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MEASURES WHICH CAN BE USED TO PREDICT, PREVENT AND RESOLVE THE PROBLEMS OF LIVELINESS IN FOOTBRIDGES

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Abstract: *There are several measures which can be used to predict, prevent and resolve the problems of liveliness in footbridges. The Frequency tuning means avoiding the critical frequency ranges for the fundamental modes. Detailed vibration response assessment is the basis of many contemporary design procedures. Measures to reduce vibration response mean (i) Restricting the use of the bridge; (ii) Increasing the damping (e.g. by adding extra damping devices such as viscous dampers or TMDs). Presented article is focused on possibilities of calculation and design of Tuned Mass Damper on light-weight footbridges.*

Keywords: ***Footbridge, liveliness, damping devices, dynamic improvement, frequency tuning.***

1. Introduction

With the occurrence of the first problems related to the liveliness of footbridges, some early design recommendations, such as the one by (Walley, 1959), proposed that the fundamental vertical natural frequency of a structure below 2.7 Hz should be avoided. It is interesting to note that this corresponds to the upper limit of the range of the first walking harmonic, although at that time little was known about the actual nature of the walking force as no widely reported measurements of it existed. (Leonard, 1966) claimed that there was no need to avoid any frequency range if an appropriate damping and stiffness had been provided. For example, some footbridges are serviceable although their natural frequencies are inside the problematic ranges (Pimentel et. al., 2001) or the damping ratio is as low as 0.4% (Parker et. al., 2003). However, with modern trends towards slenderness in footbridge design, it happens that footbridges more and more frequently do not perform well in service as far as their vibration behavior is concerned. A list of examples of such problematic footbridges was compiled by (Pimentel, 1997). There are several measures which can be used to predict, prevent and resolve the problems of liveliness in footbridges (Bachmann and Amman, 1987):

- Frequency tuning: As previously mentioned, this measure means avoiding the critical frequency ranges for the fundamental modes. For vertical mode these are the frequencies of the first (1.6–2.4 Hz) and, for bridges with low damping, the second walking harmonic (3.5–4.5 Hz). Although (Bachmann and Amman, 1987) proposed the same provision for the lateral modes (namely, 0.8–1.2 Hz for the first and possibly 1.6–2.4 Hz for the second harmonic), it should be added that lower frequencies could be excited too, according to observations made on the Millennium Bridge, London where the frequency of the lowest mode excited was only 0.5 Hz (Dallard et. al., 2001). For the longitudinal direction, the first subharmonic and the first harmonic, with frequencies 0.8–1.2 Hz and 1.6–2.4 Hz, respectively, should be avoided. Excessive vibrations in this direction are very rare, but one case was reported by (Bachmann and Amman, 1987). It should be stressed that the designer can influence frequencies of the footbridge by choosing an appropriate layout of the structure (Pimentel, 1997) and by studying different options for distributing its stiffness and mass.

  Structural frequency can, for example, be changed by stiffening the structure (installing stiffer handrails or adding tie-down cables); (Tilly et al., 1984) found that footbridges with stiffness in the middle of the main span which is lower than 8 kN/mm are likely to be prone to vibrations in the vertical direction.

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- Detailed vibration response assessment: This is a measure which is the basis of many contemporary design procedures. However, it is underpinned by many uncertain modeling assumptions and its reliability is often questionable.
- Measures to reduce vibration response: These measures are:
    - Restricting the use of the bridge (for example, ban marching over the bridge);
    - Increasing the damping (e.g. by adding extra damping devices such as viscous dampers or TMDs).

It can be added here that warning and/or educating people to expect vibrations can help them to tolerate higher vibration levels than they would without an explanation that their safety is not in question. This is not surprising as safety is the main concern of the bridge users in case of excessive vibrations (Zivanovic et. al., 2005).

2. Improvement of dynamic behaviour

The dynamic calculation described in next chapter exposed structure response over the comfort criteria limits given by (Eurocode 5, 2004). It wasn't possible to modify natural frequencies and moved them so that they are outside the resonance risk ranges in relation to excitation by the pedestrians, then attempts should be made to increase structural damping.

With an existing footbridge, it is also possible to try to modify its natural frequency vibrations. However, experience shows that it is generally cheaper to increase damping. Modification of vibration natural frequencies - a vibration natural frequency is always proportional to the square root of the stiffness and inversely proportional to the square root of the mass. The general aim is to try to increase vibration frequency. Therefore the stiffness of the structure needs to be increased. However, practice indicates that an increase in stiffness is frequently accompanied by an increase in mass, which produces an inverse result; this is a difficult problem to solve.

3. Increasing structural damping

3.1. Natural structural damping of the structures

The critical damping ratio is not an inherent fact of a material. Most experimental results suggest that dissipation forces are to all practical intents and purposes independent of frequency but rather depend on movement amplitude. The critical damping ratio also increases when vibration amplitude increases. It also depends on construction details that may dissipate energy to a greater or lesser extent (for instance, where steel is concerned, the difference between bolting and welding).

3.2. Damper implementation

The use of dampers is another effective solution for reducing vibrations. Appendix 3 (SETRA, 2006) describes the different types of dampers that can be used and describes the operating and dimensioning principle of a selection of dampers. As a last resort, if the previous solutions do not work, damping systems can be installed, which will most usually be tuned mass dampers (these are the easiest to install: to work properly, viscous dampers often require the construction of complex devices to recreate major differential movement). A tuned mass damper consists of a mass connected to the construction using a spring, with a damper positioned in parallel. This device allows the vibrations in a construction to be reduced by a large amount in a given vibration mode, under the action of a periodic excitation of a frequency close to the natural frequency of this vibration mode of the construction. This shall only be considered as a last resort, as, despite the apparently attractive character of these solutions (substantial increase in damping at low cost), there are disadvantages. If tuned mass dampers are used, this is the most typical case:

- As many dampers are needed as there are frequencies of risk. For complex footbridges, which have many modes (bending, torsion, vertical, transversal, longitudinal modes, etc.) of risk, it may be very onerous to implement;

- The damper must be set (within about 2 - 3%) at a frequency of the construction that changes over time (deferred phenomena) or according to the number of pedestrians (modification of the mass). The reduction in effectiveness is appreciable;
- The addition of a damper degenerates, and thus doubles, the natural frequency under consideration: this complicates the overall dynamic behavior, and also the measurement of the natural frequencies;
- Even though manufacturers claim that dampers have a very long life-span, they do need a minimum level of routine maintenance: Owners must be made aware of this;
- Because of the added weight (approximately 3 to 5% of the modal mass of the mode under consideration), this solution will only work on an existing footbridge if it has sufficient spare design capacity. On a proposed footbridge, the designer may need to resize the construction;
- Preferably, 3% of guaranteed damping will be achieved: on very lightweight constructions (for which the ratio of the exciting force divided by the mass is high), it may not be sufficient. The Fig. 1 shows the lowering of amplitude response by increasing of damper relative mass. Frequency range (between peaks) where the damper is effective with increasing mass ratio is wider. Fig. 2 shows TMD – structure frequency ration influence on response.

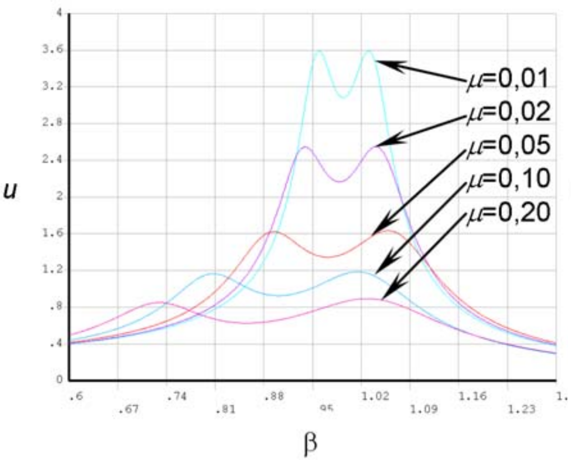

Fig. 1: Damper mass ratio influence.

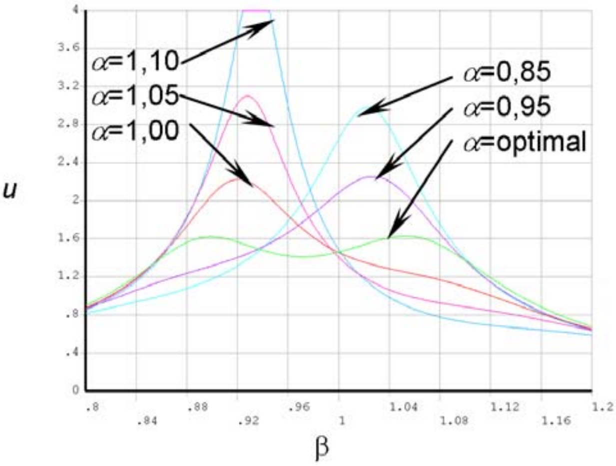

Fig. 2: Frequency ratio influence.

An important part of the computational bridge model assembly was the design of parameters for TMD. The vibration is provoked by the movement of a pedestrian on the bridge. The design of parameters consisted in the determination of the optimum damper position, mass, stiffness and damping force so that a maximum vertical vibration reduction was reached after the damper was placed into the bridge structure (Kala J. et. al., 2010b).

The first step for the design of damper parameters is the determination of its mass. TMD mass was determined as 1500 kg which approximately corresponds to 1/30 of moving structure mass in vertical direction. Subsequently, natural frequency and TMD damping ratio value were determined. In case study four variants of tuning TMD to minimize (a) displacement of empty and crowded structure, (b) acceleration of empty and crowded structure were analyzed (Kala J. et. al., 2010a).

4. Conclusion

Footbridges with well-separated modes which have vibration serviceability problem respond mainly in one mode of vibration which is lightly damped. This means that, by using appropriate modal mass and stiffness, the excited mode can be represented as a SDOF system and the optimum TMD. In that case the parameter m becomes ratio of the absorber mass and modal (generalized) mass of the SDOF system. For a simple beam structure, the assumption that the relevant pedestrian harmonic does not move produces only small differences in the tuning parameters in comparison with a moving force. The effectiveness of the absorber is nevertheless lesser for the moving force case.

Generally, an optimization of absorber parameters (stiffness and damping) could be done for different types of excitation and considering different response parameters. A lot of work has been devoted to this issue. Analyzed an undamped SDOF system under harmonic excitation but optimized response against displacement, velocity and acceleration of the main mass, and also against the force transmitted to the base. He also did optimization analysis for white noise excitation and harmonic base acceleration. They also pointed out the possibility to control the response in more than one structural mode by installation one TMD for each mode considered. Several TMDs can also be used for controlling SDOF system response due to wide-band random excitation.

In the case of footbridges, a single TMD for a dominant mode is usually considered. It is most effective to put the TMD at the point with maximum structural response that is at the antinode. This is a problem that has a lot of uncertain input factors. The effect of the influence of parameters on the mass and stiffness can be studied by methods of sensitivity analysis (Kala Z., 2009). Advanced is a method of global sensitivity analysis that allows us to analyze the higher order interaction effects (Kala Z., 2011).

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References

Bachmann, H., Ammann, W. (1987) Vibrations in Structures—Induced by Man and Machines, Structural Engineering Documents, Vol. 3e, International Association of Bridge and Structural Engineering (IABSE), Zurich.

Dallard, P., Fitzpatrick, A., Flint, A, Le Bourva, S., Low, A., Ridsdill-Smith, R.M., Willford, M. (2001) The London Millennium Footbridge, Structural Engineer 79 (22) 17–33.

Eurocode 5, (2004) Design of Timber Structures Part 2: Bridges, EN1995- 2: 2004, European Committee for Standardization, Brussels, Belgium.

Leonard, D.R. (1966) Human tolerance levels for bridge vibrations, TRRL Report No. 34, Road Research Laboratory.

Jones, R. T., Pretlove, A.J. (1979) Vibration absorbers and bridges, The Highway Engineer.

Kala, J., Hradil, P., Salajka, V. & Jutner, V., (2010a) Dynamic response of cable stayed steel bridge with tuned mass damper installed - numerical and experimental approach, In proc. 10th International conference Modern building materials, Structures and techniques, Vilnius, Lithuania, pp. 658-667, ISBN 978-9955-28-594-6.

Kala, J., Hradil, P., Salajka, V., (2010b) Comfort criteria for suspension footbridge response on single pedestrian induced vibration analysis, In proc. ESREL 2010 - Reliability, Risk and Safety, Rhodos, Greece, pp. 1535-1540, ISBN 978-0-415-60427-7.

Kala, Z. (2009) Sensitivity assessment of steel members under compression, Engineering Structures, 31, 6, pp.1344-1348

Kala, Z. (2011) Sensitivity analysis of stability problems of steel plane frames, Thin-Walled Structures, 49, 5, pp.645-651.

Parker, J.S., Hardwick, G. , Carroll, M. Nicholls, N.P. & Sandercock, D. (2003) Hungerford bridge millennium project-London, Civil Engineering 156 (2) 70–77.

Pimentel, R.L. (1997)Vibrational Performance of Pedestrian Bridges Due to Human-Induced Loads, PhD Thesis, University of Sheffield, Sheffield, UK.

Pimentel, R.L. , Pavic, A & Waldron, P. (2001) Evaluation of design requirements for footbridges excited by vertical forces from walking, Canadian Journal of Civil Engineering 28 (5) pp. 769–777.

SETRA, (2006) Footbridges: Assessment of vibrational behaviour of footbridges under pedestrian loading, Technical guide SETRA, Paris, France.

Walley, F. (1959) St James's park bridge, In proceedings of the Institution of Civil Engineers 12 (6257) pp. 217–222.

Zivanovic, S., Pavic, A. & Reynolds, P. (2005) Vibration serviceability of footbridges under human-induced excitation: a literature review. Journal of Sound and Vibration 279. pp.1-71.