Sealed tuned liquid column dampers: a cost effective solution for vibration damping of large arch hangers

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ABSTRACT: The paper describes the applicability of a sealed tuned liquid column damper (STLCD) for the control of wind induced vibrations of long and slender arch hangers. Such intolerable transverse hanger vibrations were observed on a large railway arch viaduct with hangers up to 35 m in the Netherlands. As a result of a thorough investigation, the vibrations were attributed to unexpectedly low material damping at $\zeta = 0.0011$. A number of possible solutions were investigated, and a final solution with hydraulic dampers was chosen. As an alternative solution for cases such as this, the sealed configuration of a tuned liquid damper may be proposed. The STLCD device allows absorbing the fundamental hanger vibrations, even when exceeding 2.5 Hz. For the aforementioned example, the effect of the STLCD is analysed numerically and tested at reduced scale, indicating that the STLCD satisfactorily increases the material damping of the hangers, excluding the excitation type responsible for the intolerable vibrations.

1 INTRODUCTION

In their paper published in SEI, Vrouwenvelder and Hoeckman describe a case study on theoretical and practical considerations of wind induced vibrations observed on the tubular hangers of a railway viaduct, the Werkspoorbridge, in the Netherlands (Vrouwenvelder and Hoeckman, 2004). The authors describe the process of problem identification and solution optimization, starting from the observation in the fall of 2002 of intolerable transverse hanger vibrations on the 250m span tied arch (Fig. 1). The vibrations were attributed to Von Karman excitation made possible by an unexpectedly low material damping at $\zeta = 0.0011$. The paper reports a number of rejected solutions and the analysis method for the final solution with viscous dampers. Although effective, this can be seen as a costly solution (Reiterer, 2004), and an interesting alternative may be the sealed configuration of a tuned liquid damper. It is this solution that will be addressed in this paper.

A tuned liquid column damper (TLCD) is a specific type of motion damper, relying on the motion of a liquid mass in a rigid U shaped tube (Sakai et al, 1989). The external motion of the structural element on which the damper is attached induces a phase delayed motion of the liquid mass. This motion creates internal forces in the tube, counteracting the external forces. Additionally, the kinetic energy accumulating in the structural element is dissipated by turbulent damping forces, arising from a built-in orifice plate with small opening. The effectiveness of a traditional TLCD with open vertical tubes decreases rapidly for frequencies over 0.5 Hz.

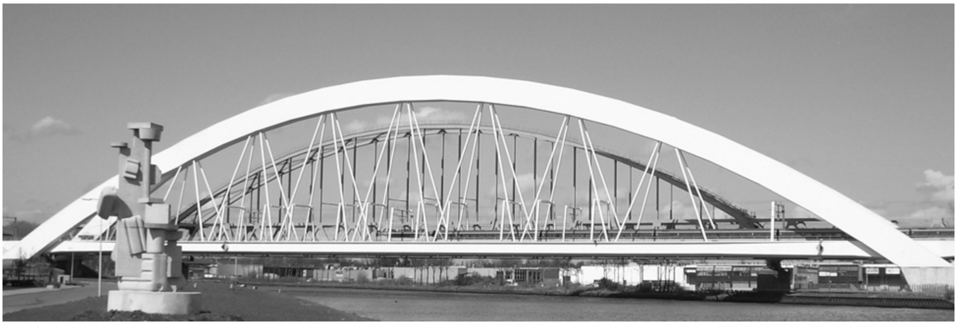

Figure 1 : The Werkspoorbridge – side view

Consequently, it can only be used for low frequency. However, if the vertical tubes are sealed, a pressure can build up in either side of these sections, increasing the undamped natural circular frequency. Such a device is named Sealed Tuned Liquid Column Damper (STLD).

In a first part of this paper, general considerations and calculation related issues on the STLCD concept will be presented. In a second part scale model tests, based on the dimensions of the Werkspoorbridge, are discussed. Finally, practical issues and further research steps are addressed.

2 MATHEMATICAL MODELLING

2.1 Equations of motion

When an STLCD is attached to a single degree of freedom structure (Fig. 2), the set of equations of motion can be written as Eq. (1) (Kwok et al, 1996).

$$\begin{cases} (1+\mu)\ddot{v}_s + \dfrac{\mu\gamma L}{L_{em}}\ddot{w} + 2\zeta_s\omega_s\dot{v}_s + \omega_s^2 v_s = \dfrac{P_w(t)}{m_s} \\ \dfrac{\gamma L}{L_{ee}}\ddot{v}_s + \ddot{w} + \alpha^2\dfrac{\xi|\dot{w}|}{2L_{ee}}\dot{w} + \dfrac{2g}{L_{ee}}w + \dfrac{p_0}{\rho L_{ee}}\left[\left(\dfrac{H_a}{H_a - w}\right)^n - \left(\dfrac{H_a}{H_a + w}\right)^n\right] = 0 \end{cases} \tag{1}$$

where A = vertical section cross-sectional area, A_1 = horizontal section cross-sectional area, α = A/A_1, g = gravitational acceleration, H_a = air spring height, L = liquid column length, L_{em} = L – B + B/α = equivalent uniform column length (equal mass), L_{ee} = L – B + αB = equivalent uniform column length (equal energy), m_s = equivalent structural mass, p_0 = initial air spring pressure, n = polytropic index (n=1.2), P_w = amplitude of external wind force, ζ_s= structural damping ratio, v_s = horizontal structural displacement, $\dot{v}_s$ = horizontal structural velocity, $\ddot{v}_s$ = horizontal structural acceleration, w = vertical relative liquid displacement, $\dot{w}$ = vertical relative liquid velocity, $\ddot{w}$ = vertical relative liquid acceleration, γ = B/L, ratio of STLCD horizontal length to total length, μ = ratio of liquid mass (m_l) to eq. structural mass (m_s), ρ =liquid density, ω_s = circular structural frequency, ω_d = circular STLCD frequency, ω_w = circular frequency external force, ξ = coefficient of head loss of liquid column.

In the cases where during vibration, the vertical relative liquid displacement w remains small, compared to the air spring length H_a, the last term of the second equation in Eq. 1 can be simplified to a linear term, from which a simplified expression for the natural circular frequency of the STLCD can be deduced (Eq. 2).

$$\omega_d = \sqrt{\frac{2g}{L_{ee}}\left(1 + \frac{np_0}{\rho g H_a}\right)} \tag{2}$$

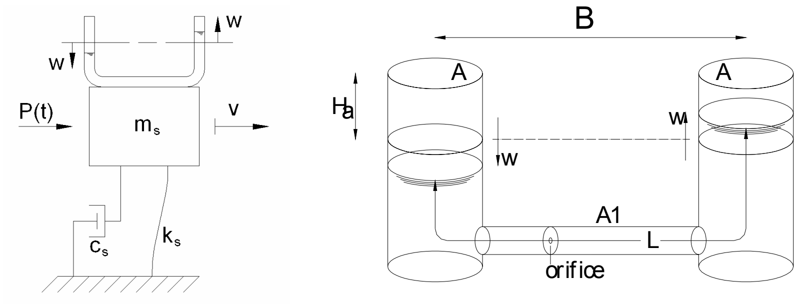

Figure 2 : STLCD fitted on a SDOF structure : notations

In the equations of motion the fluid velocity is assumed constant across the cross-sectional area of the horizontal and vertical tubes. They can be solved by a direct integration method, and render displacements, velocities, accelerations, and energy levels in structure and dampers as a function of external forces and initial conditions, and enable to calculate frequency response curves. The values of m_s, ω_s and P_w of the SDOF analogy can be found by Rayleigh quotient based methods and require calculation prior to the possible solution of the equations of motion.

2.2 Determination of structural eigenfrequency

From observations (Vrouwenvelder and Hoeckman, 2004), it is stated that the vibration of an arch hanger is independent of the movement of the remainder of the bridge, and in the damper design, the structure can be limited to the hanger only. However, the hanger vibration still depends on the rotational stiffnesses of the connection between the hanger and the bridge. The hanger can be modeled as a mass-spring single degree of freedom system, and its first natural frequency can be approximated by Eq. (3).

$$\omega_s^2 = R[y(x)] = \frac{\frac{1}{2}K_1\alpha_1 + \frac{1}{2}K_2\alpha_2 + \frac{1}{2}\int_0^l EI\left(\frac{d^2y}{dx^2}\right)^2 dx + \frac{1}{2}\int_0^l N\left(\frac{dy}{dx}\right)^2 dx}{\frac{1}{2}m_{nl}y_d^2 + \int_0^l \rho A(y)^2 dx} \tag{3}$$

where K_1 = rotational stiffness at 0 (0 being the lower boundary), K_2 = rotational stiffness at l (l being the upper boundary), α_1 = rotation at 0, α_2 = rotation at l, y_d = horizontal displacement at STLCD position, y(x) = vibration shape, ω_s = circular structural frequency, E = Young's modulus of hanger material, I = moment of inertia of hanger, N = normal force in the hanger, A = cross-sectional area of hanger, ρ = density of hanger material, m_{nl} = non-liquid mass of the STLCD. In this expression, the values of α_1, α_2 and y_d are given by y(x) or its derivative at their respective locations.

2.3 STLCD Optimization

The design and the optimization of the damper comprises the determination of 6 characteristics of the TLCD: A, A1, B, L, H_a and ξ. The choice of these parameters is an iterative process, starting with the choice of the product $\gamma.\mu$, which is the ratio of the liquid mass in the horizontal tube to the equivalent structural mass; $\gamma.\mu$ does not require to be larger then strictly necessary, and a value of 0.01 to 0.02 will generally be sufficient. With the necessary liquid volume calculated, one can choose a tube diameter practical for the construction of the damper. In general, an equal diameter is used for the vertical tubes and for the horizontal one because in the case of a sealed TLCD, the most important factor is the air spring volume, which can be achieved with any diameter. In the vertical tubes, the water level has to be as low as possible as its mass does not actively contribute to the damping. However, it has to be high enough to allow the water level to entirely fluctuate in the vertical tube. This means that γ (B/L) has to have a value as close to 1 as is possible. Based in these initial values of A, A1, B and L now determined, the remaining characteristics can be determined from Eq. (1) in order to tune the damper to the first natural frequency of the hanger. In fact, the damper has to be tuned for a somewhat lower frequency, as the damper mass has a small influence on the structural eigenfrequency. This influence is determined by the tuning ratio χ (ω_d/ω_s). The final steps of the optimization consist of finding the optimum values for χ and ξ, according to the general method presented by Gao and Kwok (Gao and Kwok, 1997). The optimum value of the tuning ratio thus defines the height of the air spring H_a, and the optimum value for the head loss coefficient determines the dimensions of the orifice plate.

2.4 Numerical Example

This numerical example is based on the dimensions of the Werkspoorbridge hangers (Hoeckman and Vrouwenvelder, 2004). These dimensions are : maximum hanger length = 35m, outer diameter = 394mm, inner diameter = 340mm, density = 7850 kg/m³, normal force = 2148kN, Young's modulus = 210 GPa, structural damping ratio = 0.0011. Eq. (3) calculates the first natural vibration of the hanger as ω_s = 15.43 rad/s or f_s = 2.46 Hz. This value is close to the reported value of 2.50 Hz (Vrouwenvelder and Hoeckman, 2004).

The position of the damper is chosen at 2/3 of the length of the hanger; this to be out of the free space required for railway traffic and services. Second, a choice is made for the mass ratio $\gamma.\mu$ = 0.01 and a choice for the non-liquid damper mass m_{nl} = 100 kg. With the values of m_{nl} = 100 kg and y_d = 23.33 m, the first natural vibration frequency can be calculated as ω_s = 15.30 rad/s or f_s = 2.43 Hz. With an equivalent mass of m_s = 5667 kg and the mass ratio $\gamma.\mu$ = 0.01, the mass of the horizontal liquid volume is equal to 56.67 kg. Based on this values, the horizontal tube diameter can be chosen as 0.2 m. With this, the area of the horizontal tube A is equal to A = 0.0315 m². To obtain a mass of 56.67 kg at ρ_{liquid} = 1000 kg/m³, the horizontal length B becomes B = 1.8 m. Generally it is chosen to have A = A_1, which is done in this example as well. The length L should be taken as short as possible since the vertical liquid mass does not effectively co-operate in the damping process. Nevertheless, the length of each vertical part should be sufficient to allow the water level to remain in the vertical part during the vibration. The liquid height in each tube is taken at 0,1 m. The length L becomes L= 2 m.

The tuning ratio χ, defining the air spring height H_a and the coefficient of head loss ξ, defining the orifice opening ϕ can be found by searching the (χ,ξ) combination generating the minimum horizontal displacements. These displacements are calculated by numerical integration of Eq. (1). Using this method, the damper is found to be tuned at (χ = 0.995,ξ = 60). These values correspond to Ha = 0.552 m and $\phi_{orifice}$ = 0.086 m.

Without a TLCD, the maximum displacement in the centre of the hanger with a material damping ratio equal to ζ = 0.0011 is $y_{stat}/2\zeta$ = 56 mm for a load oscillating at the eigenfrequency of the original system. With the damper installed, the maximum displacement is reduced to 1.8 mm. As the damping ratio is proportionate to the maximum displacement ($y_{max} = y_{stat} / 2\zeta$), the damping ratio of the hanger is increased to ζ = 0.027. Evidently, the proposed solution will control vibrations in one direction only, although damping will be needed in at least two orthogonal directions.

The proposed solution considers a damper attached to a single hanger only. A solution which is more practical, is to attach one damper to two transversely opposite hangers by means of a connecting rod. In addition, this configuration is also visually more acceptable. In this situation, with the geometry of the damper kept equal, the mass ratio is equal to $\gamma.\mu$ = 0.005. With the damper tuned at (χ = 0.997,ξ = 20), the maximum displacement in the centre of the each hanger is reduced to 2.5mm. This is also a value within acceptable limits, hence even smaller values of the mass ratio $\gamma.\mu$ could be applied.

3 SCALE MODEL

3.1 General Characteristics

The numerical example presented in paragraph 2.4 was tested in a scale model. For this, a scaled model of the 2 longest hangers of the Werkspoorbridge was fabricated. The model was designed according to the Werkspoorbridge geometry at a 1/10 scale. Fig. 3 gives a 3D representation of the scale model, while Fig. 4 shows the model as built.

Figure 3 : 3D representation of the scale model.

Figure 4 : As built scale model.

The scale model differs from the real situation on 2 points. The first is obviously that the model only represents the hangers, and the rest of the structure is omitted. The second is the absence of the normal force N, which changes the structural eigenfrequency with about 25%. It was decided that attempts to introduce a normal force into the specimen, still allowing for easy handling, would lead to unacceptable changes of the boundary conditions and probably of the structural damping. The first eigenfrequency was calculated in the absence of the normal force, and consequently measured on the test specimen. Finally, all damper related values were recalculated based on these new data.

The vibrations were registered with resistive strain gauges mounted on the hangers at the centre position. The recorded strain signals were transformed into displacements and the frequency analysis is done through Fast Fourier Transform of the recordings. Using strain gauges has the advantage over accelerometers that they are extremely small compared to the model dimensions. As a result, they do not change the frequency and structural damping characteristics.

3.2 Scaling relations

The scale model can predict the behaviour of the real hangers only if both structures are geometrically, kinematically and dynamically uniform. To comply with these conditions, all terms in the equations of motion should be multiplicable with a scale factor. For a chosen linear geometric scale α_L = 0.1, the geometric, kinematic and dynamic uniformity conditions require the remaining scale factors to be : α_w = 10 (frequency); α_t = 0.1 (time); α_v =1 (velocity); α_a = 10 (acceleration), and α_F = 0.01 (force). This set of scale factors determines the frequency and time scale, as most of the other scale factors can also be derived from the geometry. With well chosen values for the spring height H_a and the coefficient of head loss ξ, an overall scale factor can be calculated which is approximately the same for each term of the equations of motion.

The dimensions of the model, obviously based on commercially available tube sections are : hanger length = 3.58m, outer diameter = 42.4mm, inner diameter = 37.2mm, density = 7850 kg/m³, normal force = 0 kN, Young's modulus = 210 GPa. Eq. (3) calculates the first natural vibration of the scaled hanger as ω_s = 127.48 rad/s or f_s = 20.29 Hz. As will be explained later, this value is not achieved in the test setup, as the boundary conditions do not fully restrain the angular rotations at both ends of the hangers.

3.3 Measured eigenfrequencies

The eigenfrequency of the hangers in the scale model found from Fourier analysis of the strain results are equal to f_x = 17.6 Hz, and f_y = 13.86 Hz (Fig. 3). This difference in vibration frequency can be explained be unequal boundary conditions in longitudinal and transverse direction of the upper hanger connection. Indeed the connection with the tubular member of the frame is less rigid in the transverse direction, although evidently neither connection is fully rigid, since the calculated value of f_s = 20.29 Hz is never reached.

3.4 Scaled damper characteristics

Based on the model dimensions of paragraph 3.2, a scaled damper with the following dimensions is calculated : B = 0.25m, L = 0.332m, inner diameter = 0.0272m, orifice opening = 0.0095m, H_a = 0.106m. This damper is intended for use in transverse direction only, and in a first test, the effect of such a damper is tested by a simple measurement of the structural damping ζ, without and with the damper installed. Fig. 5 displays the measured strain values in the undamped hanger, while Fig. 6 displays the measured strain values in the damped hanger with the damper installed at the centre position (x_d = 1.6m).

From Fig. 5, and using the logarithmic decrement $\Lambda = 2\pi.\zeta$ (for small values of ζ), the structural damping of the undamped scale model is calculated as ζ = 0.00107. This value practically coincides with the value of ζ = 0.0011 from the Werkspoorbridge.

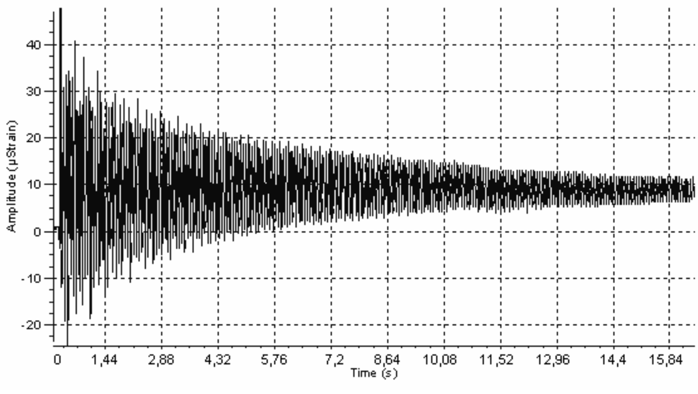

Figure 5 : Undamped strain signal.

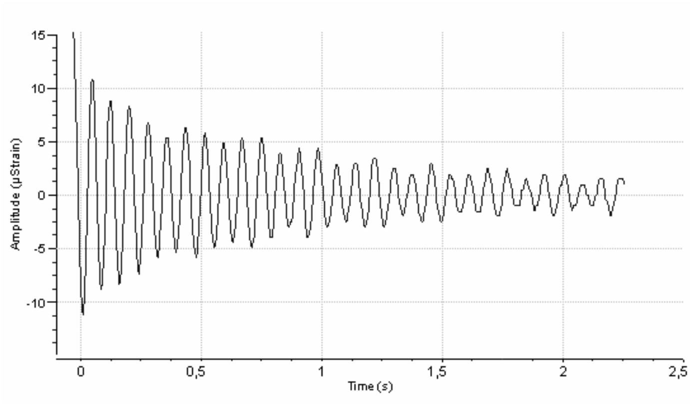

Figure 6 : Damped strain signal.

In the same way, Fig. 6 reveals that the structural damping is increased to $\zeta = 0.0125$ with the damper installed. This is a more than 10 fold increase of the structural damping.

The effect of the damper can also be calculated with the equations of motion of the SDOF analogy. Although the calculated logarithmic decrement is not constant, given the non linear damping, and the effective damping depends on the initial deformation, a structural damping value of $\zeta = 0.029$ was calculated. This calculated value more than doubles the measured value, which can be attributed to the fact that in the model vibration is considered in one direction only while in the scale model vibration energy is distributed over two orthogonal eigenmodes. Hence, in the scale model the damper will act in both directions, although intended for uniaxial damping only. As a result, the logarithmic decrement is approximately half of what was expected initially. In addition, when building a reduced scale damper, a difference of up to 3 % between calculated and achieved eigenfrequency is possible. This, however, translates to a proportionally larger difference in logarithmic decrement, as was indirectly noticed in the field experiments described in paragraph 3.5.

3.5 Field experiments

Measurements were done on the Zeebrugge harbour breakwater. The wind speeds at this location are of sufficient magnitude to obtain useful results. Following the model reassembly with slightly stiffer connections, the eigenfrequency in the damper direction was measured at 15.52 Hz, and the damper was reconfigured following this frequency change. Measurements were done by recording the strain signal over a period up to 100 seconds, and for consequent measurements, the damper is tuned to slightly different frequencies, and is placed on various heights.

$f_d = 14.30$ Hz ; $\chi = 0.972$; $\xi = 58$

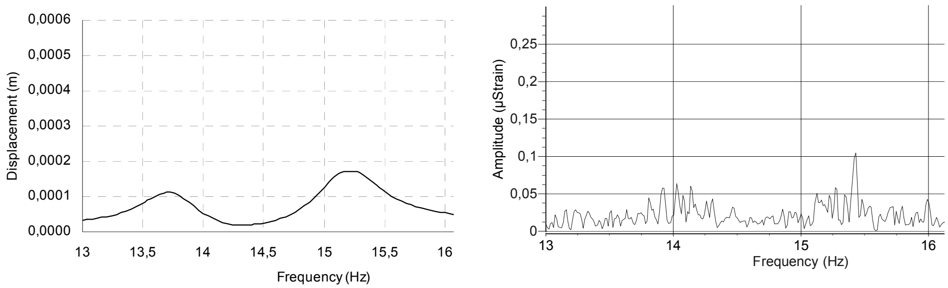

Figure 7 : Predicted and measured frequency response curve for near - optimum damper.

$f_d = 13.72$; $\chi = 0.933$; $\xi = 58$

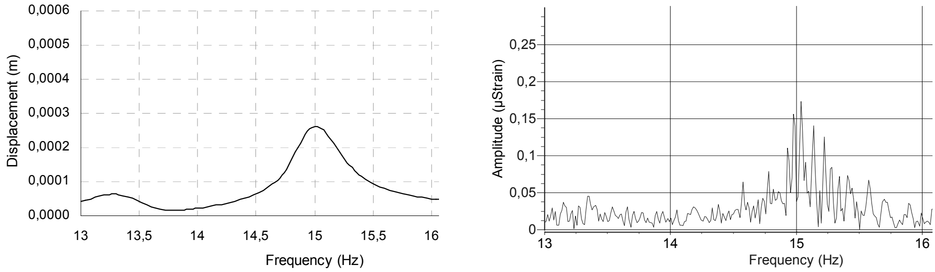

Figure 8 : Predicted and measured frequency response curve for non - optimum damper.

Because of the turbulent nature of the wind, the model is excited at a broad range of frequencies. Consequently, a frequency response curve is derived directly from a Fast Fourier Transform of the data set. Because of the fact that the wind speed is likely not to be constant for a period of time long enough to achieve a maximum displacement and because of the relatively long measuring time, the obtained frequency-response curve has a lower amplitude than the theoretical curve. In spite of that, the shapes of the calculated and measured frequency response curves correspond very well, although the measurements revealed an approximately 2.5 % (0.4 Hz) higher than calculated damper frequency. This taken into account, the curves agree very well, as can be seen in Fig. 7 and 8.

4 CONCLUSIONS

Wind induced vibrations of steel arch hangers can effectively be controlled by the use of sealed tuned liquid column dampers (STLCD). It was implied that the vibrating hanger can be identified to a SDOF system. After calculation of the relevant parameters of such a system, and by adequate choice of a ratio of damper mass to hanger mass, the damper can be optimized. Scale model tests indicate that the STLCD is effective although it does not completely functions as predicted by the mathematical equations. Several reasons including the uniaxial nature of the calculation model, and the indirect nature of the frequency measurement can be put forward. Further practical research, including direct frequency measurement are necessary before implementation.

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