TUNED-MASS SYSTEMS FOR THE DYNAMIC UPGRADE OF BUILDINGS AND OTHER STRUCTURES

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ABSTRACT

The application of tuned-mass dampers (TMD) is effective in improving the dynamic performance of structures. A TMD consists of a relatively small mass which is attached elastically to the main structure. The elastic connection is tuned in regard to the disturbing natural frequency of the system. The main structure usually possesses little damping and hence, it is easily excited by wind, traffic or earthquakes. A TMD is equipped with dampers as they control the relative motion between main structure and the TMD. Additionally the damping spreads the operation frequency band of the TMD and thus, the operation of the TMD becomes more stable in regard to frequency changes. This change can be observed in bridges, e.g. with and without traffic load. TMDs can be installed to increase the safety of structures by reducing the induced motion and as a result their installation reduces fatigue problems. Moreover, they can also be used to improve comfort conditions, for example in bridges and buildings. A TMD should be taken into consideration during the design stage of a project, but it is also possible to design such a system later. Then, frequency measurements can be taken as a reliable basis for the layout.

Keywords: Passive control system, Tuned-mass damper, Resonance effect, Upgrade of structure, Increase of damping, Dynamic performance, Fatigue, Comfort.

I. INTRODUCTION

Most of the construction projects nowadays have many constraints regarding very different aspects. Economical restrictions as well as architectural preferences do not always satisfy engineering requirements even for structures like bridges and high-rise buildings. Sometimes it becomes also necessary to find compromises regarding the serviceability and even the structural integrity of a structure. High and slender structures as well as the need for light-weigh materials increase the danger of unintended disturbing and even dangerous vibration. Hence, the check of dynamic performance should always be taken into consideration when wind, pedestrians, traffic, machinery or earthquakes have to be considered.Natural structural frequencies as well as possible excitation frequencies are always very important first indicators for the judgement of structural behaviour. Resonance effects may occur when the excitation frequency is close to structural ones. Sometimes this does not play a very important role or it can be accepted. In other cases, the serviceability level of the structure is reduced significantly; people do not feel comfortable. There are even cases in which fatigue problems may occur. By increased amplitudes the stress levels are varying in a dangerous manner and thus, fatigue has always to be investigated for bridges and similar structures.Fig. 1 illustrates the well known resonance problem in the frequency range. The ratio of frequencies reflects the excitation vs. natural frequency here. When it is not possible to reduce the excitation force intensity or change the excitation frequency, generally 3 ways are possible for its solution:

a) Left hand side of Fig. 1, area "A" shows the increase of the structural frequency. The stiffness of the structure is increased or the main dimensions are reduced, e.g. by placing supplementary beams or columns.

b) Right hand side, area "B" indicates the increase of mass to bring down the structural frequency. Also the strategy of vibration isolation may be visualized here as flexible isolators reduce the relevant structural frequencies and change the corresponding mode shapes.

c) Area "C" specifies the effects of damping – without any changes of the frequencies. Increased damping reduces the motion in or close to resonance. Also the achievement of a TMD can be described like a higher structural damping.

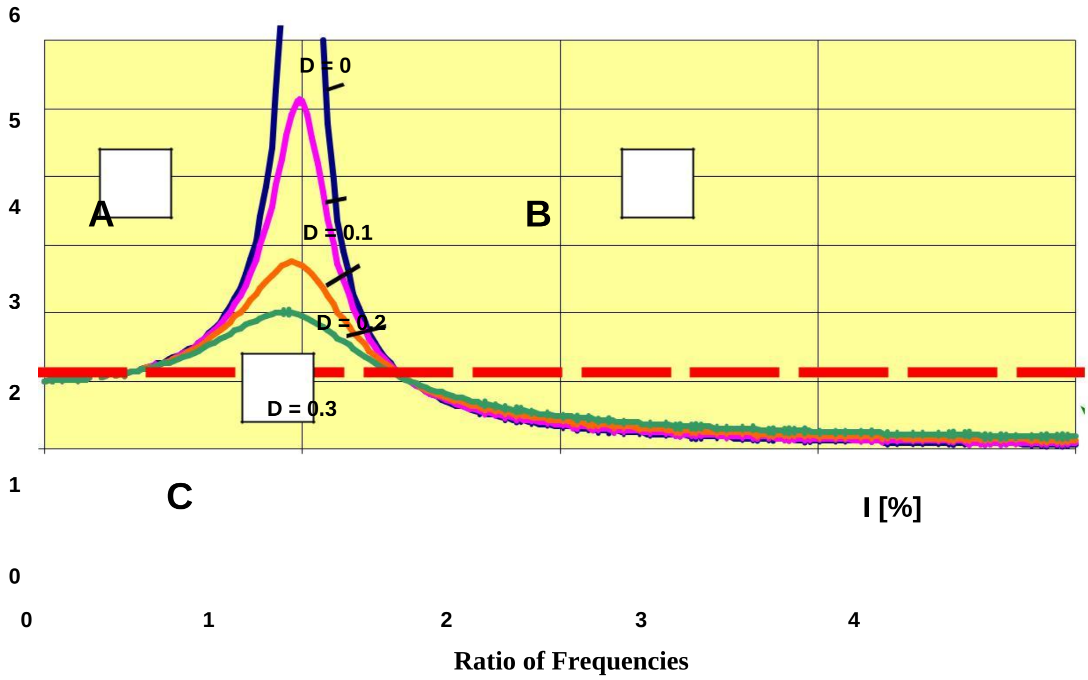

Fig. 1 Resonance Curve and Mitigation Strategies

There are some basic algorithms to achieve the most favorable parameters of the TMD. The most important frequency observations are based on findings of Den Hartog [1]. Generally the mass ratio between tuned mass and generalized structural mass plays a very important role. A high ratio in favour to the tuned mass increases the efficiency. Additionally the position of the TMD in regard to the main mass, the structural damping as well as the damping of the TMD are additional layout parameters.Structure like bridges, wide-spanned floors and roofs, tribunes, large stairs, stacks and high-rise buildings generally possess low structural frequencies with little damping only. Hence, many of these structures originally exhibit medium to high vibration levels. Sometimes no traditional measure is suitable or applicable so that the installation of TMDs becomes necessary. Recent examples show that this is also the most effective as well as economical solution.The application of TMDs against wind- or traffic induced vibration belongs to the state-of-the-art nowadays. On the other hand TMDs can also be arranged in order to reduce the effects of earthquakes. Here, some additional requirements have to be fulfilled. At the end of this paper some general hints are given based on results of shaking table experiments.

II.DESIGN ASPECTS OF TUNED-MASS SYSTEMS

TMD systems can generally be divided into two groups: vertically and horizontally working devices. The application depends on the shape of the disturbing mode as well as on the position / direction of the TMD in order to reduce this vibration.Vertically working TMDs are usually supported by helical steel springs. The frequency simply depends on the mass and the spring stiffness. The viscous dampers are used to spread the frequency band of operation. A typical example of such a system is shown in Figure 2. The spring system can also be designed as a hanger system so that the springs are loaded in tension. Also combined applications with tension and compression springs are possible.Horizontally working systems can generally also be arranged like shown in Fig. 2. Then, the horizontal stiffness of the springs as well as the shape of the mass are responsible for the target frequencies. In some cases the mass is arranged as a pendulum system. The flexibility is achieved by the horizontal motion of the mass at the bottom of the hanger system. The mass may work in one direction only, but it may also work in the horizontal plane.The design of the TMD is mainly depending on parameters like the material of the mass (e.g. concrete or steel), the shape of the mass, available space for the installation, possible fixation to the main structure and adjacent structural members, target frequencies and damping as well as architectural restrictions.Vertically working TMDs are mainly arranged in structures with horizontal orientation like bridges or floors. They can be utilized to control the bending modes of the structure. The arrangement is also possible to limit torsional modes especially when they are arranged in pairs.

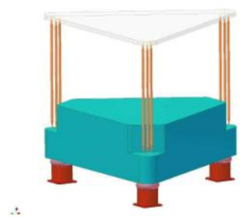

Fig. 2 Typical Vertical TMD Fig.3 Pendulum Type TMD

III. STRUCTURAL SAFETY AND SERVICEABILITY

The past has given various examples of lost structural safety and even collapse because of the above mentioned external hazards and the corresponding system behaviour. The failure of the *Tacoma Bridge* in 1940 represents the most famous example in this category. Steady state wind action caused oscillations in the bridge and by increased amplitudes, the excitation forces became larger. For these cases, the entire system damping capability may cause a limitation of the corresponding external vibration amplitudes. For this bridge the duration of the excitation was too long and thus, material and connection fatigue caused the structural collapse. TMD systems increase the damping for the related natural frequency and hence, vibration amplitudes become smaller. The reduced differential stresses cause a higher structural safety and generally an increased lifetime of the structure.

Tuned-mass systems used to improve the serviceability of bridges and high-rise structures are widely used nowadays. In some cases they are taken into consideration in the tenders for the corresponding construction work. The structures are tested after completion and if there are some dynamical insufficiencies, the TMD system is designed, produced, installed and usually verified by measurement

Table 1. Effects of Acceleration Levels on Users of Buildings acc. to [2]

Acceleration	Perception
< 0,5 % g	not noticeable
0,5 % - 1,5 % g	noticeable
1,5 % - 5 % g	inconveniently
5 % - 15 % g	unacceptable

Depending on the type and use of buildings, there are different reference values for the acceleration and their effect on humans. Some ideas for the selection of serviceability levels at low frequency oscillation are given in table 1. Later regulations like ISO 10137 ([3]) take also into account the desired purpose of the structure, the predominant natural frequencies as well as the target return periods for the exceedance of these values.

IV. APPLICATION ON BRIDGES

One of the most spectacular examples for the application of TMD systems in bridges is the *Millennium Bridge* in London (Fig. 4). In the year 2000, it was closed after a few days of operation as severe vibration levels have been observed. Vibration measurements as well as analysis have shown different mode shapes which are in the range of the pedestrian excitation. Furthermore, some other effects have been found. Like observed in self-excited structures under motion-depending loads, the dynamic forces of the pedestrians became higher with increased vibration amplitudes. This instability phenomenon was caused as the pedestrians tried to adjust their steps in order to stabilize the walking motion. By this adjustment they intensified their power to each step with increasing oscillation. The corresponding references talk about "locking effect s".After intensive studies on the nature of the disturbance, the counter measures were analyzed. This lead to the installation of 8 horizontally working TMDs in the center of the bridge span. Moreover, 50 pieces of vertically operating devices have been arranged to mitigate the effects of several bending and torsional modes. Fig. 4, right-hand side, shows the arrangement of a laterally working TMD on a cross beam of the bridge.

An important constraint for this application was defined by the architect who did not allow the TMD to appear significantly below the bridge. Passengers on boats or ships on the river should not be disturbed by the additional measures. This is a the reason why the laterally working TMDs are very specific – the principle is based on the behaviour of a double pendulum in the transverse direction of the bridge.

The resulting dynamic performance of the updated bridge is more than satisfactory nowadays.

Fig. 4 Millennium Bridge in London and the Installation of TMDs

V. APPLICATION ON BUILDINGS AND HIGH-RISE STRUCTURES

Towers and stacks (e.g., see Fig. 6) are typical industrial structures which are undergoing high wind loads and possess frequently problems with their dynamic performance. The damping capability is usually poor as corresponding strain rates are small and the structure can be classified as "slender". Usual damping ratios correspond to 0,2 – 0,8 % of c ritical and hence, the dynamic performance may be in question.Fig. 6, left-hand side, shows as refinery tower in Hungary which had significant problems with the foundation. Bolts and the corresponding counter parts in the foundation were affected by large differential loads. Measurements have shown that the first natural bending mode is excited in an excessive manner. Vibration amplitudes for the empty tower have been in the range of 700 mm.The installation of a TMD was suggested, of course, in combination with classical methods for the retrofit of the foundations. A ring-type pendulum with a mass of 16 t was arranged with 3 ropes and the damping was controlled with 3 viscous dampers. A similar installation is shown on the right hand side of Fig. 6. Many restrictions for the installation have been arising from the pipe-work around the tower. Hence, the relative displacement between tuned mass and the tower had to be restricted to 150 mm. This was one of the most important layout criteria which lead to the amount of mass to be installed and damping to be chosen.The chosen retrofit strategy of the refinery tower was the only possibility to avoid the total demolition and re-built. The application of the TMD was the most cost effective and time saving solution for this problem.

Fig. 6 Refinery Tower with TMD and Typical Arrangement of Ring Type Systems

Also high-rise buildings may be equipped with TMD systems – there are a few examples worldwide. The *Aspire Tower*, located in the *Sport City Complex* of Qatar is one of these examples (Fig.7, left). The building with restaurant and hotel is 318 m high. It was a landmark of the 2006 Asian Games due to its size and proximity to the main venue, the *Khalifa International Stadium*. The tower housed the Olympic Flame during the games and holds the record for tallest ever Olympic Flame and highest positioning of the Flame, which was visible throughout Doha for the duration of the games. The design employs a concrete core which acts as the primary support. The remainder of the building is a steel structure that cantilevers out from the concrete core. The exterior of the building is covered in a steel mesh which, during the Asian Games, was festively illuminated by vibrant LED lights [4].Of course, the designers had to have a careful look at the dynamic performance of the tower as it is exposed to high wind loading. As a result of the structural analysis, a TMD with a mass of 140 t was required to keep the expected acceleration amplitudes within the limits. As the available space for the installation of the mass was restricted and hence, the design of the TMD itself became a challenge. As the basic concept, a double pendulum system has been chosen. The main frame is supported by a cable system and the mass is hanging from the top bars of this frame. A special tuning system has been developed to bring the operating frequency between 0,16 and 0,23 Hz. 2 viscous dampers are arranged on both longitudinal sides of the mass (Fig. 7, right).

Fig.7 Doha Sport City Tower in Qatar and its 140 t Double Pendulum System

VI. SPECIAL ASPECTS FOR TMD SYSTEMS AGAINST SEISMIC ACTION

TMD systems against wind or traffic excitation usually possess efficiencies of 80 – 90 % when comparing the responses with and without activated TMD. In comparison to these applications, TMDs against earthquakes reduce the acceleration or stress responses by about 25 – 40%, mainly depending on the mass ratio. Excessive tests have been performed at IZIIS in Skopje, Macedonia. The steel frame structure according to left hand side of Fig. 8 underwent 11 different measured and artificial seismic waves with different intensities. The efficiency of the additional mass (1,4% of the total mass) was investigated. The results show that the tuned mass is working well, when the structure is mainly excited in its predominant natural frequency (e.g. Fig. 8, right).

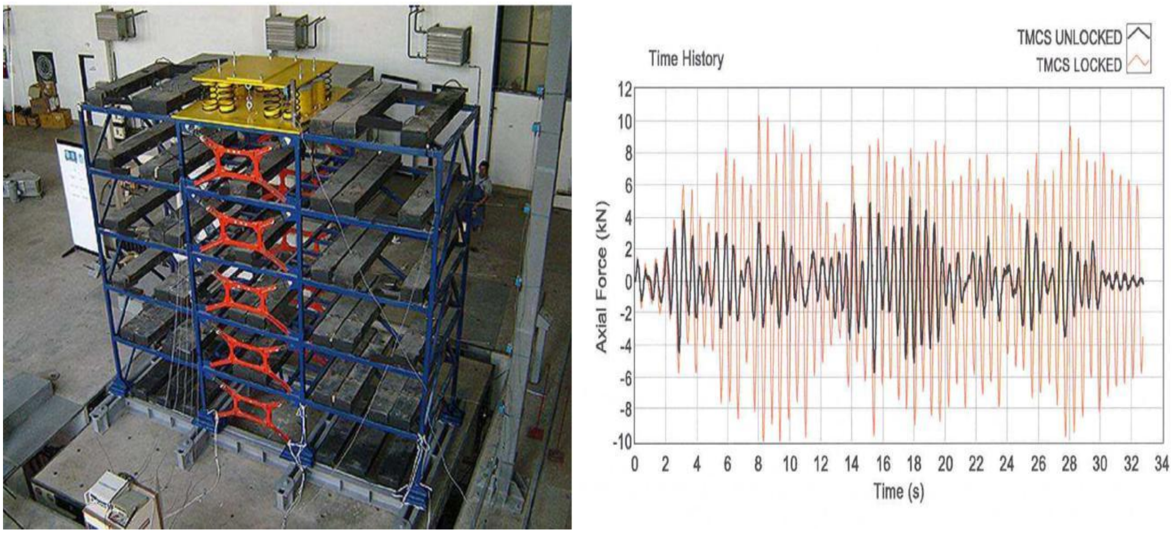

Fig.8 Shaking Table Tests of TMD System and Typical Seismic Responses

VII. CONCLUSIONS

The present paper starts with a brief classification of tuned-mass systems in regard to improvement of dynamic performance of structures. Since, their effects are similar to the increase of damping for the corresponding structural mode, TMDs may be used to mitigate resonance excitation by wind or traffic. Tuned-mass system are mainly installed to improve the comfort conditions of structures, but they can also be used to reduce fatigue effects. In this manner, they may be understood as primary members in regard to the structural integrity.Dynamic problems of two important bridges have been discussed. In these applications TMDs were installed to mitigate effects of wind and pedestrian excitation. The comfort conditions in both bridges have been improved significantly. Examples of towers and high-rise buildings under dynamic wind action have been shown. The operation of horizontally working TMDs was described. Two different approached can be distinguished here, mass on elastic support systems as well as pendulum type arrangements. Finally the efficiency of tuned-mass systems against earthquakes was discussed. Also here, they represent an effective measure to improve the structural performance. This may be one effective approach for the seismic upgrade of buildings in the future [6].

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