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*MICHAEL REITERER**), *MARKUS J. HOCHRAINER***)

DAMPING OF FOOTBRIDGE VIBRATIONS BY TUNED LIQUID COLUMN DAMPERS: A NOVEL EXPERIMENTAL MODEL SET-UP

The application of tuned liquid column dampers (TLCD) for suppressing excessive lateral pedestrian-induced vibrations of footbridges is investigated experimentally and numerically. In order to study the effectiveness of TLCD, a novel three-degree-of-freedom (DOF) bridge model is constructed in the laboratory of the TU-Institute. A single TLCD is attached to the bridge model to counteract the bridge's fundamental vibration mode. Modal tuning of the TLCD is performed using an analogy to tuned mass damper (TMD). A new excitation device has been developed for simulating the time-periodic contact forces due to walking pedestrians. All vibration tests performed indicate a large reduction of the maximum lateral vibration response amplitude. In order to verify the experimental results, numerical simulations of the laboratory model are performed, which show a good agreement. The application of TLCD at least doubles the effective modal damping coefficient when compared to the original bridge model.

1. Introduction

The recent developments in construction techniques and light-weight materials have resulted in an increasing number of long span and highly flexible bridges. These bridges may suffer from excessive lateral vibrations when subjected to pedestrian loads, thus sometimes even the serviceability limit states are exceeded. Hence, the vibration mitigation of footbridges has become a major concern amongst structural engineers. Widely known

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*) *Department of Civil Engineering, Vienna University of Technology, Kulmgasse 5, 1160 Vienna, Austria; Bernard Ingenieure ZT-GmbH, Niederlassung Wien, Nordbahnstraße 36/Stg 2/Top 2.7, A-1020 Wien, Austria; E-mail: rem@bernard-ing.com*

**) *Geoconsult Wien ZT GmbH, (address) Vienna, Austria; E-mail: Markus.Hochrainer@vienna.geoconsult.at*

examples of vibration prone footbridges are the original Millennium Bridge in London, Dallard et al. [1], and the original Toda Park pedestrian cable-stayed bridge in Japan, Nakamura and Fujino [2].

One effective way of reducing excessive bridge vibrations is the application of dynamic vibration absorber. In this group, the tuned mass damper (TMD) is one of the most popular passive control devices, which has been studied extensively and is applied to several footbridges in order to reduce the vertical vibration amplitude, see Petersen [3]. However, TMD are not very effective in reducing low frequency lateral and torsional vibration amplitudes, e.g. due to stick-slip problems, etc. Hence, in the present investigation it is proposed to apply the more efficient and more economical TLCD, see Reiterer [4]. The TLCD is a damping device operating in the low frequency range (< 5.0 Hz), which relies on the motion of a liquid mass contained in a rigid U-tube. The external motion of the main system (bridge) induces a phase-delayed motion of the liquid mass and hence, interaction forces and moments that finally counteract the external excitation forces. Furthermore, a built-in orifice plate increases turbulent damping and dissipates kinetic energy. For optimal tuning of the TLCD, the natural circular frequency ω_A and the linearized damping coefficient ζ_A have to be chosen suitable, likewise to the conventional TMD, as discussed by Den Hartog [5]. In case of a single TLCD and well separated vibration modes, the tuning is performed with respect to a selected mode of the bridge using an analogy to TMD-tuning, see Hochrainer [6]. The analogy applies Den Hartog's optimal parameters, properly transformed by introducing geometry coefficients from the TLCD design. Final adjustments are easily performed in the course of in-situ testing. In many respects, TLCD exceed by far the capabilities of other vibration absorbing devices. Their main advantages consist in low costs of design and maintenance, easy application to bridges in course of retrofit and a simple tuning mechanism.

In order to study the effectiveness in vibration reduction achieved by TLCD, a novel experimental model-setup is developed and constructed in the laboratory of the TU-institute. It is indicated that TLCD reduce the resonant vibrations by about 70%. According to the excellent results, TLCD turn out to be an effective damping device for pedestrian induced footbridge vibration.

2. Experimental investigation

A side and front view of the experimental model set-up is illustrated in Figure 1. The three-DOF bridge model is materialized by the rigid rectangular plate at the tip of a skeletal box girder. The latter provides stiffness and the elastic support of the plate. To prevent undesired natural vibrations of the brazen profiles, several stiffening elements, made of Styrofoam, are mounted along the cantilevered beam.

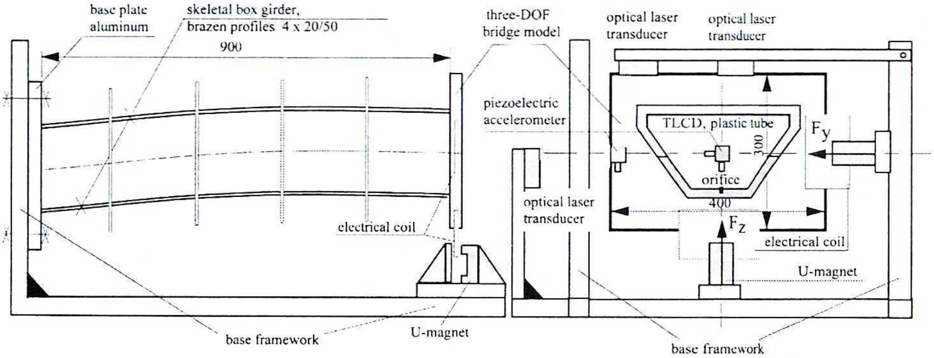

Fig. 1. Side and front view of the experimental model-setup

The TLCD, made of a flexible plastic tube, is symmetrically fixed to the bridge model, and orifices induce turbulent damping in order to increase the energy dissipation of the moving liquid column to the desired optimal value (optimal linearized damping coefficient $\zeta_{A,opt}$). A novel contactless excitation device has been developed to simulate walking pedestrians. Although it is widely known that people walk with a frequency of about 2 Hz, it is not commonly known that about 10% of the vertical dynamic force acts laterally, as described by Bachmann [7]. The frequency of this lateral dynamic force is always half the walking pace, i.e. about 1 Hz. Hence, the excitation must provide different dynamic forces in lateral and vertical directions. Therefore, the bridge's cross section is equipped with two electrical coils, which are exposed to a constant magnetic field. Subsequently, an electric current within the coils will cause exciting forces (lateral and vertical) acting on the bridge profile, see e.g. Heymann and Lingener [8]. The time periodic excitation signals are generated by means of the software LabView. The displacements of the rigid bridge profile are measured by contact-less laser transducers, type micro-epsilon, optoNCDT 1605. All measured signals are recorded digitally. To measure the TLCD liquid surface displacement an electric resistance measurement set-up is used. The piping system is equipped with two pairs of wire electrodes, whose resistance changes according to the water level displacement inside the pipe. Further details of the measurement device are given in a recent paper by Reiterer and Hochrainer [9]. To determine natural frequencies and equivalent linear viscous damping coefficients free vibration experiments of the bridge model and TLCD were performed. All relevant parameters are listed below: Mass of the bridge model $M = 1.57$ kg and mass moment of inertia with respect to the center of stiffness C_S, $\bar{I} = 0.0375$ kg m^2. Modal stiffness coefficients in lateral, vertical and rotational directions $k_y = 57.282$ N/m, $k_z = 174.83$ N/m, $k_x = 5.80$ N/m with the corresponding damping coefficients $\zeta_y = 0.04$, $\zeta_z = 0.041$, $\zeta_x = 0.039$, respectively. The natural frequencies are $f_1 = \omega_1/2\pi = 0.96$ Hz, $f_2 = \omega_2/2\pi = 1.68$ Hz and $f_3 = \omega_3/2\pi = 2.01$ Hz with dominating lateral, vertical and torsional response components. The lateral and vertical distances between the center of stiffness and the center of mass C_M are given by $c = -0.004$ m and $d = 0.02$ m, as illustrated in Fig. 2. The vertical distance between C_S and the accelerated reference point A is $d_A = 0.075$ m. The TLCD used to suppress the horizontal motion has an opening angle of the inclined pipe sections of $\beta = \pi/4$ and a constant cross-sectional area of $A_A = 0.0003$ m^2. The horizontal and inclined length of the liquid column in equilibrium state is $B = 0.10$ m and $H = 0.15$ m, thus the effective liquid column length becomes $L_{eff} = 2H + B = 0.40$ m, with a total fluid mass of $m_f = 0.12$ kg. Consequently the mass ratio between TLCD and bridge model becomes — $m = m_f/M = 0.076$. The optimal values of the natural frequency $f_A = \omega_A/2\pi$ and the linearized damping coefficient $\zeta_{A,opt}$ are determined in Section 3.

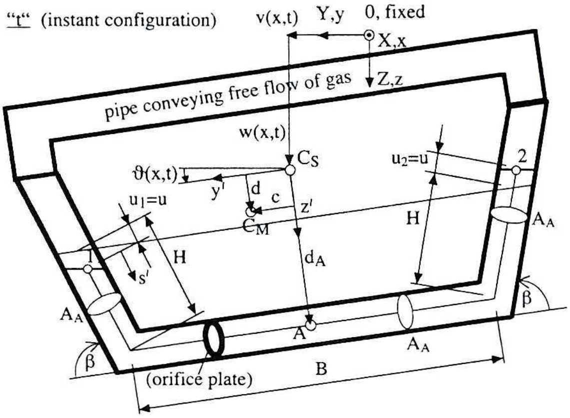

Fig. 2. Symmetrically shaped TLCD under general in-plane excitation, A_A = const.

3. Numerical simulation

The numerical simulations are performed according to the experimental investigation by considering the parameters listed above. A more detailed derivation and discussion of the equations of motion and theoretical aspects is given in Reiterer [4]. The attached TLCD is modally tuned to the fundamental lateral vibration mode, $f_1 = 0.96$ Hz. Note that the natural frequencies of the bridge model are well separated, which is a necessary assumption for successful modal tuning. The TLCD tuning problem can be reduced to a conjugate TMD tuning problem with optimal TMD design parameters δ^*_{opt} and ζ^*_{opt}, see [6]. The optimal design parameters of an equivalent TMD require, see Den Hartog tuning [5],

$$\delta^*_{opt} = \frac{\omega^*_A}{\omega^*_1} = \frac{1}{1 + \mu^*}, \qquad \zeta^*_{A,opt} = \sqrt{\frac{3\mu^*}{8(1 + \mu^*)}}, \tag{1}$$

where the conjugate mass ratio μ^* depends on the geometry coefficients κ and $\bar{\kappa}$, which are equal in case of constant cross-sectional area $A_A = \text{const.}$, thus $\kappa = \bar{\kappa} = (2H\sin\beta + B)/L_{eff} = 0.78$,

$$\mu^* = \frac{\kappa^2\mu}{1 + \mu(1 - \kappa^2)}. \tag{2}$$

With $\mu = 0.076$ Eq. (2) renders $\mu^* = 0.0449$, and thus the actual mass ratio μ is above the recommended mass ratio for real bridge structures of about $\mu = 0.5 - 3\%$. Evaluating Eq. (1) in consideration of the relations for the optimal TLCD parameters, defined in [6], yields the optimal frequency ratio and damping coefficient of the TLCD,

$$\delta_{opt} = \frac{\omega_A}{\omega_1} = \frac{\delta^*_{opt}}{\sqrt{1 + \mu(1 - \kappa\bar{\kappa})}} = 0.943, \qquad \zeta_{A,opt} = \zeta^*_{A,opt} = 0.127. \tag{3}$$

Thus the optimal natural frequency of the attached TLCD becomes to $f_A = \delta_{opt} f_1 = 0.904$ Hz. The numerically and experimentally assigned lateral and vertical pedestrian excitation forces, F_y and F_z are chosen according to Bachmann [7] and are approximated by the superposition of altogether three harmonics.

The numerical computer simulation is performed considering a nonlinear coupled bridge/TLCD system, see Reiterer [4], where the nonlinear turbulent damping is replaced by its equivalent linear one, see again [4]. This approximation is possible, if the vertical TLCD acceleration, which causes parametric excitation is not dominating. Reiterer [4] has shown that the application of a linearized damping model is valid, and parametric excitation is avoided, if the TLCD damping is larger than the cut-off value $\zeta_{A,0} = v_{t0}\,\omega_A^2/g = 0.033$, where $v_{t0} = 0.01$ m is the maximum vertical displacement response of the bridge at the critical vertical excitation frequency $v_z = 2\,\omega_A$, selected according to the experiment. The required value $\zeta_{A,0} = 0.033$ turns out to be much lower than the optimal one $\zeta_{A,opt} = 0.127$, Eq. (3), and thus, no undesired worsening effects of the vertical response on the optimal damping behavior of the attached TLCD are expected. An extensive investigation of the effectiveness of vertical excitations on the damping behavior of TLCD including the undesired phenomenon of parametric resonance is given in Reiterer [4].

4. Comparison of experiment and theory

The steady state horizontal displacement $v(t)$ of the bridge's center of stiffness C_S with and without TLCD, for both experimental and numerical simulation, is illustrated in Fig. 3. All simulations are performed using a time periodic excitation forcing with corresponding frequencies of $f_{y1} = 0.95$ Hz, $f_{y2} = 2f_{y1}$, $f_{y3} = 3f_{y1}$ and $f_{z1} = 1.90$ Hz, $f_{z2} = 2f_{z1}$, $f_{z3} = 3f_{z1}$ i.e. the excitation frequency f_{y1} is close to the fundamental natural frequency f_1, and the vertical excitation frequency is double the horizontal one, which is typical for pedestrian walking.

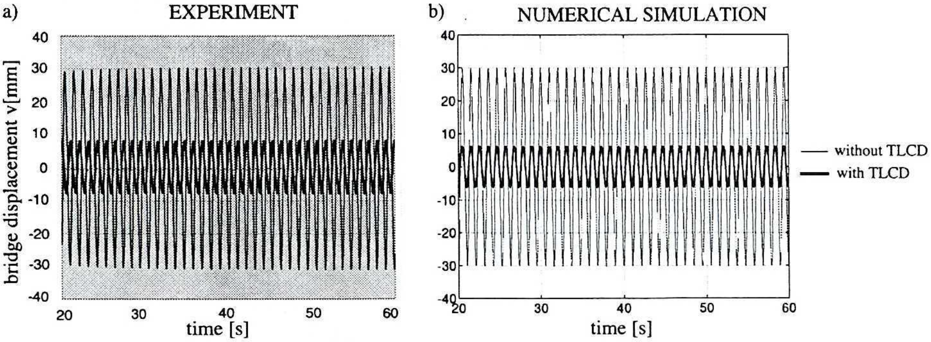

Fig. 3. Experimental a) and numerical b) results of steady state lateral displacement $v(t)$ of the bridge's center of stiffness C_S with and without TLCD under combined lateral and vertical forcing

By inspection of Fig. 3, a very good agreement is observed. Apparently, the attached TLCD reduces the maximum steady state vibration amplitude significantly, thereby increasing the pedestrians walking comfort, and avoiding the dangerous "lock-in" effect, which was the reason for severs vibrations problems with several bridges. Another important response parameter, the dynamic magnification factor (DMF) with and without TLCD, is shown in Fig. 4. Again, there is an excellent agreement between numerical and experimental results. The TLCD reduces the resonant peak of the bridge's fundamental mode by about 70%, which corresponds to an increase of the bridge natural material damping from $\zeta_y = 0.04$ to the effective value (with acting TLCD) of $\zeta_{y,eff} = 0.10$.

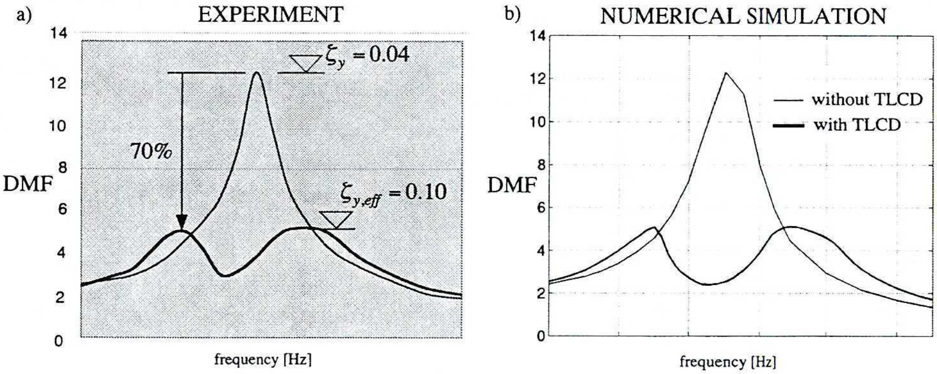

Fig. 4. Experimental a) and numerical b) results of the DMF for the lateral bridge displacement $v(t)$ under combined lateral and vertical force excitation

5. Conclusion

The application of TLCD to vibration prone footbridges is studied experimentally and numerically. In order to evaluate the vibration damping effects of TLCD a novel three-DOF bridge model with a single TLCD attached is constructed and tested under laboratory conditions. Using a simple analogy to TMD, the TLCD is tuned to the fundamental frequency of the bridge, whose corresponding mode has a dominant lateral response characteristic. The time-periodic contact forces of the walking pedestrians are assigned in both lateral and vertical directions. Therefore, a new contactless excitation device has been developed. It is indicated that the optimally tuned TLCD achieves a large reduction of the maximum lateral vibration amplitude. For the bridge model studied the modal damping of the fundamental mode is increased from $\zeta_y = 0.04$ to the effective value of $\zeta_{y,eff} = 0.10$. Hence, it is concluded that TLCD are very effective and economic damping devices for the control of pedestrian induced footbridge vibrations.

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REFERENCES

[1] Dallard P., Fitzpatrick A.J., Flint A., Le Bourva S., Low A., Ridsdill Smith R.M., Willford M.: The London Millennium Footbridge. The Structural Engineer, 2001, 79, No 22, pp.17÷33.

[2] Nakamura S., Fujino Y.: Lateral Vibration on a Pedestrian Cable-Stayed Bridge. Structural Engineering International, 2002, IABSE, 4.

[3] Petersen C.: Schwingungsdämpfer im Ingenieurbau. Herausgeber: Maurer Söhne GmbH&Co.KG, München, 2001.

[4] Reiterer M.: Damping of Vibration-prone Civil Engineering Structures with Emphasis on Bridges. Dissertation (in German), TU-Wien, A-1040 Vienna, Austria, 2004.

[5] DenHartog J. P.: Mechanical Vibrations. Reprint of 4th ed., McGrawHill, New York, 1956.

[6] Hochrainer M. J.: Control of vibrations of civil engineering structures with special emphasis on tall buildings. Dissertation (in English), TU-Wien, A-1040 Vienna, Austria, 2001.

[7] Bachmann H., Ammann W.: Schwingungsprobleme bei Bauwerken. Durch Menschen und Maschinen induzierte Schwingungen, Structural Engineering Documents, IABSE-AIPC-IVBH, 1987.

[8] Heymann J., Lingener A.: Messverfahren der experimentellen Mechanik. Springer Verlag, Berlin, 1986.

[9] Reiterer M., Hochrainer M. J.: Parametric Resonance in Tuned Liquid Column Dampers: An Experimental Investigation. IAZ (Ingenieur und Architekten Zeitschrift), 2004 (in print).

Tłumienie drgań mostu dla pieszych przy pomocy dostrajanych płynowych amortyzatorów kolumnowych. Nowy doświadczalny zestaw modelowy

Streszczenie

Przedmiotem pracy są doświadczalne i numeryczne badania dostrajanych płynowych amortyzatorów kolumnowych (TLCD) zastosowanych do tłumienia bocznych drgań mostu dla pieszych. By zbadać skuteczność amortyzatorów TLCD, w laboratorium Instytutu Politechniki Wiedeńskiej zbudowano nowy model mostu o trzech stopniach swobody. Pojedynczy amortyzator TLCD, dołączony do mostu, ma przeciwdziałać drganiom mostu w modzie podstawowym. Strojenie modalne amortyzatora TLCD jest wykonane przy użyciu analogii do tłumika o strojonej masie (TMD). Opracowano nowe urządzenie wzbudzające drgania do symulacji okresowo zmiennych sił kontaktowych powstających jako efekt kroków przechodniów. Wszystkie wykonane testy wibracji wykazały znaczną redukcję maksymalnej amplitudy drgań bocznych. W porównaniu do pierwotnego modelu mostu, zastosowanie tłumików TLCD zwiększa, co najmniej dwukrotnie, efektywny współczynnik tłumienia modalnego. Wyniki doświadczalne porównano z wynikami dla numerycznej symulacji modelu laboratoryjnego, uzyskano dobrą zgodność wyników.