the application of passive bearings. The concept of passive bearings is presented in [1-3]. Base-isolations have become a very popular and effective way to reduce building vibration [4-5]. In particular they are used for seismic excitations [6-8]. Elastomeric bearings and friction pendulums are used to produce additional forces of elasticity and damping. In this respect many interesting solutions are in the works [9-12].

Isolation bearings are assembled between building and foundation. The purpose of applying of these dampers is reduction of the effect of large horizontal movement, e.g. during earthquakes. Three types of dampers are commonly used: high density rubber bearings, laminated rubber bearings, both built of rubber discs and friction pendulum bearings. Friction Pendulum Bearing was patented by Touaillon in 1870 [13]. A similar system was proposed by Wu [14].

In the paper the experimental analysis of double friction pendulum bearing under the steel frame is performed. The efficiency of pendulum is analyzed for eleven levels of lateral excitation generating by shaking table.

2. Dynamical model of the analyzed structure with friction pendulum bearing

The structure shown in figure 1 is being analyzed for horizontal vibration under the influence of horizontal movement u (t). The motion equation for the system can be written as:

$$B\ddot{q}_c + C\dot{q}_c + Kq_c = \mathbf{0} \tag{1}$$

where q_c is the total displacement vector, B, C, K are matrices of inertia, damping, and stiffness, respectively. The vector of total displacements q_c can be expressed by the horizontal displacement u and the dynamic displacement q

$$q_c = r\,u + q \tag{2}$$

where r is the so-called influence vector.

By substituting the relation (2) to (1), one can obtain the equation of forced vibrations

$$B\ddot{q} + C\dot{q} + Kq = -Br\,\ddot{u}\,(t) \tag{3}$$

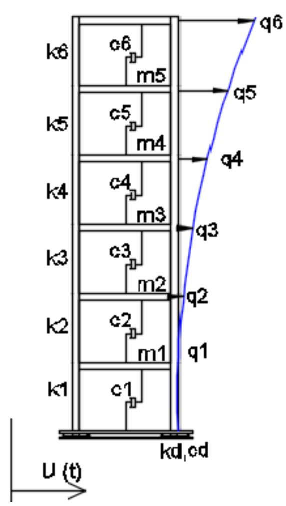


Figure 1. Model of the frame with Friction Pendulum Bearings

3. Concept of friction pendulum bearing

Friction Pendulum Bearings (FPB) work in the same way as a simple pendulum. During dynamic excitation, the element of the damper moves along the concave surface causing slight movement of the structure (Figure 2). The damper increases the natural vibration period of the structure by moving the object on a passive damper. In addition, dynamic damping occurs due to friction due to the moving object on the support. As a result of horizontal displacement, the horizontal force transmitted to the structure from the moving damper is reduced. Proper selection of the damper geometry has the ability to self-center the structure.

In the analyzed design FPB with spherical surface of curvature R1 and coefficient of friction μ. Assuming the small deformation of FPB, the response of the device is

$$P = N\mu \, sgn\,(\dot{x}) + \frac{N}{R_1} x \tag{4}$$

than can be written separately

$$P_n = \frac{N}{R_1} x \;,\; P_m = N\mu \, sgn\,(\dot{x}), \tag{5}$$

where N is the normal force acting on the surface, x is the sliding deformation, $\dot{x}$ is the sliding velocity and $sgn\,(\dot{x})$ is the signum function, i.e. equal to 1 or -1 depending on whether $\dot{x}$ is negative or positive, respectively.

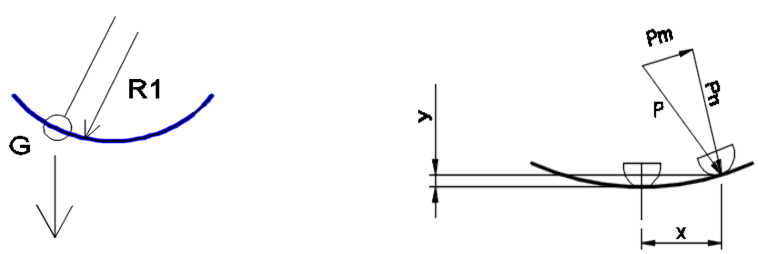


Figure 2. Concept of pendulum on the left, forces acting on the friction pendulum bearing on the right

Horizontal force given by the FPB is

$$H = \mu N + k_d x \tag{6}$$

where k_d is the horizontal stiffness of the FPB. The effective horizontal stiffness is defined as:

$$k_{d,eff} = (\mu + 1)\frac{N}{R_1} \tag{7}$$

4. Experimental study.

The purpose of this paper is to present the experimental model of the steel frame equipped with friction pendulum bearings under the dynamical excitation. The response of the frame is measured using the accelerometer attached to the top of the structure. The analysis were performed for different accelerations of lateral excitation - eleven levels of excitations from the shaking table.
As seen in figure 3, six storey building frame with FPB, which is used for experiment setup, is made of S235JR steel. Physical features of this model is summarized in Table 1 as shown below.

Table 1. Physical features of structural model

Frame weight	500 gr
Each storey height	24 cm
Frame column steel angle dimensions	2.5 cm x 2.5cm, thickness=0.1 cm
Frame beam steel angle dimensions	2.5 cm x 2.5cm, thickness=0.1 cm
Frame floor dimensions	22 cm x 34 cm
Dimensions of FPD	8.5 cm x 8.5 cm x 0.5 cm
Radius R_1 of friction pendulum bearing	350 mm
Radius R_2 of friction pendulum bearing	10 mm

The shaking table used in this experiment has a compact shape and its dimensions are 40 cm x 50 cm and h= 100cm. Shaking table can produce one dimensional horizontal vibrations that can produce desired number and range (1-10 Hz) of frequency and its amplitude changes in between -50 mm to + 50 mm at maximal range. Acceleration measurements are connected to the device and a software data recorded from this device can be saved and used.

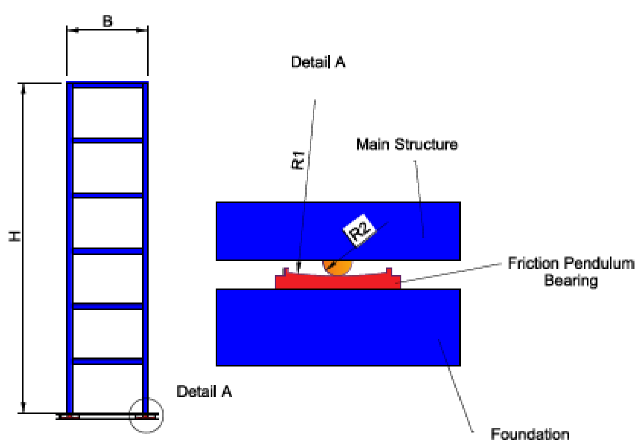


Figure 3. Friction pendulum bearing under the analyzed frame.

In the figure 4 response of the model structures under free vibration is presented. Natural frequency is 6.86 Hz.

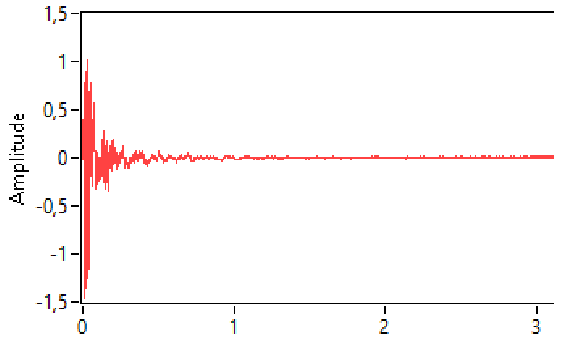
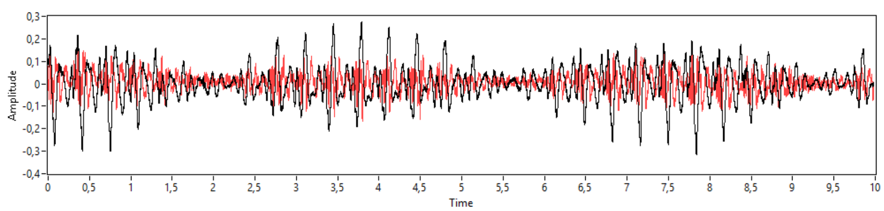


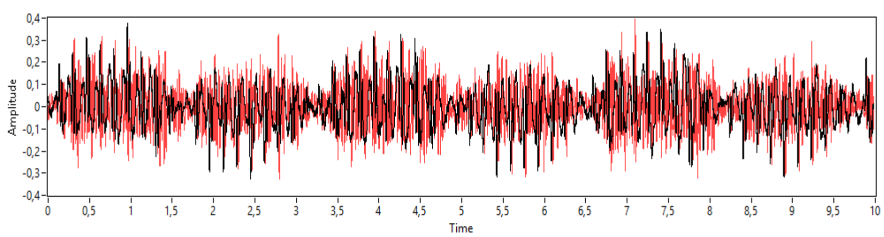
Figure 4. Responses of the model structures under free vibration

In the figure 5 accelerations of the shaking table and top of the frame in time domain for steps 0.5 to 5.5 are shown. Following the measuements, amplitudes of accleration increase from the 0.22 m/s^2 for table and 0.12 m/s^2 for the frame for step 0.5, and for frame 2.52 m/s^2, for table 1.49 m/s^2 for step 5.5.

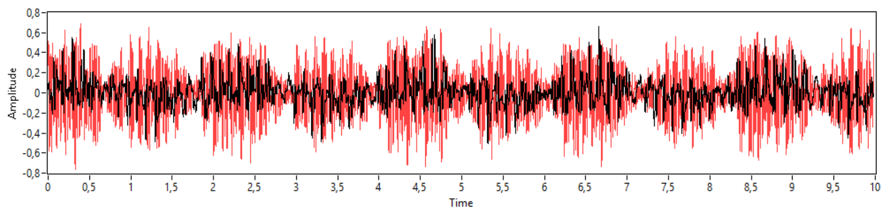
Step 0.5



Step 1.0



Step 1.5



Step 2.0

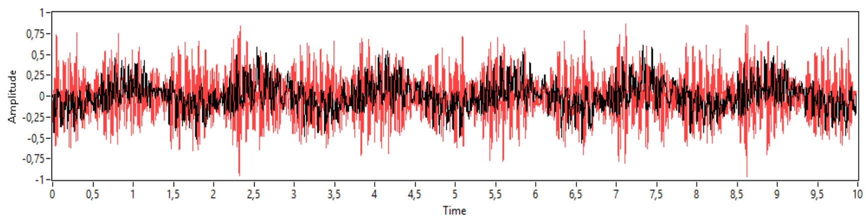
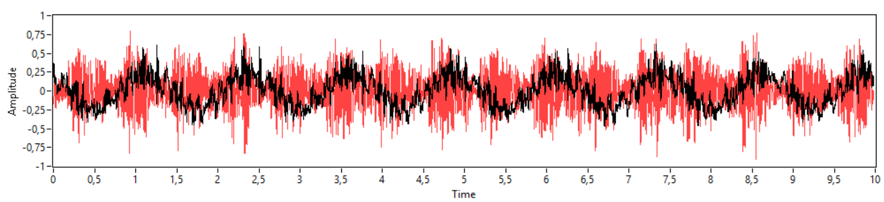
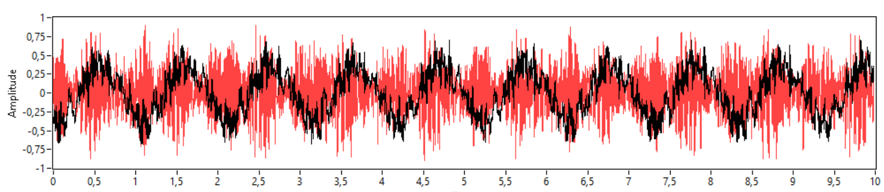


Figure 5. Acceleration [m/s^2] of top of the frame (red line) and the table (black line) in time domain [s]

Step 2.5



Step 3.0



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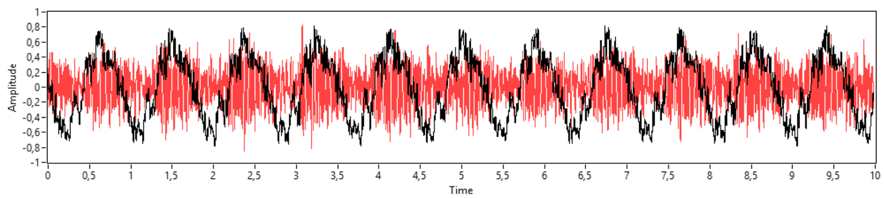


Step 4.0

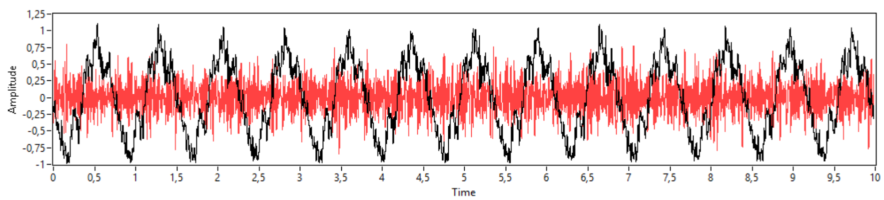
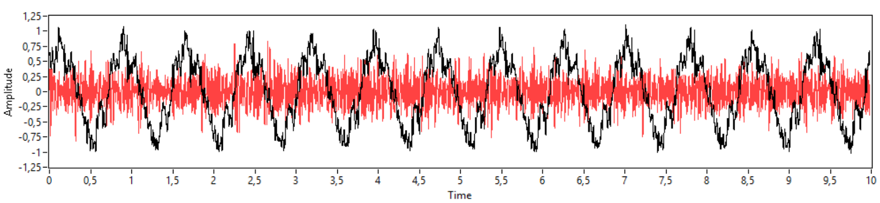
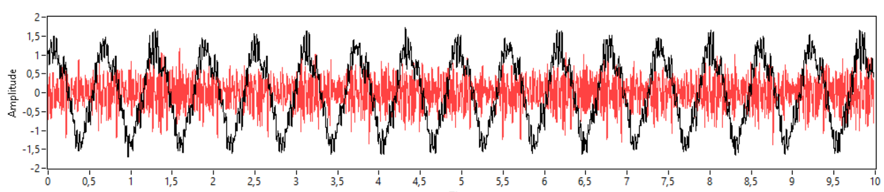


Figure 5. Continued

Step 4.5



Step 5.0



Step 5.5

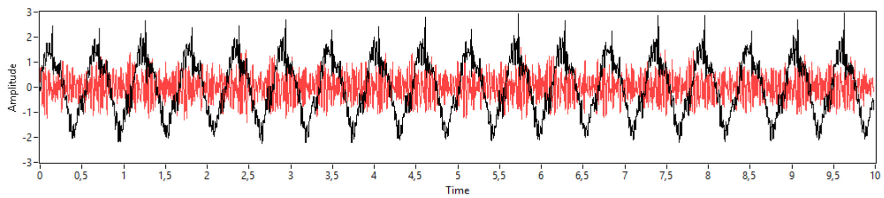
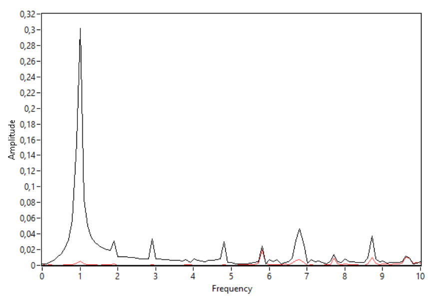


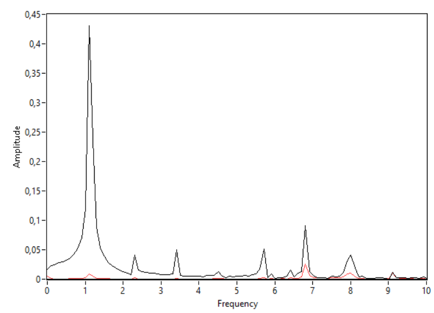
Figure 5. Continued

Figure 6 presents acceleration amplitude spectrum. The highest value of power amplitude spectrum (PAS) changes for the step 0.5 from 0.25 Hz for table and 0.3 for frame and for step 5.5 is 1.98 Hz for frame and table.

Step 3.0



Step 3.5



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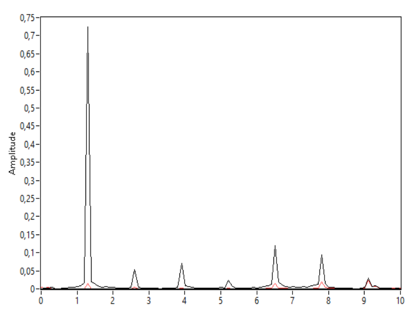
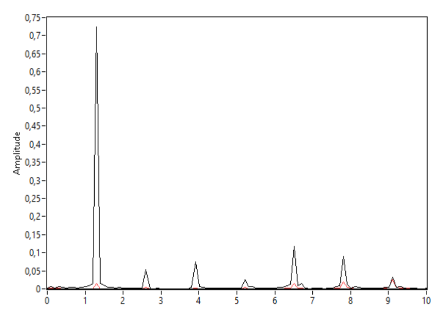


Step 4.5



Step 5.0

Step 5.5

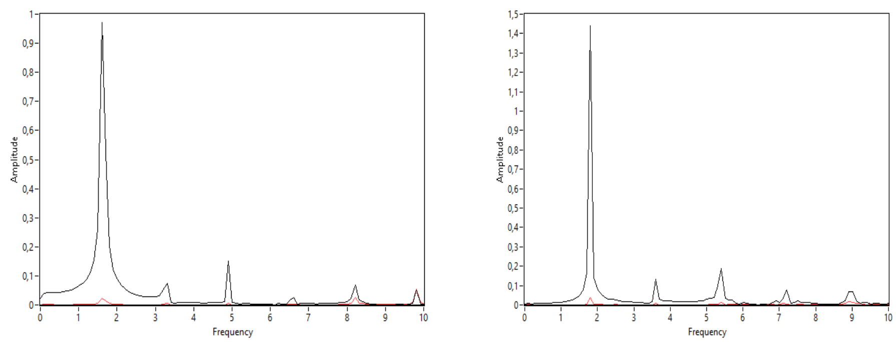


Figure 6. FFT of acceleration of top of the frame for steps from 0.5 to 5.5, black line - table, red line - frame.

Intensity of vibrations of the place where the structure is located is the most important issue. This information is described in the Modified Mercalli Intensity scale. Table 2 classifies the amount of damage regarding to response accelerations of the shaking table.

Table 2. Classification of vibrations according MMI scale

Step no.	I_{MM} value	Description	Maximum acceleration of the table, [cm/s^2]
1	2	3	4
0.5	VI	Everyone feels movement. Poorly built buildings are damaged slightly. Plaster in walls may crack. Small bells in churches ring.	od 20 do 50
1.0	VI	- *II* -	- *II* -
1.5	VII	People have difficulty standing. Considerable damage occurs in poorly built or badly designed buildings, old walls. Weak chimneys break at roof lines.	50 do 100
2.0	VII	- *II* -	- *II* -
2.5	VII	- *II* -	- *II* -
3.0	VII	- *II* -	- *II* -
3.5	VII	- *II* -	- *II* -
4.0	VIII	Poorly built structures suffer severe damage. Ordinary substantial buildings partially collapse. Tall structures such as towers and chimneys may twist and fall.	100 do 200
4.5	VIII	- *II* -	- *II* -
5.0	VIII	- *II* -	- *II* -
5.5	IX	Most buildings suffer damage. Some underground pipes are broken. Reserviors suffer severe damage	200 do 500

Figure 7 presents PAR of acceleration of top of the frame for steps 0.5 to 5.5. Based on the analysis, with the increase of excitation, the frame accelerations increase. In the step excitation range from 0.5 to 2.0, IMM = VI and IMM = VII, the acceleration increase of table and frame is at the similar level. Significant differences in acceleration increase of table and frame are observed from the step 2.5 and higher, IMM = VII. In the final phase of experiment at the step 4.5, IMM = VIII, the acceleration factor for the table is 0.46 and for the frame is 0.17. From the step 4.5 the influence of the friction pendulum bearing is observed, while the large accelerations of the table base, there are small accelerations of the frame structure.

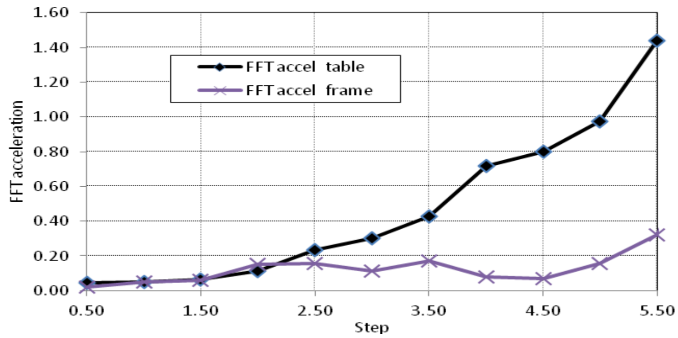


Figure 7. FFT of acceleration of top of the frame for steps 0.5 to 6.0, black line - table, red line - frame.

Figure 8 presents response curves of the friction pendulum bearing for fixed dynamic friction coefficient 'mi' and sliding surface curvature radius 'R1'. The bigger dissipation is for mi=1.2 and R_1=0.35 m and the smaller for mi=0.5 and R1=1.2.

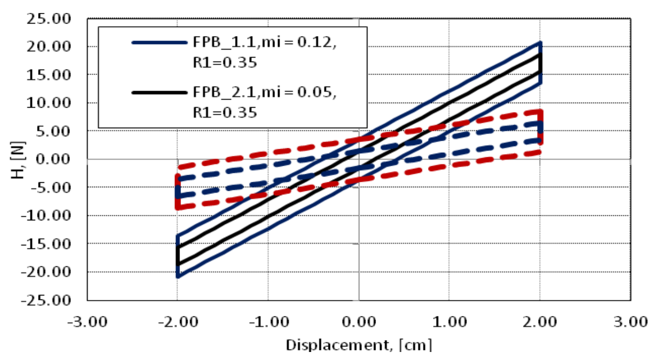


Figure 8. Response curves of the friction pendulum bearing for fixed dynamic friction coefficient 'mi' and sliding surface curvature radius 'R1'

5. Conclusions.

The experimental results of the frame building equipped with friction pendulum bearing located on the shaking table is studied. The analysis cover the acceleration response of the frame in time domain as well as power amplitude spectrum for eleven levels of shaking table's horizontal excitation movement. On the basis of analysis the clasification of vibrations of the frame according to earthquake Modified Intensity Mercalli scale is performed. Discussion on effectivennes of friction pendulum depending on concave radius of the friction pendulum bearing and its friction coefficient is performed. From the step 4.5 the influence of the friction pendulum bearing is observed, while the large accelerations of the table base, there are small accelerations of the frame structure.

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