Tuned Mass Dampers for Vibration Control of Footbridges from an Architectural Point of View

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DOI: https://doi.org/10.14459/icbdb24.34

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 (TMD) into the bridge project. The aim is to protect people and bridge structure from vibration and damage. The following paper presents findings from the design, production and tuning of mass dampers, their optimization possibilities and benefits for bridge engineering.

From an architectural point of view, the TMD should be fully or at least partially integrated into the bridge design in order not to disturb the overall bridge appearance from the frog or side perspective. There are several ways to achieve this, from the materials, covers or colors used, over the TMD design aligned with the bridge design, to a special TMD chamber within the bridge deck to house the damper. The main challenges are extremely slender bridge structures or structures densely interrupted by beams. The goal is to marry form and function.

This paper presents best practice from the Czech Republic and Slovakia regarding TMD function and form. It concerns the Štvanice footbridge over the Vltava River in Prague, the footbridge over the Jizera river in Mladá Boleslav connecting Škoda Auto with a meadow, footbridge in Bílovice nad Svitavou with extremely slender bridge structure and the bicycle bridge over the high-speed road in Banská Bystrica, Slovakia. Dynamic tests including measurements were carried out before and after the installation of the dampers. The dynamic monitoring of the compliance of modal parameters was performed 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.

1 Vibration Damping of Footbridges

1.1 Vibration of Bridge Structures

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. The most common construction materials for pedestrian bridges are concrete, steel and nowadays also UHPC. Steel footbridges in particular are characterised by low inherent damping (typical damping ratio for steel is 0,4 %, for UHPC ca. 0,6 % and for concrete around 1 %) [1]. 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 (lateral) 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.

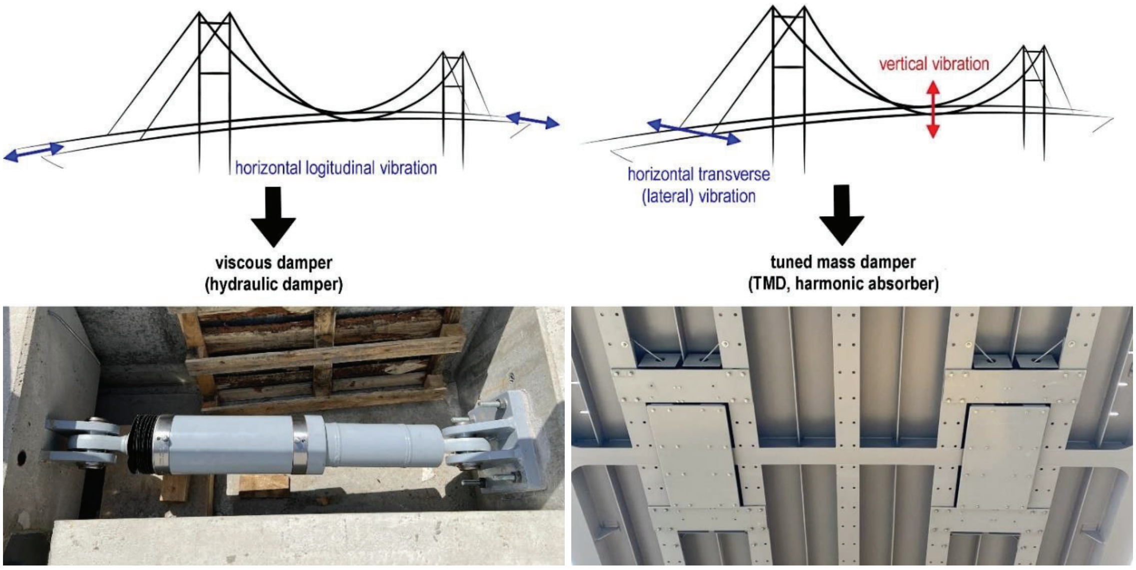

Figure 1: Relationship between the direction of vibration and the type of damper (Kučera, Nečas, 2024)

1.2 Viscous Damper vs. Tuned Mass Damper (TMD)

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 – FVD (Fluid Viscous Damper), bridge LUD (Lock-Up Device), STU (Shock Transmission Unit)

- 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 abutment pier, as the viscous damper fixes the load-bearing structure to the abutment. **In most cases the viscous damper is positioned well so that it does not interfere with the architectural concept of the footbridge and therefore does not affect its appearance**.

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 a hydraulic damping element is positioned to dissipate the energy of the vibrations. Tuned mass dampers are typically located at the points on the bridge deck where the vibration amplitude of the natural frequency is maximum. TMD can be placed either on the underside of the bridge deck (most commonly) or in a special chamber in the bridge deck (only if the architect or bridge designer considers TMDs from the beginning of the project). **If TMDs are placed on the underside of the footbridge, they can significantly affect the architectural appearance of the footbridge. This is particularly the case if a standard type of TMD is used which is not custom made and therefore does not correspond to the particular superstructure and design of the footbridge**. The solution is a TMD tailored to the specific type of footbridge, respecting the design of the superstructure in terms of arrangement of longitudinal and transverse girders and also diagonal stiffeners. The aim is to integrate the TMD into the superstructure in such a way that it does not significantly exceed the transverse profile of the bridge deck and does not interfere with the design of the bridge, either from the bottom or from the side view.

The use of tuned mass dampers and viscous dampers significantly reduces the vibration of the footbridge, thereby increases the comfort of pedestrians and cyclists and enables to comply all relevant vibration limits and recommendations according to the corresponding standards, in particular the Technical Guide for the Design of Footbridges published by Sétra [4] or ČSN 73 6209 [5].

Viscous dampers from the producer KGF hydraulika 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 from KGF hydraulika have been used, for example, in the footbridge over the Jizera River in Mladá Boleslav, or in Prague in several footbridges over the Moldau river, e.g. in the new Troja footbridge and, since summer 2023, in the Štvanice footbridge. **The following part of the paper will focus on the use of tuned mass dampers (TMD) in practice, their damping effects demonstrated on four selected footbridge projects in the Czech Republic and Slovakia, and their seamless integration into the bridge deck from an architectural point of view**.

1.3 Challenges for TMD Design

One of the challenges is the current trend in bridge design towards footbridges with a very slender superstructure (cross-sectional profile height up to 200 mm). The main reason for such a flat bridge profile is to simplify the supporting structure, give the bridge a subtle and slender appearance, and in most cases, achieve significant material and cost savings. However, these footbridges are more susceptible to vibration. The specific possibilities of integrating TMD's into flat bridge decks are explained in the next chapter, using the example of a pedestrian bridge in Bílovice nad Svitavou in the Czech Republic (Chapter 2.1). Another challenge are bridge decks in which longitudinal and transverse girders, and also diagonal stiffeners are densely embedded (for windage reasons, especially to increase transverse stiffness). This requires a special damper design, as demonstrated on the pedestrian bridge over the Jizera River in Mladá Boleslav, which connects R&D centre of a car production company with the green area "Beautiful Meadow" (Chapter 2.2).

In other projects, the integration of dampers can be solved more easily, i.e. it is a matter of partial aspects such as matching in terms of shapes, covers and colours to the underside of the bridge deck. The goal is to marry form and function. As an example, the TMDs in the Štvanice footbridge in Prague are featured here (Chapter 2.3).

Figure 2: Challenges: flat bridge deck profile (footbridge in Bílovice nad Svitavou, CZ) – bridge deck with densely embedded girders (footbridge in Mladá Boleslav, CZ) – integration regarding form & function (Štvanice footbridge in Prague)

2 Case Studies: TMD Integration Demonstrated on Four Footbridges in the Czech Republic and Slovakia

2.1 Footbridge in Bílovice nad Svitavou, CZ – Extremely slender Profile of only 160 mm

Figure 3: Footbridge in Bílovice nad Svitavou, CZ

The initial bridge under evaluation is situated in Bílovice nad Svitavou, Czech Republic. It crosses the Svitava River and connects the municipal center with the Fügner bankment. It is a single-span pedestrian bridge with a span of 33,2 m (Fig. 3). The footbridge is designed as a steel parapet girder with a one-sided inclination towards the left bank abutment. The wooden deck of the bridge deck rests on steel stringers welded to steel cross girders. These crossbeams 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). **All main and cross girders are made of I160 beams. This determines the height dimension of the bridge deck cross-section (160 mm), which is crucial for the damper design**. On the left bank the bridge structure is embedded in a massive concrete 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.

Based on the proposal of the bridge designer the damper manufacturer (KGF hydraulika, Czech Republic) designed and installed one vertical tuned mass damper (TMD) on this footbridge, the technical parameters of the damper are shown in Tab. 1. The TMD should not significantly exceed the height of 160 mm, so that it is integrated into the bridge deck and thus does not interfere with the architectural design of the bridge, particularly with the cross-section profile from the side view. The TMD used in this case, including the frame, has the following dimensions: x = 1,800 mm, y = 1,022 mm, z = 163 mm) and fits perfectly into the bridge deck.

The production of some components and the tuning of the damper were determined by first dynamic measurement (conducted on the bridge before the TMD was installed) using OMA (operational modal analysis) [6] on the bridge after the completion of construction. The correct operation of

Table 1: Technical parameters of the vertical TMD installed in the footbridge in Bílovice nad Svitavou, CZ.

TMD	Values
# of TMDs	**1**
Oscillating mass (kg)	**350**
Total weight (kg)	**440**
Natural frequencies (Hz)	**2,93**
Spring constant (kN·m^{-1})	**118,72**
Damping constant (kN·s·m^{-1})	**0,99**
Dimensions (mm)	**1.800 x 1.000 x 163**

the dampers was verified by a second dynamic measurement after the TMD was installed.

Results of the TMD Efficiency Measurements

The installation of the TMD results in an immediate damping effect on the structure at the frequency of the excitation force. There is no harmonic vibration of the structure due to the applied impulses.

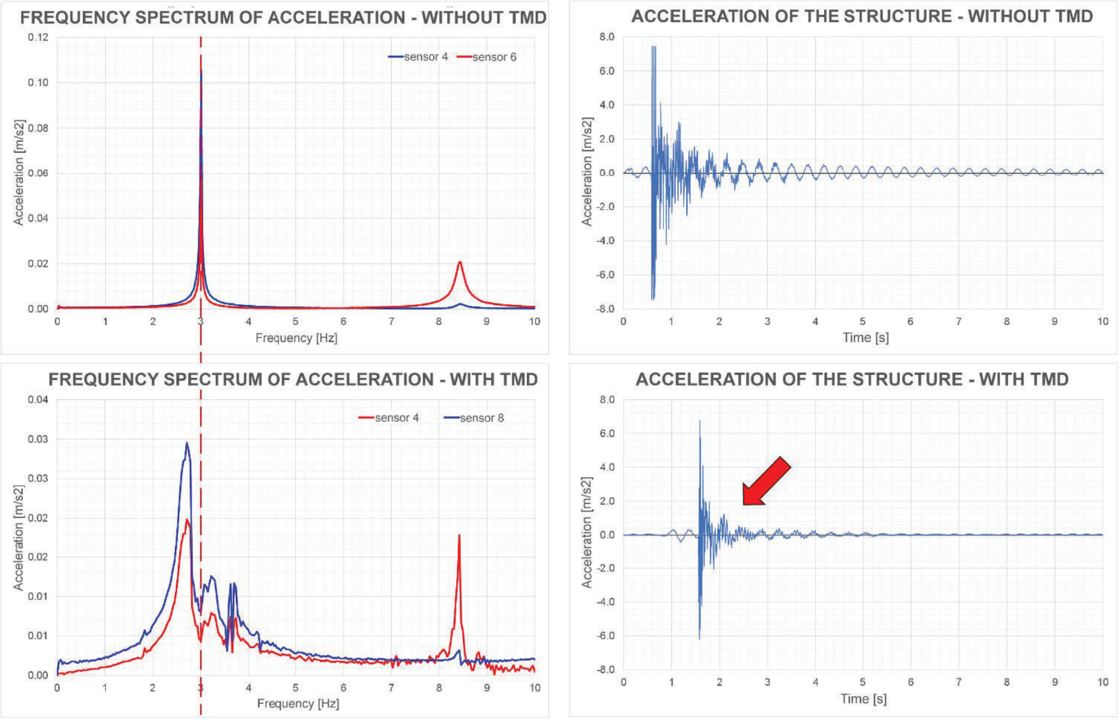

Figure 4: Acceleration over time, frequency spectra - footbridge in Bílovice nad Svitavou

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 the structure appears as a rigid element. The faster damping is also evident from the measured acceleration records on the time axis (Fig. 4, on the right). After installation of the TMD on the footbridge in Bílovice nad Svitavou, 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, Fig. 4, on the left bottom). 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. 4, 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. For the sake of clarity, the frequency spectra shown in Fig. 4 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.

Further results of the dynamic measurements are presented only briefly. 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). 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 TMD** was approximately 1,0 m/s2, which was well above the limit values. The RMS value of the acceleration on the **damped** structure is 0,311 m/s2, i.e. due to the TMD was reduced more than three times.

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 2022) to a value of 2,05 – 2,80 % (measurement in 2023).

2.2 Footbridge in Mladá Boleslav, CZ – Bridge Deck Densely Interrupted by Girders

Figure 5: Footbridge in Mladá Boleslav, CZ (Source: Škoda auto, 2023)

This new pedestrian and bicycle bridge over the Jizera River connects the Škoda Auto R&D centre with the area of Beautiful Meadow and is located just next to an older railway bridge. The footbridge, with a width of 4,100 mm between the main girders and 3,700 m between the handles of railings, consists of one superstructure in each of the two bridge openings. The right structure (main, longer span) with a span of 68,400 m crosses the Jizera River, and the left structure (secondary, shorter span) with a length of 23,680 m bridges the floodplain on the left bank of the Jizera River. The axis of both spans is straight. The level is in the form of a pointed arch with a radius of 811.541 m. The superstructure of the right span is placed on the right bank abutment and the left bank pier. The superstructure of the left span is placed on the left bank pier and abutment. The level of the left span drops in an arc so that at the lowest point the lower edge of the structure is about 0.8 m above the level of the 100-year flood. The bridge is connected to a bike paths. This footbridge was designed by architect Josef Pleskot and won several architectural awards.

The bridge is characterised by both the low cross-sectional height of the deck, i.e. approximately 220 mm, and the fact that the internal space of the underside of the bridge deck is quite densely reinforced with longitudinal girders and crossbeams and diagonal stiffeners, which must not be interrupted by the TMD. 4 pairs of vertical TMDs were installed on this footbridge, a total of 8 TMDs. **Some of the TMDs are even located at the intersection of the longitudinal and transverse girders. However, none of the customised dampers does exceed the underside level of the bridge deck by more than 20 mm**.

Table 2: Technical parameters of the vertical TMD's installed in the footbridge in Mladá Boleslav, CZ.

TMD Model No.	TMDV-1000-2,015	TMDV-450-3,81	TMDV-400-4,63
# of TMDs	2	4	2
Oscillating mass (kg)	1.000	450	400
Total weight (kg)	1.100	530	480
Natural frequencies (Hz)	2,015	3,810	4,630
Spring constant (kN·m^{-1})	160,4	258,3	347
Damping constant (kN·s·m^{-1})	4,05	3,02	3,77
Dimensions (mm)	1.850 x 890 x 200	1.450 x 890 x 200	

2.3 The Štvanice Footbridge in Prague, CZ – To Marry Form and Function

In 2023, the white Štvanice footbridge over the Vltava River was completed in Prague. With a length of 300 m, it curves slightly between two vibrant Prague districts Holešovice and Karlín and includes a branch (with a length of 80 m) giving access to a large fluvial island Štvanice, with green areas for leisure activities. Held up by four minimalist piers, the structure has a prefabricated concrete framework reinforced with fiberglass (UHPC). Its marble-like magnificence is accentuated by a bronze balustrade. KGF hydraulika designed, manufactured and installed two vertical Tuned Mass Dampers.

The superstructure of this footbridge consists of prefabricated H-section segments. The parapet girders are connected by a thin walking deck reinforced with a pair of transverse ribs (on a typical

Figure 6: Štvanice Footbridge in Prague, TMD from KGF hydraulika, Island Štvanice, CZ

segment). The structure is made of C120 class white UHPFRC concrete. The side parapets act as a continuous beam and flow seamlessly into the integrated side ramp of the bridge. The structure is designed without intermediate expansion joints. The length of the structure along the individual spans (in the direction from Karlín to Holešovice) is 18 + 55.4 + 55.4 + 55.4 + 55.4 m, and the span of the side ramp to the island of Štvanice is 13.05 + 49.35 m. The width of the structure is 5.0 m in the main bridge (Holešovice - Karlín) and 4.0 m in the side ramp to Štvanice Island. The height of the superstructure (side parapet) is 1.85 m. The last span towards the Holešovice bank is designed as an embedded span to enable lifting in case of flooding. This span is connected to the structure by a steel pivotable joint behind the P50 pier at the point of theoretical zero bending moment from the structure's own weight.

The Štvanice footbridge was designed by a team of four architects and structural engineers - Petr Tej, Marek Blank, Jan Mourek and Vít Najvárek, and built by Skanska. The pedestrian bridge was awarded in several architectural competitions, including Building of the Year 2023.

In this case, there was no problem with the space for placing the vertical TMDs, but due to the great emphasis on the aesthetics of the whole footbridge appearance in Prague, the main focus was on adapting the shape of the dampers to the design of the footbridge as much as possible. In addition to using the same colour, damper covers were used in such a way that the damper would harmonise with the design of the footbridge.

Table 3: Technical parameters of the vertical TMD's installed in the Štvanice footbridge in Prague, CZ.

TMD Model No.	TMDV-1500-1,180	TMDV-1500-2,067
# of TMDs	1	1
Oscillating mass (kg)	1.500	1.500
Total weight (kg)	1.730	1.730
Natural frequencies (Hz)	1,800	2,067
Spring constant (kN·m^{-1})	192	253
Damping constant (kN·s·m^{-1})	3,64	1,06
Dimensions (mm)	2.450 x 1.046 x 386	

2.4 Bicycle Bridge in Banská Bystrica, SK – TMDs in a Chamber

Figure 7: Bicycle bridge over the R1 expressway in Banská Bystrica, Slovakia (Source: Ingsteel, 2024)

The last bridge described in this article is located on the southern outskirts of Banská Bystrica, Slovakia. It bridges the R1 expressway and the Zvolen road (I/69) at the junction and connects the Hušťák - Králová urban cycle path. The bicycle bridge is designed as a suspension bridge with an inclined pylon and suspensions placed along the outer edge of the main span. This multi-span bridge consists of individual spans with the following lengths: 3,060 + 24,686 + 22,899 + 76,300 + 22,264 + 24,686 + 13,060 m. In the transverse direction, the superstructure 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 space into two chambers. 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 attached to the anchor blocks of the foundation. This bicycle bridge and the footbridge in Bílovice nad Svitavou were designed by the Czech bridge engineering company Link project, this project in Banská Bystrica was built by the Slovak construction company INGSTEEL.

In this bridge project, the future location of the TMDs was considered from the very beginning, i.e. from the first design proposal. The space for the damper was created within the twin-box girder by removing the divider between the chambers and creating a hole with a cover at the top of the deck slab to place the TMD. The TMD had to fit into this limited internal chamber space.

Results of the TMD Efficiency Measurements

Two vertical TMDs were installed on this bicycle bridge, as described above, each placed in a special chamber. The damping ratio of the undamped suspended steel structure in Banská Bystrica was only 0,13 % for the dominant frequency. Due to the TMDs, the dominant frequency of the vertical bending vibration changes from 1,75 Hz to 1,64 Hz. The RMS value, of the vertical acceleration in the main suspension field of the structure without TMDs, was 0,263 m/s2 for the dominant frequency. After installation of the TMDs, the RMS value decreased to 0.101 m/s2. The installed TMDs reduced the vertical acceleration by more than 2,5 times.

Table 4: Technical parameters of two vertical TMDs installed in the footbridge in Banská Bystrica, SK.

TMD	Values
# of TMDs	**2**
Oscillating mass (kg)	**1.000**
Total weight (kg)	**1.280**
Natural frequencies (Hz)	**1,706**
Spring constant ($kN\cdot m^{-1}$)	**115,0**
Damping constant ($kN\cdot s\cdot m^{-1}$)	**2,25**
Dimensions (mm)	**1.446 x 860 x 265**

3 Conclusion

Footbridges or bridges are often the dominant feature of towns and cities and can become a symbol of the town. They can also frame the panorama of the landscape, embellishing mountains or valleys. Great importance is therefore attached to their aesthetics and how they fit into the urban or landscape concept. Current trends in bridge and pedestrian bridge design and investor preferences are often leading to elegant, slender to subtle structures without multiple piers. These structures are not only visually attractive but, in most cases, also economical in terms of the amount of material used. This can significantly reduce the overall construction costs for the investor. Nevertheless, in some cases, this can also lead to vibration of the structure. Vibration can be solved by integrating tuned mass damper into the bridge structure. For aesthetic reasons, it is desirable to integrate TMDs as seamlessly as possible into the deck slab.

This paper has shown examples of TMDs solving the vibration problem, significantly improving pedestrian comfort and ensuring the bridge meets all vibration standards. [4] [5]. Additionally, these TMDs are installed in footbridges in such a way that they do not disturb the frog view of the footbridge from below or exceed the transverse profile of the footbridge structure. The customised design of the TMDs, i.e. tailor-made solutions based on standardised components, allows the TMDs to be optimally adapted to the architectural concept. KGF hydraulika has developed several solutions for the integration of TMDs into different types of superstructures. It is therefore not necessary to hesitate or even avoid slender bridge structures when designing pedestrian bridges, but this aspect must be taken into account.

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