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Proposal of a tuned mass damper with friction damping to control excessive floor vibrations

Jorge Eliecer Campuzano Carmona [a], Suzana Moreira Avila [b,*], Graciela Doz [a]

[a] Department of Civil Engineering, University of Brasilia, Brasilia, Brazil
[b] Gama Engineering College, University of Brasilia, Brasilia, Brazil

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ABSTRACT

A numerical and experimental study is carried out for a tuned mass damper (TMD) to control excessive floor vibrations. To verify the performance of this control device, free and forced vibration experiments were performed on the platform for dynamic tests located at the University of Brasilia Structure Laboratory. The platform and the TMD were previously modeled via the finite element method using ANSYS software for harmonic and transient analysis, varying damper parameters to find design values for TMD mass, damping and stiffness. The control device was constructed so that it could be installed above the platform. Experimental tests were performed on the platform by people doing rhythmic activities of continuous jumping, walking randomly and synchronized movements with semi bended knees. The results of the tests verified the reduction of the response acceleration of the structure with TMD installation. This control system is of simple construction and maintenance, and has a low manufacturing cost.

1. Introduction

Design of most modern buildings considers dead and live loads, since these loadings always act on constructions. Load magnitudes can be easily determined from dimensions of structural elements, material characteristics, and occupancy needs. Another type of loading that has to be taken into account is dynamic excitations. For example, design of structures subjected to excitations from human activities, such as running, jumping and dancing, should consider these loadings. Modern structures are increasingly more slender, flexible, with higher spans having ever lower natural vibration frequencies. More flexible structures imply higher amplitude vibrations that are transmitted to people that use these spaces, causing discomfort and interference in human activities, for example, damaging vision and inhibiting the movement of hands and feet.

In cases of strong vibrations, changes can occur in physiological functions such as increased heart rate, neuromuscular disorders, cardiovascular, respiratory, endocrine and metabolic disorders, sensory disturbance and the central nervous system; they can also cause risk of spinal cord injuries [1]. It is important to know that these vibrations rarely affect the safety of the structure and are therefore usually treated as a serviceability problem [2]. Movements of the human body when performing rhythmic movements, such as walking, running, jumping and dancing, cause some of the common problems that show up in structures due to severe vertical vibrations. Induced vibration caused by moving people can interfere with the operation of constructions. Examples of structures that are subjected to vibrations caused by people practicing some sort of rhythmic activity are footbridges, stairs, floors and buildings, stadiums, etc. [3].

To solve this kind of problem for structures such as offices, shopping areas, gyms, dance studios, laboratories, theatres and walkways, structural control devices such as tuned mass dampers (TMD) [4–6] can be used.

Tuned mass dampers (TMD) reduce energy dissipation of structural members subjected to dynamic loads. This reduction occurs because part of the energy is transferred to the TMD, a spring mass damper system that vibrates out of phase with the main structure. It is one of the oldest devices of structural control, proposed for the first time by Frahm in 1909 [7]. Later, Den Hartog [8] published a more detailed study on this subject. In the beginning the use of TMD was limited to mechanical engineering systems. It was in the 60s that it became common on civil engineering applications such as high buildings, bridges, towers and industrial chimneys. Another successful application of this device is the installation of TMDs in building floors for improved comfort by reducing

* Corresponding author.
E-mail address: avilas@unb.br (S.M. Avila).

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excessive man-induced vibrations. Following are some studies among others in the literature that concern vibration control in building floors using TMD:

Allen and Pernica [9] developed a dynamic absorber to reduce the vibrations of floors with large spans. The authors used an experimental platform, where they performed studies to compare the graphical response curves of the structure with and without the dynamic absorber. From these charts they provided rules and formulas to guide the construction of floor absorbers with optimal parameters.

Webster and Vaicaitis [10] successfully implemented multiple TMD to reduce the vibrations of a mixed steel-concrete slab in a restaurant in the Terrace on the Park Building, located in the city of New York. The vibrations were produced by people who danced, and they caused discomfort to the occupants. To reduce the vibrations, multiple TMD were installed at the tip of a cantilever beam, one of the points of greater amplitudes of vibration, achieving a vibration reduction of up to 60%.

Setareh and Hanson [11] implemented a multiple tuned mass damper (MTMD) system to mitigate the vibrations of a theater box in the city of Detroit, Michigan, which featured live concerts.

Al-Hulwah et al. [12] have studied a scale model of a typical office floor with uncomfortable vibrations. The objective of making this model in a laboratory is to verify the effectiveness of a damper mechanism proposed by the authors.

Varela and Battista [13] designed a dynamic tuned absorber for an experimental platform located in the Laboratory of Structures of the Federal University of Rio de Janeiro, Brazil. A system consisting of two absorbers was installed in the center of the slab. The system was calibrated to attenuate the vibrations of the first mode of the structure, which is the one that presents the greatest amplitudes of responses when the structure is excited by people. From experimental studies it can be concluded that the absorbers greatly reduced the amplitude of vibrations of the structure, and therefore, they are efficient.

Saidi [14] developed a TMD in a simple and low cost way, to solve floor systems with uncomfortable vibrations. The damper consists of a sandwich-type cantilever beam of two different materials, limited at the top and bottom with steel and inside with a viscoelastic rubber. The advantage of this type of device is that it can be installed in false roof spaces.

Picauly [15] used a concrete slab 4 m long, 0.90 m wide and 0.08 m thick to test a type of TMD of two degrees of freedom with an additional plate metal absorber with an X shape.

In practical construction, there are problems well solved using control devices. In the case of Millennium Footbridge in London where due to strong lateral vibrations [16], people-induced vibrations caused closure shortly after the bridge's inauguration. During the following 18 months, the construction company spent 7 million dollars developing a passive damper system destined to control excessive vibrations [17].

Another example is the luxury hotel "Marina Bay Sands" located in the city of Singapore. The hotel structure is composed of 3 towers of 200 m height and 55 floors each. On the north tower, a cantilever slab of 65 m supports a garden. Strong undesirable vertical vibrations caused by wind loads and pedestrian movement were present. To solve this problem, a TMD tuned with a 6000 kg mass, resonant frequency of 1.047 Hz and damping of 3978 Ns/m [5] was designed. In Brazil, Morumbi Stadium in São Paulo, where TMDs were installed, deserves to be mentioned. The passive control system was installed in 1998 and 2000 after a study showed great displacements in the grandstands during soccer games. During games accelerations of up to 9% of acceleration of gravity were observed that exceed the acceptable maximum values of 4% and 7%, according to the international standard setting service National Building Code of Canada. The installed dampers were tuned on the three first natural frequencies of the stadium, and with this solution reductions of vibration amplitudes were verified [18].

The aim of this work is to design and build a TMD in which the damping mechanism is from friction. Numerical analysis was performed by the finite element method using ANSYS software [19]. The TMD was installed on a dynamic platform that has low natural frequencies and excessive vibration caused only by people walking. This platform is located at the Structures Laboratory of the University of Brasilia. As a way to reduce amplitude vibrations when a platform is excited by human activities such as walking or jumping, a passive control device is proposed that can be used in commercial buildings to reduce excessive vibrations caused by rhythmic activities of people.

2. Experimental dynamic platform

The dynamic platform considered in this paper consists of a concrete slab with two semi-rigid edges and two free edges. Constructed and placed in the Structures Laboratory of the University of Brasilia, the platform, shown on Fig. 1, has a length of 6.1 m, a width of 4.9 m and a thickness of 0.1 m, with the compressive strength of 25 MPa and elastic modulus of 29 GPa. These dimensions were set up so that fundamental natural frequency of the structure was in the frequency range of human induced vibrations. It exhibits strong vertical vibrations when it is excited by jumping, dancing and other aerobic activities [20].

After construction the slab of the platform had various fissures. This can be explained by the retraction that occurs when concrete dries. The numerical model considering these fissures was dynamically analyzed by performing harmonic and transient analysis using the "Full Method" option of ANSYS software [19].

The finite element types adopted to better simulate structural response was SHELL63 for the platform and COMBIN40 for the TMD. Modal analysis provided natural frequencies and associated modes, the three first frequencies were 3.36 Hz, 15.67 Hz and 23.64 Hz, the three correspondent modes are shown from Figs. 2–4.

2.1. TMD linked to the platform – study 1

In the design of a TMD, the first step is to tune the device, setting its parameters of mass, damping and stiffness. This work performs a parametric analysis, starting the parameter values from those suggested in the literature [8]; parameters of mass, stiffness and damping coefficients are varied trying to reduce peak frequency responses. It is also important to set the number

Fig. 1. Dynamic Platform of Structures Laboratory of University of Brasilia.