The 3rd International Conference on Structural Health Monitoring of Intelligent Infrastructure
Vancouver, British Columbia, Canada
November 13-16, 2007

TUNED LIQUID COLUMN DAMPERS – EFFECTIVE DAMPING OF VERTICAL VIBRATIONS

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Abstract

In this paper tuned liquid column dampers (TLCD) are proposed for suppressing the vertical vibrations of bridges. The conventional TLCD is not suited for damping the vertical vibrations and thus, the configuration has been changed by imprinting a vertical distance of the water level in the static equilibrium position, according to Sun et al. [1]. A novel experimental model setup of a continuous bridge attached with passive TLCDs is presented. Free and forced vibration tests with and without TLCD are performed and several improvements of TLCD parameters are studied. It is shown that TLCDs in a changed configuration are effective damping devices for suppressing the vertical vibrations of bridges. Furthermore the main advantages of TLCDs over classical TMDs are discussed. Based on studies conducted, possibilities of implementing active control systems allowing optimizing the TLCDs eigenfrequency and damping coefficient are presented.

INTRODUCTION

A large number of railway, road, and footbridges show very low inherent structural damping and hence, they are susceptible for large vibrations. In order to dissipate the kinetic energy of the vibrating bridge, mechanical dampers like the tuned mass damper (TMD), are properly adjusted and applied [2] for their general design. Reiterer [3] developed the detailed model of TLCD interacting with the bridge in coupled oblique bending-torsional motion paralleled by laboratory testing. Generally, the conventional TLCD suppresses horizontal and/or torsional motions of bridges. For damping, the vertical vibrations of bridges a changed configuration has been proposed by Sun et al. [1]. In this configuration a vertical distance of the water level in the static equilibrium position has been applied by over-pressure on the sealed side of the piping system. Optimal tuning with respect to the vertical vibrations is performed analogously to the classical Den Hartog tuning of a mechanical damper (TMD), see Hochrainer [4] and Den Hartog [5].

MECHANICAL MODEL OF TLCD FOR VERTICAL VIRBATIONS

The rigid, symmetrically designed piping system of the absorber is fastened to the cross-section of the bridge at point $x = \xi$ to form a rigid frame with three DOF, see Figure 1. In the following study a dominant vertical motion of the bridge according to equation (1) is considered.

$$w^{(t)} = w_g(t) + w(t) \qquad (1)$$

The pipe is partially filled with fluid with its relative motion described by the displacement amplitude of its interface to gas acc. to equation (2).

$$u_1 = u_2 = u(t) \qquad (2)$$

The cross section and total liquid column length is defined by A and L, i.e. the total liquid mass $m_f = \rho AL$. For an open piping system, the gas pressures p_1 and p_2 are equal to the atmospheric gas pressure $p_0 = \rho g h_0$ and $H(p_1 = p_2 = p_0)$ marks the fictive water level. In case of the proposed TLCD for suppressing vertical vibrations of bridges a changed configuration according to Sun et al. [1] has been chosen. The piping system has been closed at one side and a gas over-pressure $p_1 > p_0$ in equilibrium position has been selected. The gas pressure p_2 still remains unchanged ($p_2 = p_0$). In the static equilibrium position of the TLCD a vertical distance H_0 occurs and forms together with the cross section and liquid density the active damper mass $m_A = 2\rho AH_0$. The ratio $\kappa = 2H_0 / L$ defines the effectiveness of the vertical TLCD.

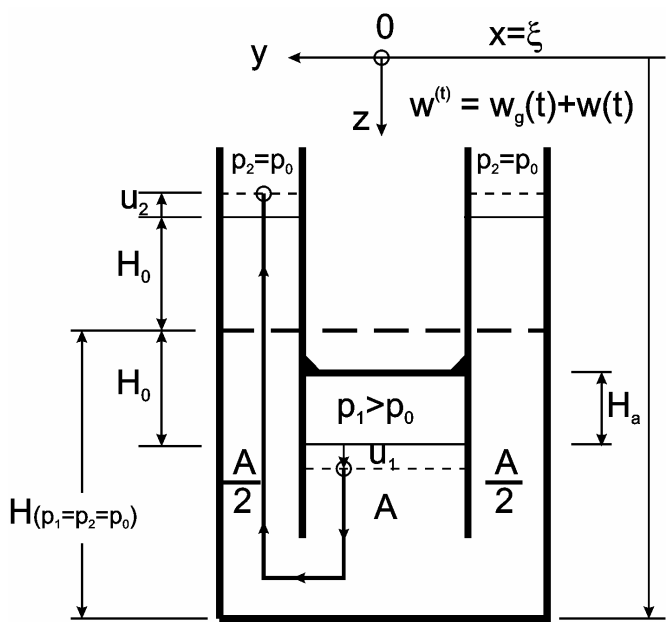

Figure 1. Symmetrically shaped TLCD for suppressing vertical vibrations of bridges

The gas inside the inner air chamber is quasi-statically compressed by the liquid surface in relatively slow motion. Hence, the pressure difference $p_2 - p_1$, see Figure 1, when properly linearized, changes the undamped circular natural frequency of the TLCD. Applying the modified Bernoulli equation along the streamline of the relative non-stationary (incompressible) flow in the rigid piping system, Figure 1, in an instant configuration, see Ziegler [6], vertical coordinate pointing downward, yields the equation of motion of the TLCD, where the linear frequency is given by

$$f_A = \frac{1}{2\pi}\sqrt{\frac{2g}{L}\left[1+\frac{n h_0}{2H_a}\left(1+\frac{2H_0}{h_0}\right)\right]}, \text{[Hz]}, \quad g = 9{,}81 m/s^2, \quad h_0 \approx 10m \qquad (3)$$

The linear frequency f_A of the TLCD includes the gas-spring effect in the tube sealed on one side. The gas pressure difference $p_2 - p_1$ approximately follows the quasistatic polytropic law, see Ziegler [6]. When linearized, with respect to the equilibrium pressure p_0, the pressure difference becomes roughly proportional to the fluid displacement $p_2 - p_1 \approx 2n\, p_0\, u / H_a$, in which $1 \le n \le 1.4$ is defined as polytropic index. The maximum stroke of gas compression is limited to $\max|u| = U_{\max} < 0.3H_a$, to keep the natural frequency nearly constant, in which $H_a = V_0 / A$ and V_0 denotes the pre-stressed volume in the gas chamber.

DEN HARTOG TUNING IN ANALOGY TO MECHANICAL DAMPER

Optimal tuning of the linearized damper model (parametric forcing neglected) is tuned in analogy to the mechanical damper attached to an SDOF-main system, all parameters referring to the tuned mechanical damper (TMD) are carrying a star, the mass ratio is

$$\mu^* = m_A^* / M^*, \quad \delta_{opt}^* = \frac{f_A^*}{f_S^*} = \frac{1}{1+\mu^*}, \quad \zeta_{A,opt} = \sqrt{\frac{3\mu^*}{8(1+\mu^*)}} \qquad (4)$$

Standard formulas apply for the optimal frequency ratio δ_{opt}^* and for the linear TMD-damping coefficient $\zeta_{A,opt}^*$, see Den Hartog [5]. In case of dominating vertical vibrations of the bridge, tuning of the TLCD is based on the comparison of the equations of motion of a TMD and the TLCD, see Hochrainer [4]. The mass ratio of the equivalent TMD results

$$\mu^* = \frac{m_A^*}{M^*} = \frac{\mu\kappa^2}{1+\mu\left(1-\kappa^2\right)}, \quad \mu = \frac{m_f}{M}, \quad \kappa = \frac{2H_0}{L} \qquad (5)$$

Consequently, the optimal frequency ratio of the TLCD changes according to

$$\delta_{opt} = \frac{f_A}{f_S} = \frac{\delta_{opt}^*}{\sqrt{1+\mu\left(1-\kappa^2\right)}}, \quad \zeta_{A,opt} = \zeta_{A,opt}^* \qquad (6)$$

The optimal linear damping coefficient remains unaffected.

LABORTATORY TESTS

After the theory for the TLCD had been worked out, laboratory testing was the logical next step. Since especially slender footbridges are susceptible for large vibrations, a laboratory beam with analogous slenderness and similar first natural eigenfrequency of approximately 2.5 Hz was to be chosen. Instead of trying to build a suitable laboratory beam, a modular approach was preferred, basically consisting of a 3.5m long lying IPE 100 steel beam with an eigenfrequency of app. 8 Hz and additional mass – steel or concrete blocks – that can be affixed to the beam to tune its circular natural frequency to a pre-determined value. Thus the dynamic properties of the simulated "bridge" can be changed allowing testing the TLCD's applicability at different frequencies.
For the laboratory test the first vertical bending mode was considered to be critical. Thus the TLCD was mounted in the middle of the beam, where the best effect can be obtained.

Figure 2 shows the dimensions of the laboratory beam as well as both bearings for statically determined support. Both bearing plates were mounted onto sockets to facilitate testing.

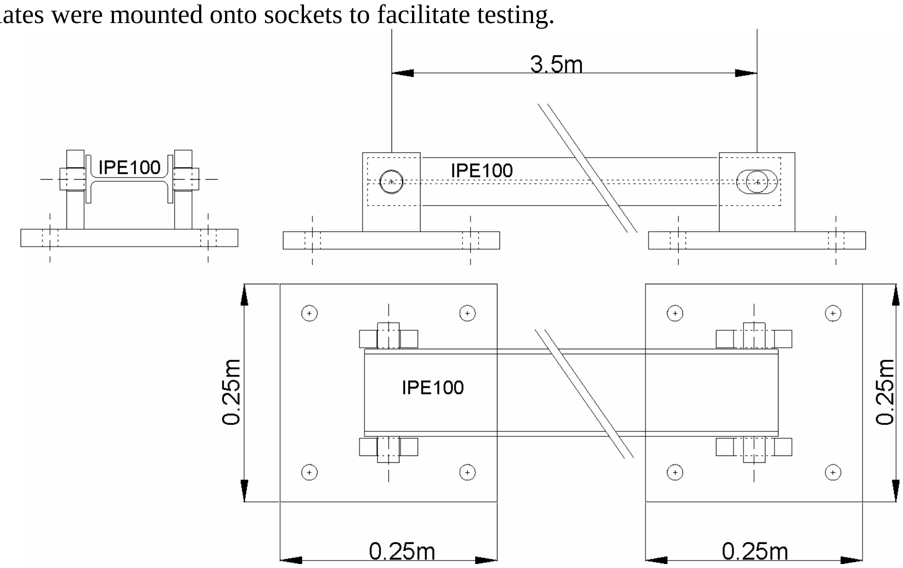

Figure 2. Steel beam model without additional mass

To counteract torsion, the active mass was divided and two identical tuned liquid column dampers with half the active mass each were installed and the gas spring placed on different sides of the beam. For schematics see Fig. 3.

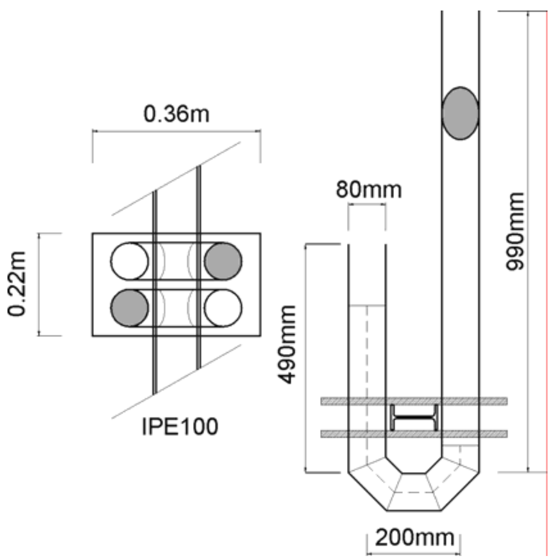

Table 1. List of Properties

beam:	
1st eigenfrequency	2.72 Hz
total mass M_{tot}	243 kg
TLCD:	
opt. frequency f_A	2.67 Hz
opt. damping $\zeta_{A,opt}$	5.29 %
active mass m_A	3,92 kg
total mass m_f	7,89 kg
equiv. mass ratio μ^*	0.78 %
volume gas spring V_0	3.42 dm³
initial deflection $2H_0$	39 cm

Figure 3. Tuned liquid column damper drawing + table of properties

EQUIPMENT

Based on a simplified model of a beam susceptible for large vibrations, the operability of a tuned liquid column damper was to be proven. To accurately capture the structure's dynamic properties with and without a TLCD, suitable means to actuate the beam in a defined way and to measure the frequency characteristic had to be derived.
Due to the fact that a moving coil actuator is able to exert forces independently of the displacement and linearly with the applied voltage, one such actuator was applied approximately 50cm from one bearing allowing in combination with a frequency generator and a suitable amplifier actuating the structure in a wide frequency range. Parallely, the generated forces were constantly measured using a precise load cell. For the measurement of the displacement over time a high precision laser sensor with a maximum resolution of 2 microns and a maximum sampling rate of 1 kHz was placed roughly in the middle of the beam. Additionally two accelerometers were affixed to the beam – again in the middle – to be able to capture torsion. Finally, the movement of the water column was to be measured. This is important to determine the natural frequency and damping coefficient of the TLCD itself as well as to monitor the behavior of the active mass during a frequency sweep. After some consideration, an ultra low differential pressure sensor with a range of 0 to 28" H_20 was selected and connected with the pressurized gas chamber. In figure 4 the laboratory beam as well as the TLCD, the actuator with load cell and two experimental improvements to increase damping.

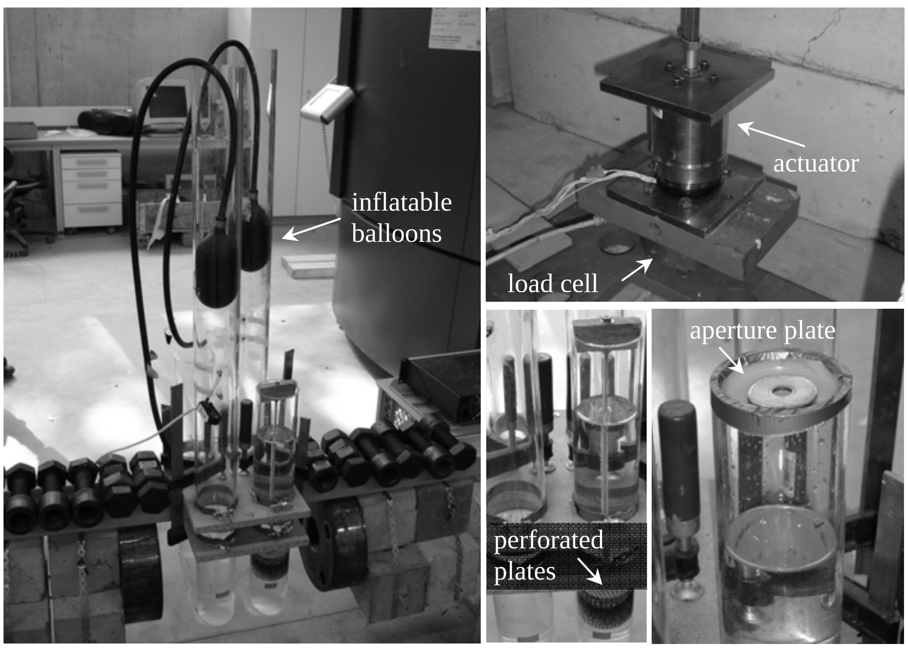

Figure 4. Photos of experimental set up

TUNING AND BASIC TESTING

Based on the already known first natural frequency, the optimal eigenfrequency for the TLCD, as well as the ideal damping coefficient, can be calculated by the equations presented in the first part of this paper. Thus for a determined geometry of the tube-system, an appropriate active mass and the corresponding gas volume are chosen. Then a frequency sweep is performed, meaning linearly increasing the frequency of the sinusoid force actuation between lower and upper bound, the performance of the TLCD is evaluated and the gas spring adjusted. These steps only need to be repeated 2 to 3 times until a good adjustment is achieved. To facilitate this process in the laboratory stage, a simple inflatable balloon (see figure 3) is used to seal one end of the tubing in a certain position, thus allowing the volume of the gas chamber to increase or decrease. Considering the applied forces during a sweep, a system-immanent loss of actuation force can be observed around resonance. Based on some measurements on this laboratory beam, a nearly linear relation between actuation force and amplitude can be observed. Thus the measured amplitude $a(t)$ is scaled with respect to the actual actuation force $p(t)$ and the static force p_0, which is necessary to determine the static displacement a_0. After that the transfer function – the ratio between dynamic and static displacement – can be calculated.

In figure 5, the enclosing curves for amplitude of the beam and pressure of the TLCD over time are shown. Looking at the data from both accelerometers an area during the sweep with torsion can be identified. The signal from the pressure sensor clearly denotes that the TLCD started to consume energy in this frequency range, although tuned to a higher vertical bending mode, where the main effect can be observed.

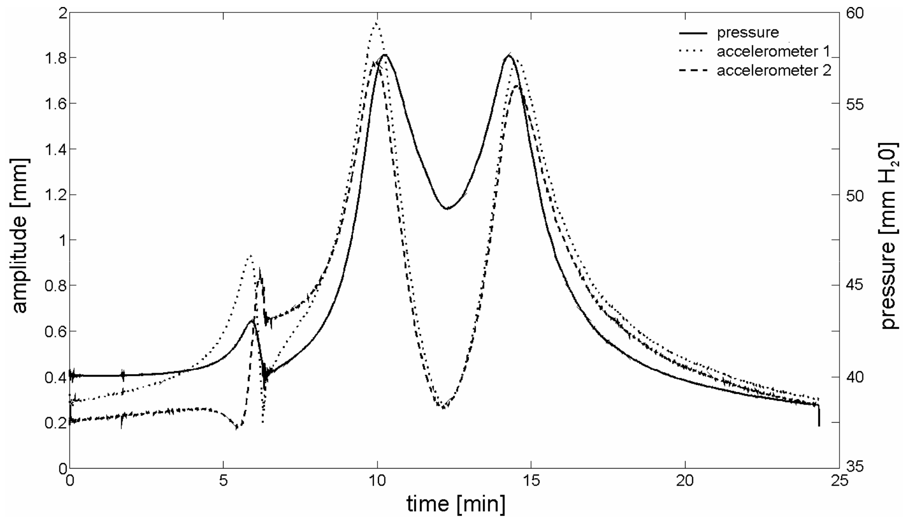

Figure 5.Amplitude of beam and pressure in TLCD plotted against time.

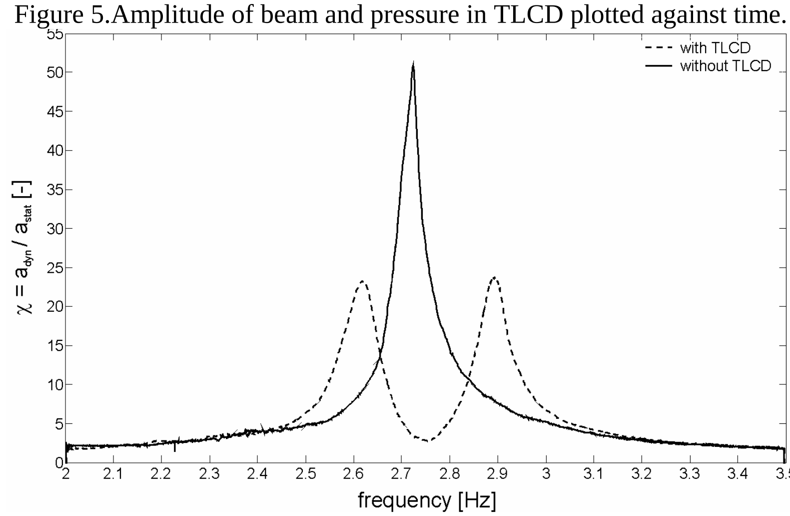

Figure 6. Transfer function with and without TLCD

Figure 6 shows the (scaled) transfer function with and without the presented TLCD using only clean water. As can be seen in this figure, without any additional improvements already a large reduction of amplitude of approximately 54% in resonance can be obtained leading to the conclusion that by increasing the damping coefficient of the TLCD itself the effect can be further improved. Evaluating the following equation

$$\zeta \approx \frac{1}{2 \max \chi} \tag{7}$$

the effective damping coefficient ζ of the system with TLCD results to 2.13% in contrast to 0.96% without TLCD.

OPTIMIZATION AND PARAMETER STUDIES

Mainly three approaches have been considered to achieve a more efficient damping effect. Firstly, the viscosity of the liquid itself can be increased by exchanging water with oil, for instance, or by adding certain components like xanthan – a substance used in producing food with the additional benefit of reducing the freezing point. On this subject experiments are currently conducted.

Secondly, the idea of creating local disturbances by introducing perforated plates in combination with several layers of steel-wool was worked out. This should increase energy dissipation without changing the TLCD's first natural frequency or functionality.

Thirdly, an aperture plate – reduction of the tubes' cross-section at the open end – was considered, as proposed by [1]. Both the second and the third approach could be developed to an active control system allowing constantly optimizing the TLCD's damping coefficient.

Figure 7 shows the (scaled) transfer functions without and with TLCD in 3 variants – 1 to 3 layers of steel wool. In figure 8 the effects of 3 different aperture diameters, with remaining cross-sections of 7.07 cm², 0.5 cm² und 0.25 cm², on overall damping are shown.

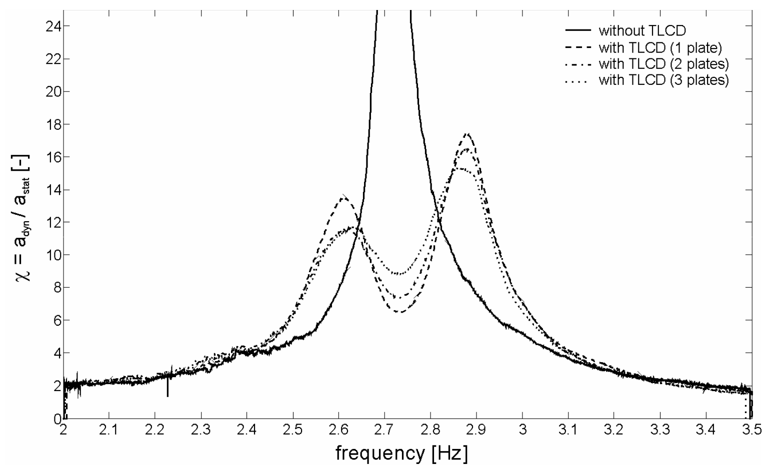

Figure 7. Ttransfer function with perforated plates and different amount of steel wool

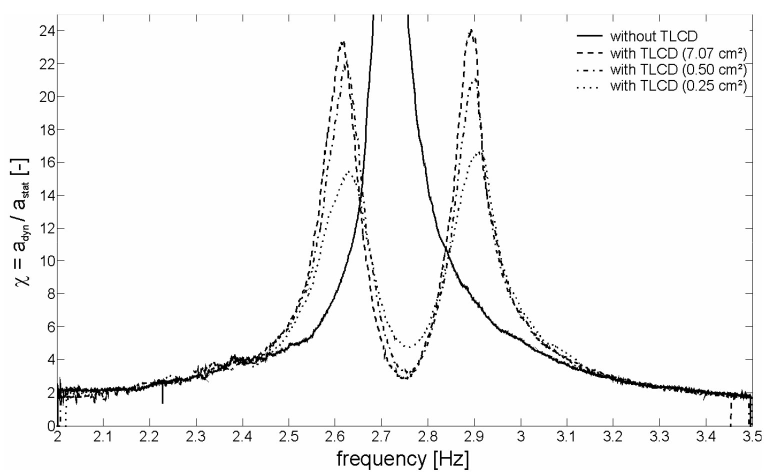

Figure 8. Transfer function with changing cross-section against atmosphere

As can be seen in figures 7 and 8, both methods – creating disturbances in the liquid column and reducing the cross-section of the opening to atmosphere – work. The maximum amplitude in resonance can be reduced by 70% and 67% respectively – for the best variant each. Thus, an effective system damping coefficient of 3.3% or 3.0% can be reached.

OUTLOOK AND CONCLUSIONS

In our experiments, it could be shown, that tuned liquid column dampers are an efficient means to damping vertical vibrations. Effects on torsion modes near the target frequency were proven too. One of the main benefits of TLCDs is their easy and very flexible installation, as well as robustness because they lack any moving mechanical parts. Unlike classical tuned mass dampers (TMDs) they need not be dimensioned exactly before manufacturing and can be effortlessly adapted to new conditions.

Some of the work presented in this paper is aimed at developing active control systems. Both approaches to increase damping in the TLCD – on the air side and in the liquid column – can be used in connection with control systems, thus allowing regular automatic adjustment of the damping coefficient to its optimal value. Additionally, the TLCD's gas chamber can easily be changed in size, for example by using a controllable cylinder piston, leading to a changed natural frequency. Consequently a TLCD could be designed to effectively dampen more than one vibration mode, depending on the situation.

During the next months, supplementary experiments on the effects of changed viscosity of the fluid and the TLCD's applicability to higher frequencies up to 8 Hz will be conducted.

ACKNOWLEDGEMENT

This research was conducted with the financial support of the FFG- Austria within the project "Flüssigkeitstilger". The support of the FFG is gratefully acknowledged. Similarly, gratitude is expressed to the industrial partner Bernhard Engineers, Vienna, Austria.

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