Experimental Investigation on Structural Vibrations by a New Shaking Table

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Abstract. In this research work, our goal is to test vibration mitigation and seismic devices for slender parametric structures subject to winds, seismic induced vibrations, and vehicular traffic. The obtained results will allow us to extend this experimental approach to other and more complex structures, such as long-span bridges. Our test-rig consists of a shaking table (designed in our labs) capable of supporting different types of structures. We designed a tuned liquid damper (TLD) with the purpose of mitigating vibrations in a vertical irregular three-story structure. We used aluminum bars for the modeling the stories and harmonic steel bars for the beams. For the shaking table, we used a solid block of aluminum weighing around 130 kg. On both sides of the frame, there are Hiwin guides, with two carriages each, on which we mounted a sled made of bosh profiles. We actuate the vibrating table with an electrodynamic shaker of Brüel & Kjær. The wave generator Textronix Arbitrary Function Generator AFG320 generates the signal and the power amplifier Brüel & Kjær - Type 2732 amplifies the signal. On each floor of the structure, we installed Brüel & Kjær Type 4371 accelerometers for acquiring the acceleration time history of the structure. We created a 3 degrees of freedom (DoF) lumped-mass model for evaluating the natural frequencies of the system and validated these data by a hammer impact test. We were able to set the sloshing frequency of the TLD by using the equation proposed by Housner. We studied the structure by positioning the TLD on each floor, at the same input frequency. Our results demonstrate the excellent capability of an appropriately sized TLD to mitigate vibrations under resonance conditions.

Keywords: Vibration mitigation · Structural design · Tuned Liquid Dampers · Dynamic absorber · Modal testing

1 Introduction

Experimental investigation of structural dynamics allows us to understand and control many vibrational phenomena that occur in real life [1]. The problem of structural vibrations continues to represent a significant risk for the design of structures with innovative design. Structural integrity is of primary importance,

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thus a more precise knowledge of the dynamic characteristics is required [2,3]. Vibration levels are directly related to the structure's performance. Specifically, excessive motion is known to cause temporary structure malfunctions and provoke discomfort. The Millennium Footbridge in London represents a clear example of wrong assessment opened in June 2000 and closed immediately after because of the alarming swaying due to self-excitation caused by the enormous flow of pedestrians [4].

It is possible to anticipate the vibration levels before service during the design phase. The vibration effects of a machine or a structure, can be evaluated by two main techniques: (1) by measuring the response of the system under analysis during operation; (2) by exciting the system with a known law in strictly monitored and specific setup. This second study is called Modal Testing. Taken together, a deeper understanding of the phenomena of vibration propagation, will provide and improve the development of effective mitigating methods. For example, the development of specific mechanical connections can mitigate the vibrations that propagate inside the structure more efficiently than others [5]. A multitude of passive vibration isolators is available on the market, using unique mechanisms and material connections, capable of attenuating and absorbing unwanted mechanical waves.

In the study of vibrations in structures, natural frequencies of the system assume a fundamental role [6]. Energy is transferred more efficiently for frequencies close to natural frequencies, to a lesser extent for frequencies lower than the natural frequency and with a decreasing efficiency for frequency values higher than the natural frequency. In the field of vibration mitigation, the transmissibility curves allow evaluating the goodness of the isolation system measuring the ratio between the response of the system, respect to the exciting source. The behavior of a typical passive mitigation system with negative rigidity shows, at a lower frequency levels, a transmissibility value close to the unit. At the resonance frequency, the energy is efficiently transmitted, and the incoming vibration is amplified [7–9]. Dampers play a key role in containing such amplification. Above the resonance frequency level, instead, little energy can be transferred, and the curve returns values lower than one [10,11]. A passive isolator can therefore be seen as a mechanical low-pass filter for vibrations. Among the different kinds of devices, the use of Tuned Liquid Dampers or TLD, represent a successful alternative for reducing vibrations in structures [12,13]. Furthermore, due to their easy installation, low maintenance, and excellent performance, TLDs have been employed on a large scale for vibration mitigation in structures [14]. The operating mechanism of such mitigators uses the sloshing energy of the water confined in a tank to reduce the dynamic response of the system when subjected to excitation [15,16]. The intrinsic friction of the liquid, its boundary layer friction, and wave breakage, dissipates the applied external energy. The tuned liquid inside the tank provides an anti-phase inertial force to the structure, resulting in a reduced vibration [17,18].

Other studies have already identified ways to make the conventional TLDs more efficient. Zhao and Fuhino, for example, used metal compartments for augmenting the damping of water sloshing while attenuating non-linearities of fluid motion [19]. Cassolato et al. instead, proposed the usage of inclined screens for modifying the damping ratio [20]. It was also found that, for a wide range of excitation amplitudes, the new TLD could maintain constant damping ratio [21–23]. Ruiz et al. [24], instead, proposed a new type of TLD with a floating roof, able to prevent wave breaking during the sloshing of the water, and therefore leading to a linear response even for high excitation amplitude [25,26]. In the majority of applications, the first natural frequency of structures is used for synchronizing the sloshing frequency. In regular structures, the first mode of vibration represents the main contribution to the dynamic responses. This not valid for irregular structures, were higher mode shapes often play a significant role in the dynamic behavior [27–29]. In this work, design a new test-rig for vibration mitigation activities for testing the behavior of irregular structures for several kinds of devices. This approach allowed us to investigate the dynamic behavior of parametric structures by modifying their configuration [30,31]. Specifically, we report the design and development of our new test-rig and our first experimental investigation conducted for testing the efficiency of conventional TLDs. We chose such a device, for its easy installation and maintenance, and reduced cost. We used a one-bay three-story scaled steel structure, representing a vertically irregular building. This structure was then subjected to free and forced vibration tests with and without the presence of TLDs [32,33]. For this study, we tested different arrangements of conventional TLD on the test structure by using the equation proposed by Housner [34]. As for the structure of this manuscript, in Sect. 2 we describe the design and the development of the test-rig and the following experimental application. In Sect. 3 we report the results and in the final sections our conclusions.

2 Materials and Methods

One of the drawbacks that can occur during an experimental campaign is the coupling of one or more frequencies of the structure with those of the vibrating table [35]. To avoid this, we analyzed the natural frequencies of the structure before assembling it. We analyzed a lumped-mass model, and modeled the structure in the 3D Solidworks modeling environment. We then performed a modal analysis in the ANSYS Workbench finite element calculation software, and finally, to validate the results obtained, we performed a hammer impact test [36,37].

2.1 The Test-Rig

The frame of the shaking table is made of aluminum and weighs about 130 kg. Two Hiwin guides are installed on the frame allowing the sliding of the sleigh on which we installed the structure. In order to achieve passive insulation, we placed anti-vibration feet under the shaking table [38–41]. The purpose of our test-rig was to avoid possible coupling between the vibrating table and the structure under analysis. For modeling the structure used for the experimental analysis reported in this paper, we used Bosh profiles and harmonic steel bars. The profiles are made of aluminum with a section of $45 \times 45\,\text{mm}^2$, ensuring high rigidity. For the pillars, we used harmonic steel bars. This material has remarkable elastic properties that do not compromise the total stiffness of the component, thus ensuring excellent flexibility. In order to give an irregular shape to the structure, we used bars of equal length for the pillars connecting the base and the first floor, whereas longer bars were used between the first and second floors.

In Fig. 1, we report the essential laboratory equipment used for a shaker modal testing activity. The devices used are the following:

- Wave generator (Textronix Arbitrary Function Generator AFG320);
- Oscilloscope (Textronix TDS3014B);
- Power Amplifier (Brüel & Kjær – Type 2732);
- Shaker (Brüel & Kjær Modal Exciter – Type 4824);
- Accelerometers Type 4371 Brüel & Kjær.

The Textronix wave generator is used to create the signal to be sent to the amplifier to drive the shaker. Two output channels allow to view the signal on a oscilloscope and send it to the amplifier.

The Textronix TDS3014B oscilloscope is an electronic measuring instrument that allows visualizing, on a two-dimensional graph, the trend in the time domain of electrical signals. This instrument displays measurements of direct voltage reading (represented on the vertical axis) and period (with time represented on the horizontal axis). A vital function implemented through the application module TDS3FFT, is the *Fast Fourier Transform (FFT)*. The FFT shows the signal spectrum by converting the signal from the time domain to the frequency domain.

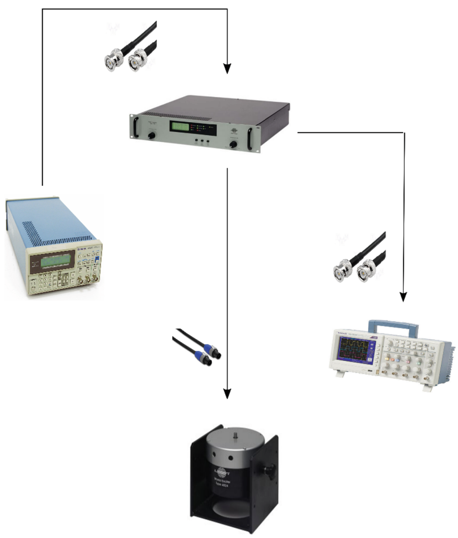


Fig. 1. Laboratory equipment used for the shaker modal testing

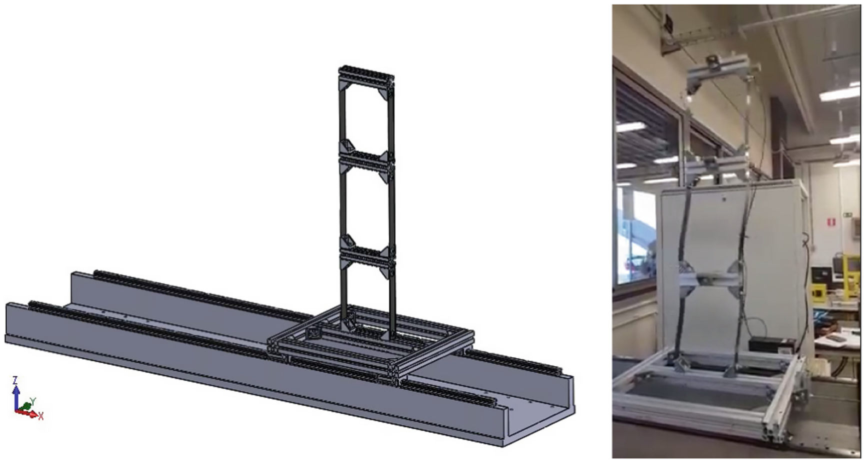
The Brüel & Kjær - Type 2732,122/5000 power amplifier, is a device that allows to amplify the signal coming from the generator in amplitude and transmits it to the shaker.

For the data acquisition instead, we used the signal analyzer 2825, connected to a computer with PULSE Labshop v.4.2. The sensitivities of the input signals must be set, together with the acquisition time, the sampling frequency and the offset function. In this way it is possible to set the measured signal in order to make the average noise value tend to zero.

The behavior of the structure is measured by piezoelectric transducers (accelerometers), positioned laterally to the structure, in correspondence of each floor. The details of the three single-axial accelerometers used for the experimental activity are specified below:

- 2 Type 4371 Brüel & Kjær with sensibility 1,01 (pC/(m/s2)) connected to the Brüel & Kjær Change Amplifier Type 2635 which is set in such a way that at each 1,01 (pC/(m/s2)) in input it gives 10 (mV/(m/s2)).
- Brüel & Kjær Type 4379 with higher sensibility 31.79 (pC/(m/s2)) with head and side connectors, for low vibration measurements. The signal is sent to Nexus Charge Amplifier Type 2692 of Brüel & Kjær which is set up so as to transform the signal from 31, 79 (pC/N) to 100 (mV/N) and then send it to the signal analyzer type 2825 of Brüel & Kjær.

Once we developed the vibrating table and the structure to test, we passed to the final assembly. We rigidly connected the structure to the slide and installed the accelerometers on each floor. The shaker, instead, installed on the shaking table, was rigidly connected by a threaded bar to the slide. Figure 2(a) shows



(a) Solidworks 3D model (b) The test-rig.

Fig. 2. Concept design and developed test-rig for vibration mitigation activities

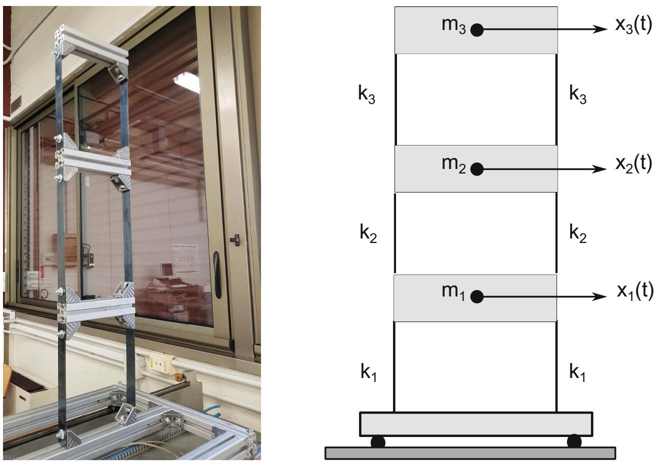
the concept, in an initial phase, reproduced in the 3D Solidworks modeling environment, while in Fig. 2(b), we report the real test-rig during an experimental campaign. For defining the final design of the table, it was necessary to make sure that the frequencies of the analyzed structures were different from the frequencies of the vibrating table itself. For this reason, we carried out a numerical analysis for estimating the natural frequencies considering a lumped-mass model and a finite element model. The results obtained were then validated by a modal analysis activity using an instrumented hammer.

2.2 The Mathematical Model

The mass and the stiffness of the system (see Fig. 3(a)), are key factors for the evaluation of the natural frequencies of the system. For this purpose, we developed the lumped-mass model reported in Fig. 3(b). The values of the three masses are not equal. This is due to the connecting element used for every storey. The values are for the first mass $m_1 = 0.890\,\mathrm{kg}$, for the second mass $m_2 = 0.951\,\mathrm{kg}$ and for the third mass $m_3 = 1.115\,\mathrm{kg}$. We used the formula reported in (1) for evaluating the real stiffness of the individual harmonic steel bars:

$$k_i = 12\frac{EI}{L^3} \tag{1}$$

with E Young's modulus for harmonic steel equal to $206\,\mathrm{kN/mm^2}$, I is the moment of inertia of the rectangular section of the pillars equal to $2.917 \times 10^{-12}\,\mathrm{m}^4$ and L_i are the length of the three pillars: L_1 and L_3 equal to $0.205\,\mathrm{m}$ while L_2 is equal to $0.255\,\mathrm{m}$. The calculated values of stiffness coefficients are $1682\,\mathrm{N/m}$ for k_1 and k_3 while for k_2 the stiffness coefficient is equal to $874\,\mathrm{N/m}$.



(a) The structure (b) The lumped-mass model

Fig. 3. The three-storey structure and the mechanical scheme

Table 1. Natural frequencies of the Three-DOF structure.

	Lumped - mass model	Modal analysis
$f_{n,1}$	2.05	1.95
$f_{n,2}$	6.23	5.97
$f_{n,3}$	8.23	8.03

To further compare the results obtained, we performed a modal analysis using the Ansys Workbench finite element simulator. This software allowed us to evaluate the first three frequencies of the system, by using a 3D CAD model of the structure. All the bodies were considered flexible for this analysis.

In Table 1, we report the values of the natural frequencies determined by using the lumped-mass model and the finite element model. To validate these values, we resorted to the real structure through the hammer impact test. In Fig. 4, we report the FFT signal of the acceleration signal. Once we identified the different frequencies in our system, specifically that frequencies of the vibrating table were indeed higher than our structure's, it was possible to design the tuned liquid damper for the experimental investigation. We used the first natural frequency of the three-story structure for tuning the TLD [42,43]. For this experiment, we considered two cases: the TLD installed on the first and second floor, respectively. The mass ratio (i.e., the mass of liquid respect to the mass of the structure) for

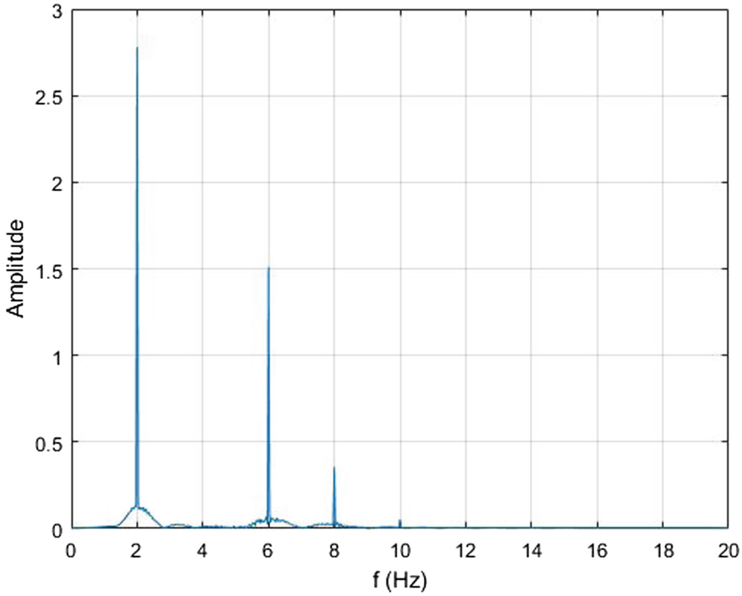


Fig. 4. FFT result for the recorded time history of acceleration on the third floor.

the two cases was set at 33.3%. Previous studies conducted on TLDs propose a mass ratio range of 10–25% [44–46]. In our study, such a ratio is higher, in order to increase the effectiveness of TLDs. We used the equation proposed by Housner for determining the sloshing frequencies of TLD. Such relation is reported in (2).

$$f_{n,liquid} = 12\sqrt{\frac{3.16g}{L}\tanh\left(\frac{3.16H}{L}\right)} \tag{2}$$

Taking into account the hypothesis of shallow waters ($HL \neq 0.15$), in Fig. 5, we report the final dimensions of the tuned liquid damper and the water level.

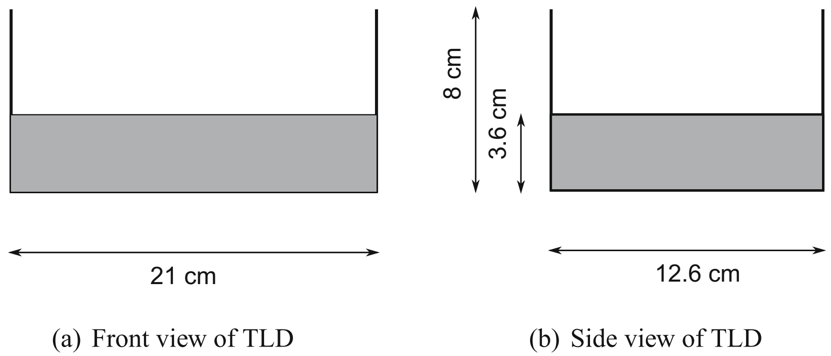


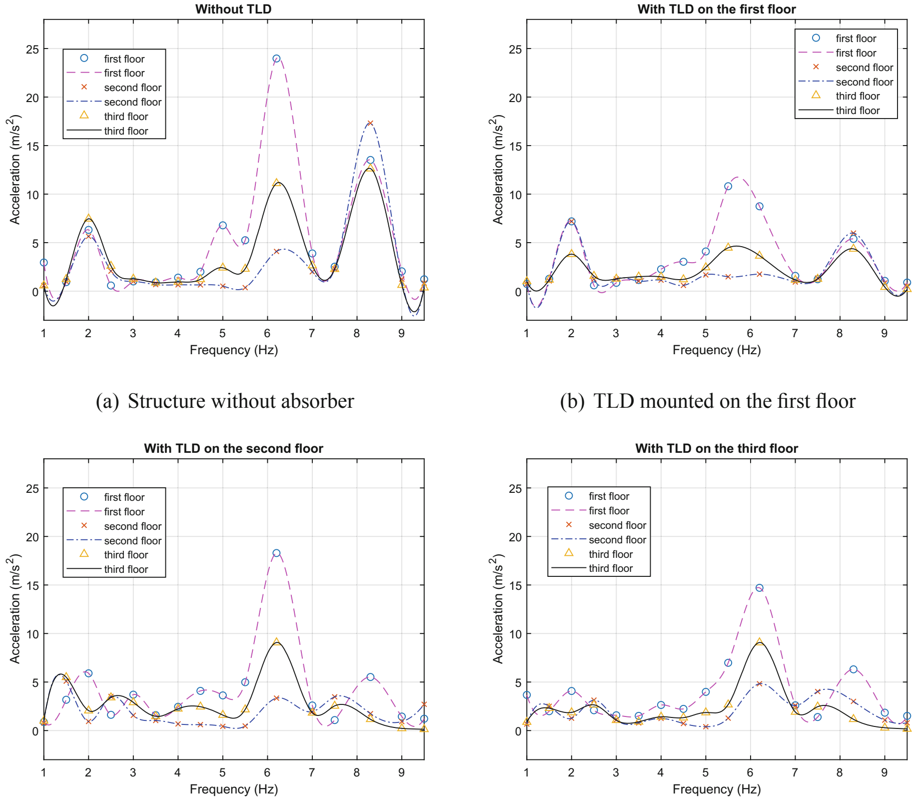
Fig. 5. Dimensions of the constructed TLD

3 Results

Our goal for this work was to verify the effectiveness of a TLD device when mounted on different floors (or levels) of a structure. In Fig. 6, we report the acceleration response of the structure with and without the TLD, for a frequency range from 1 Hz to 9.5 Hz. In this graph, we compare the peak acceleration values measured by the three accelerometers. The values are indicated in the graph by a circle for the first-floor acceleration, by a cross for the acceleration of the second floor and with a triangle for the acceleration of the third-floor.

In particular, Fig. 6(a) shows the maximum accelerations in the absence of TLD. As it is possible to notice from the graph, the accelerations recorded at the natural frequencies of the system are relevant. In particular, for the first natural frequency, the higher acceleration is recorded on the third floor, for the second natural frequency the more significant acceleration is recorded on the first floor while for the third natural frequency is the second floor the one most stressed.

In Fig. 6(b) instead, it is possible to notice that for the first natural frequency, we record a considerable reduction in the acceleration of the third floor compared to the first and second floors. Moreover, the accelerations of the first and second floors have the same amplitude. For the second natural frequency, we see a reduction of about 50% of all the accelerations (see Fig. 6(a)), while for the third frequency we notice a reduction of about 60% for the accelerations of the three floors.



(a) Structure without absorber

(b) TLD mounted on the first floor

(c) TLD mounted on the second

(d) TLD mounted on the third floor

Fig. 6. Acceleration response of the structure in time domain.

By placing the TLD on the second floor of the structure (see Fig. 6(c)), the accelerations of the second and third floors are strongly reduced while the acceleration of the first floor was minimally reduced. Also, for the second natural frequency, there is a reduction of the three accelerations but to a limited extent. For the third frequency, on the other hand, we saw a significant reduction in the accelerations for the second and third floors. While the first floor acceleration was reduced by 50%.

In the last graph shown in Fig. 6(d), the TLD was mounted on the third floor. With this setup, we were able to determine a substantial reduction in accelerations in all three floors, but especially on the first floor. There is also an essential reduction for the second frequency on the first floor. On the other hand, a considerable reduction occurs for the third natural frequency in which we recorded a rather smooth behavior for all the acceleration values of the various floors.

Out test results demonstrate that mounting the TLD on the first floor of a structure, results in a more effective reduction in peak response of the second and third natural frequencies [51]. These conclusions indeed fit nicely with previously published results.

4 Conclusions

The design and construction of our vibrating table is part of a research project that aims to develop active and passive devices for the mitigation of seismic risk [47–50]. In this first application, we decided to test liquid absorbers to mitigate vibrations in the structures. After the design and assembly of the vibrating table and our model structure, we estimated and validated the natural frequencies of the system under examination. This information was necessary to assess that the natural frequencies of the structure and the shaking table were not in the same range of frequencies. We were also able to tune the liquid damper to the first natural frequency of the structure. We specifically designed and built a three-story aluminum and steel structure weighing about 3 kg in order to represent a three-story irregular building. We subjected the structure to free and forced vibration tests, and we extracted natural frequencies. We equipped the test structure with a TLD tuned to the first resonance frequency. For the TLD, the mass ratio used to size the device was equal to 33.3%. We studied the response of the structure by placing the TLD on each floor separately. The experimental results demonstrate the excellent ability of a TLD to mitigate vibrations in resonance conditions when adequately dimensioned.

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