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Tuned mass dampers - evaluation of the effect on two real footbridges

Radim Nečas[1] | Jiří Kučera[2] | Jan Koláček[1] | Kristína Bezručová[1]

Correspondence

Ing. Jiří Kučera
KGF hydraulika
Bohunická 1a/743
CZ-619 00 Brno, Czech Republic
Email: michaela.kucerova@kgf.cz

[1] Brno University of Technology BUT, Faculty of Civil Engineering, Brno, Czech Republic
[2] KGF hydraulika, Brno, Czech Republic

Abstract

Pedestrian comfort, subtle design, minimizing the number of fixed supports of the footbridge or material saving. These are the key arguments for integrating tuned mass dampers into the bridge project. The goal is to protect people and structure from vibrations and damage. The following paper presents findings from the design, production and tuning of mass dampers, their optimization possibilities and benefits for bridge engineering. The validity of damper design was verified on two footbridges in the Czech Republic and Slovakia. It concerns the footbridge over the Svitava River in Bílovice nad Svitavou and the footbridge over the high-speed road in Banská Bystrica. Dynamic tests including measurement were carried out on both bridges before and after the installation of the dampers. The dynamic monitoring of the compliance of modal parameters was conducted using operational modal analysis (OMA). The evaluation of the dynamic tests also includes the response to pedestrian effects (comfort criteria) and the determination of the logarithmic decrement of the damping.

Keywords

Tuned mass damper, pedestrian bridge, dynamic analysis, Operational Modal Analysis, OMA

1 Introduction

Structures such as bridges, footbridges, skyscrapers, antennas and stadiums can be susceptible to vibrations caused by wind, traffic, people or earthquakes for two main reasons. They have rather low natural frequencies in combination with a very low inherent damping ratio (less than 1 %). Without additional damping measures, undesirable situations with large amplitude vibrations may arise. One possible solution is to install vibration dampers. This paper focuses on the damping of bridge structures, especially pedestrian bridges, by tuned mass dampers. The introduction describes the possible vibration directions of the structure in relation to the type of vibration damper and outlines the principles and differences between viscous and tuned mass dampers. The effect of the tuned mass dampers on the dynamic response of the structure is demonstrated by two case studies including measurement evaluation using OMA [6]. The publication is the result of a long-term cooperation between the Faculty of Civil Engineering (BUT) and the company KGF hydraulika in the field of high-pressure hydraulics and especially in the analysis of dynamic response of bridge structures, optimisation and tuning of mass dampers.

2 Vibration damping of footbridges

2.1 Vibration in bridge structure

Footbridges, suspension bridges, cable-stayed bridges or long-span bridges are often designed as slender, subtle structures, both for architectural and material reasons and to minimise the number of fixed supports. However, these structures can be prone to dynamic forces induced by pedestrians, cyclists or wind [2]. Each structure is characterised by its own natural frequencies and shapes of vibration, which depend on its mass and stiffness. Slender bridge structures typically have low natural frequencies, which tend to be close to the frequency of the excitation forces, especially from pedestrians [1]. The most common construction materials for pedestrian bridges are concrete, steel or UHPC. Steel footbridges in particular are characterised by low inherent damping (typical damping ratio for steel is 0,4 %, for concrete around 1 %).

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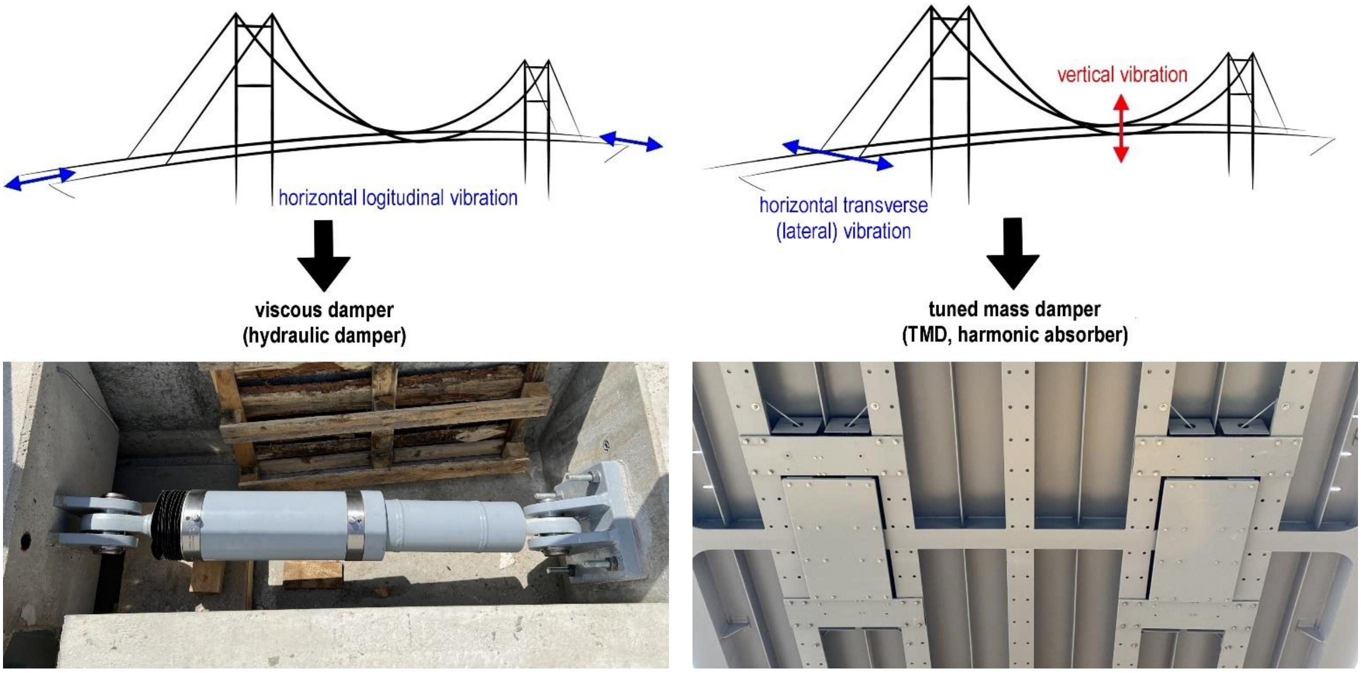

Figure 1 Relationship between the direction of vibration and the type of damper (Kučera, Nečas, 2023)

If the frequency of the excitation force resonates with one of the natural frequencies of the structure with low inherent damping, the amplitude of the vibrations can reach unacceptable values, especially in terms of pedestrian comfort or even fatigue damage to the structure.

The bridge structure can vibrate under variable loads in several directions. In terms of damping, it is useful to distinguish between the following global directions:

- horizontal longitudinal vibration (x),
- horizontal transverse (bending) vibration (y),
- vertical (bending) vibration (z) and
- torsional vibration (around the x axis).

The vibration damping of the structure can be improved in any direction by using a suitable vibration damper [3]. The most important factor in selecting a suitable type of damper is the direction of vibration. The relationship between the direction of vibration and the type of damper is shown in Fig. 1.

2.2 Viscous damper vs. tuned mass damper

Based on the direction of vibration of the structure and taking into account other technical parameters of the specific project, a suitable variant of two different types of dampers is selected:

- viscous damper - hydraulic damper and
- tuned mass damper - TMD, harmonic absorber.

Viscous dampers are suitable for fixing the bridge in the longitudinal direction, as they limit rapid movements caused e.g. by wind or variable loads from pedestrians and cyclists, but at the same time allow slow movements of the bridge deck e.g. due to thermal dilatation (Fig. 1 left). This type of damper is designed as a hydraulic cylinder with equal effective area on both sides of the piston. Viscous dampers are usually located between the bridge deck and the pier.

Tuned mass dampers (TMD) absorb vertical or horizontal transverse vibrations of the bridge deck without the need to react to a fixed support (Fig. 1 right). In principle, the damper is designed as a moving mass, typically 4-6 % of the bridge mass, mounted on springs with a precisely defined stiffness. Parallel to the springs is a hydraulic damping element to dissipate the energy of the vibrations. Tuned mass dampers are located at the points on the bridge deck where the vibration amplitude of the natural frequency is at a maximum.

The use of tuned mass dampers and viscous dampers significantly reduces the vibrations of the footbridge, thereby increasing the comfort of pedestrians and cyclists. The bridge complies with the permissible vibration limits according to the relevant standards, in particular ČSN 73 6209 [5] or Technical Guide for the Design of Footbridges published by Sétra [4].

KGF viscous dampers have been installed in the Czech Republic and Slovakia, e.g. in the footbridge to Strakonice Castle, the bicycle bridge over the Labe River in Čelákovice or the footbridge over the Bečva River near Ústí. Tuned mass dampers have been used, for example, in the footbridge over the Jizera River in Mladá Boleslav, or in Prague in the new Troja footbridge and, from summer 2023, in the Štvanice footbridge. The following part of the paper will focus on the use of tuned mass dampers (TMD) in practice.

2.3 Tuned mass damper: design, manufacturing and installation process

The number of dampers on the bridge and their technical parameters, such as tuned mass or spring stiffness, are designed on the basis of a static and dynamic calculation of the bridge project [1]. The design of the damper, its fixing to the structure and position on the footbridge are agreed between the manufacturer and the bridge designer. The final components are produced and tuned to the required frequency based on the results of the first dynamic test, which is carried out after bridge construction is completed.

This is followed by the installation of the dampers on site. An optional second dynamic test usually verifies the effectiveness of the damping and also provides an opportunity to fine-tune the dampers.

2.4 Effect of tuned mass dampers on the dynamic response of the structure

For a bridge structure equipped with tuned mass dampers, the modal parameters change. The influence of the damper on the dynamic response of the structure is essential to meet the comfort criteria, most often the limiting acceleration when people use the footbridge.

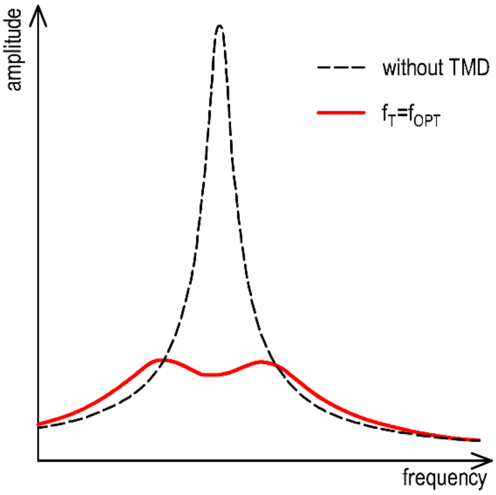

Figure 2 Effect of an optimally tuned damper on the vibration of the bridge structure

However, the influence of the damper can also be found in other properties. The damper absorbs all the natural frequencies of the structure to some extent, but it is most sensitive to the frequency range around the natural frequency of the damper itself. There are also changes in the logarithmic damping of the structure. Optimally tuned dampers reduce the oscillation of the structure several times.

A comparison of the oscillation of a structure without and with dampers is shown in Fig. 2. The figure shows fourfold reduction in the amplitude of the vibration.

The shape of the frequency dependence of the deflection or acceleration can be used to assess whether the damper is optimally tuned in terms of frequency and damping (symmetrical reduction of the maximum amplitude). If this is not the case, the damper can be tuned (Fig. 3). Symmetry can be achieved by slightly changing the damper stiffness (natural frequency). Smoothing of the amplitude is then achieved by increasing the efficiency of the damper's damping element.

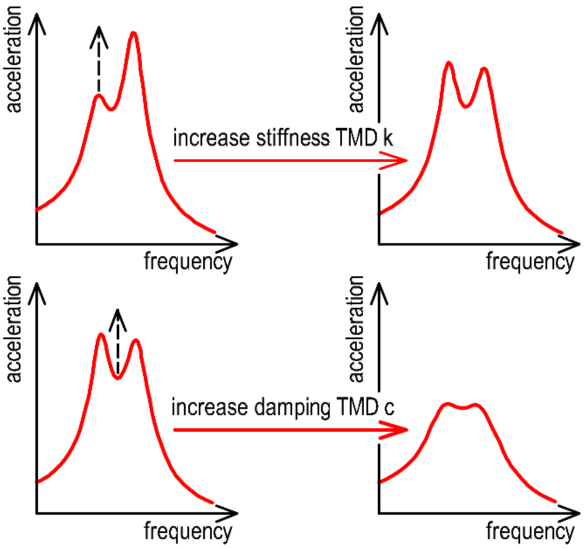

Figure 3 Tuning scheme of a suboptimally tuned damper

3 Real application of tuned mass dampers in bridge structures

3.1 Description of the measured bridge structures

The initial bridge under evaluation is situated in Bílovice nad Svitavou, Czech Republic. It crosses the Svitava River and connects the municipal centre with the Fügner embankment. It is a single-span pedestrian bridge with a span of 33,2 m (Fig. 4).

Figure 4 Footbridge over the Svitava River in Bílovice nad Svitavou, Czech Republic, equipped with a tuned mass damper KGF (Nečas, 2023)

Figure 5 Bicycle bridge over the R1 expressway in Banská Bystrica, Slovakia (Ingsteel, 2024)

The footbridge is designed as a steel parapet beam of variable height with a one-sided inclination towards the left bank abutment. The wooden floor of the bridge deck rests on steel stringers welded to steel cross girders. The cross girders are connected to the main girders at an axial distance of 2,0 m by rigid girders, which also provide the transverse stiffening of the footbridge (Vierendeel truss). On the left bank, the supporting structure is interwoven into a concrete massive weighted abutment with concrete parapet walls, while on the right bank it is supported by elastomeric bearings on a concrete abutment. The footbridge is deeply founded on micropiles.

The second measured bridge is located on the southern outskirts of Banská Bystrica, Slovakia (Fig. 5). It bridges the R1 expressway, the Zvolen road (I/69) at the junction and connects to the Hušťák - Kráľová urban cycle route. The bicycle bridge is designed as a suspension bridge with an inclined pylon and suspensions placed along the outer edge of the main span. The individual spans of the footbridge are 3,060 + 24,686 + 22,899 + 76,300 + 22,264 + 24,686 + 13,060 m. In the transverse direction, the structural system consists of a twin-box girder in the shape of an irregular trapezoid with a height of 0,75 m, which basically consists of an upper flange, a horizontal lower flange, inclined walls and a vertical wall dividing the box girder into two cells. The lower substructure consists of two abutments, two hinge blocks, a pylon foundation and six piers. The footbridge foundation is deep on large diameter piles. Permanent ground anchors are added to the anchor blocks of the foundation. Both footbridges were designed by the Czech bridge engineering company Link projekt.

3.2 Parameters of the installed tuned mass dampers

Based on the proposal of the bridge designer the damper manufacturer (KGF hydraulika, Czech Republic) installed vertical tuned mass dampers on both bridges. One damper was installed on the pedestrian bridge in Bílovice nad Svitavou (Czechia) and two dampers on the bicycle bridge in Banská Bystrica (SK).

Table 1 Technical parameters of the tuned mass dampers

TMD	**Bílovice nad Svitavou (CZ)**	**Banská Bystrica (SK)**
# of TMDs	1	2
Oscillating mass (kg)	350	1000
Total weight (kg)	440	1280
Natural frequencies (Hz)	2,93	1,706
Spring constant (kN·m^{-1})	118,72	115,0
Damping constant (kN·s·m^{-1})	0,99	2,25
Dimensions (mm)	1800x1000x163	1446x860x265

The dampers are integrated into the bridge deck in such a way that they do not interfere with the architectural design of the bridge (Fig. 4 and Fig. 6). The technical parameters of dampers are shown in Tab. 1. The manufacture of some components and the tuning of the dampers were determined by first dynamic measurement using OMA (operational modal analysis) [6] on the bridge after completion of the construction. The correct operation of the dampers was verified by a second dynamic measurement after the dampers were installed.

Figure 6 Placement of the TMD KGF in the bridge deck (Kučera, 2023)

3.3 Results of the dynamic measurements

The installation of the vibration damper in both described footbridge structures results in an immediate damping of the structure at the frequency of the excitation force. There is no harmonic vibration of the structure due to the applied impulses.

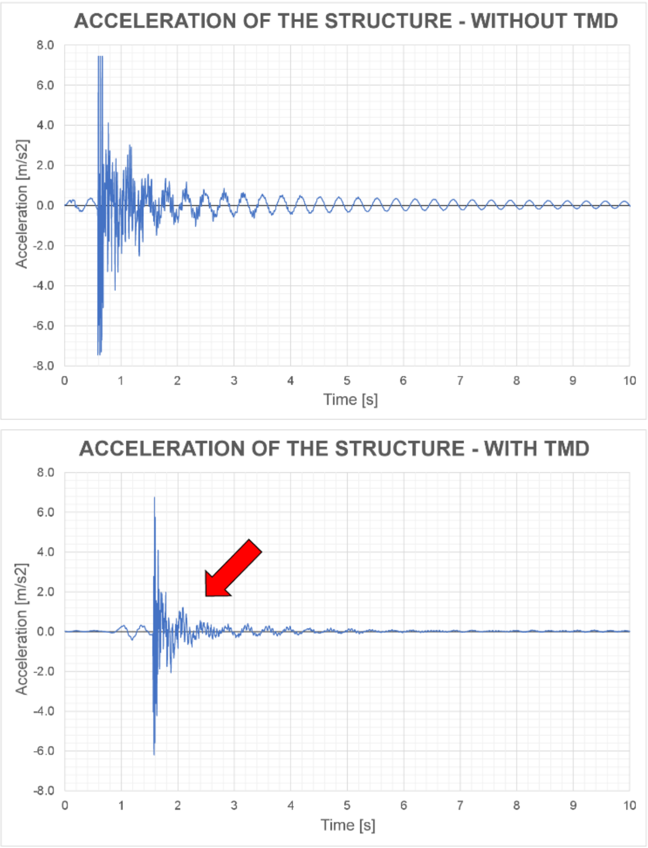

Figure 7 Acceleration over time - footbridge in Bílovice nad Svitavou

Therefore, the measured acceleration waveform does not have a typical character (gradual increase in acceleration reflecting the crossing of people to nodes of their own shapes), but both structures appear as a rigid element. The faster damping is also evident from the measured acceleration records on the time axis (Fig. 7). After installation of the damper on the footbridge in Bílovice nad Svitavou (Fig. 8), two peaks appear in the frequency spectrum at a distance of about ±0,27 Hz from the frequency of the first eigenmode (2,98 Hz). The oscillation of the structure at the frequency of both peaks is in the form of a vertical bending half-wave. This observation indicates that the TMD is correctly tuned to the frequency of the first eigenmode, which the bridge designer required to be damped. A second dynamic test confirmed the effectiveness of the damper. The waveform of the frequency spectrum (Fig. 8, bottom) indicates that the damper could be fine-tuned by slightly adjusting the TMD's eigenfrequency. This would align the two peaks on the same level (see Fig. 2). For the sake of clarity, the frequency spectra shown in Fig. 8 are not shown with the same scale on the vertical acceleration axis (the acceleration of the structure with the damper is approximately one third). It should be noted that the acceleration values depend on the size of the impulse, the damping of the structure and also the length of the section analysed. Moreover, OMA [6] does not work with a known load value, so the response cannot be compared in terms of magnitude, but the presentation is still more than sufficient to tune the damper to the structure. Similar conclusions can be drawn from the measurements taken before and after the installation of the vibration damper on the bicycle bridge in Banská Bystrica.

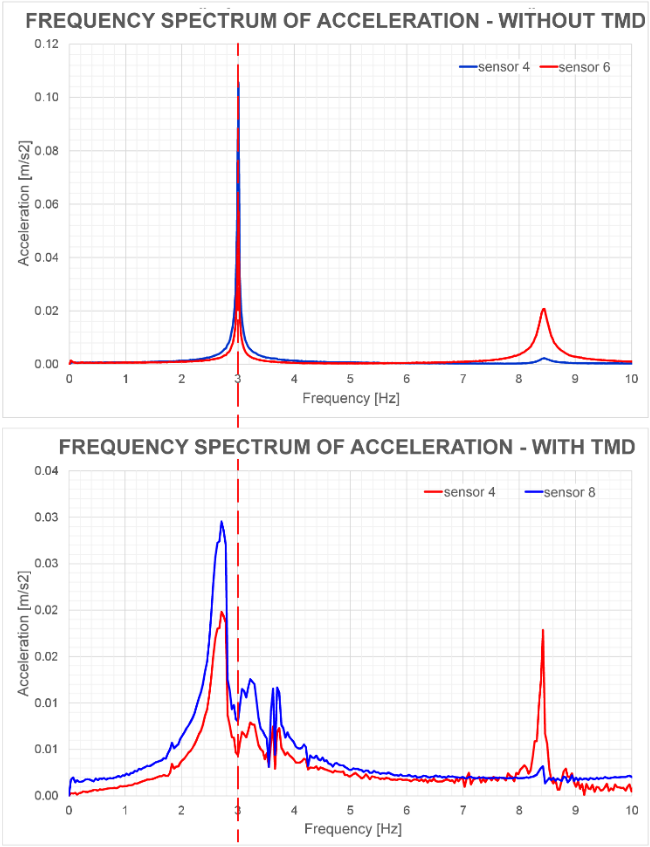

Figure 8 Frequency spectra - footbridge in Bílovice nad Svitavou

Further results of the dynamic measurements are presented only briefly. On the footbridge in Bílovice, the dominant (damped) first natural frequency of the bending vibration decreased from 2,98 Hz without the damper to 2,71 Hz with the damper (it relates to the damper tuning). In the case of the Banská Bystrica structure, the dominant frequency of the vertical bending vibration changes from 1,75 Hz to 1,64 Hz. The RMS value of the maximum vertical acceleration during human excitation with a dominant frequency of 2,9 Hz on the footbridge in Bílovice nad Svitavou without damping was approximately 1,0 m/s^2, which was well above the limit values. The RMS value of the acceleration on the damped structure is 0,311 m/s^2, i.e. more than three times lower. On the pedestrian bridge in Banská Bystrica, the installed dampers reduced the vertical acceleration by more than 2,5 times. The RMS value of the vertical acceleration in the main suspension field on the structure without dampers was 0,263 m/s^2 for the dominant frequency and 0,101 m/s^2 after installation of the dampers.

The effect of the damper on the vibration for the dominant first vertical bending eigenmode can also be seen in the increase of the damping ratio from a value of 0,70 % (measurement in Bílovice nad Svitavou in 2022) to a value of 2,05 – 2,80 % (measurement in 2023). The damping ratio of the undamped suspended steel structure in Banská Bystrica is only 0,13 % for the dominant frequency. The damping ratio for the damped structure in Banska Bystrica was not determined due to the complex interdependence of bending, transverse and torsional shapes affected by the damper.

4 Conclusion

The dynamic tests were carried out in accordance with the standards. The dynamic behaviour of both footbridges with tuned mass dampers meets the standards with respect to the comfort criteria. Both footbridges have been put into operation.

Partial conclusions resulting from the collaboration between the research organisation and the production sector in the field of structural dynamics show that pedestrian comfort, slim, subtle design, minimisation of the number of fixed supports and, last but not least, material savings are the main reasons for integrating vibration damping into the design of a bridge structure. The main objective is to protect pedestrians, cyclists and the bridge from unwanted vibrations or damage.

For future projects, KGF hydraulika has developed new friction damping elements, which extend the application of tuned mass dampers to low-cost and temporary bridges and to the damping of bridge cables without the need to modify the suspender cable and its surroundings. These new damping elements are based on rotating friction discs. The advantage is that the magnitude of the damping force is almost independent of temperature. Although the damping force is not linearly dependent on speed as in the case of viscous damping elements, the dependence of the absorbed energy can be reasonably well approximated by a suitable design. The resulting deviation of the absorbed energy from the ideal characteristic of a viscous damper can be less than that due to temperature variation in viscous damping elements.

By properly designing these friction damping elements, maintenance-free service life of the tuned mass dampers (TMD) can be achieved up to the service life of the bridge itself.

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