DEVELOPMENT OF A CABLE DAMPER – A TAILOR-MADE DESIGN APPROACH FOR STAY CABLES

Peter Furtner
VCE - Vienna Consulting Engineers – Hadikgasse 60, 1140 Vienna – Austria
furtner@vce.at

Introduction

This paper is dedicated to the development of an innovative cable damper, which is a result of expertise from cable dynamics and bridge engineering well as from a manufacturer of damping materials and systems made available in close collaboration of Getzner Werkstoffe and VCE. The basic idea of the cable damper is the tailor-made design approach which considers the individual requirements based on the stay cable's geometry and required energy dissipation. For the achievement of the objective mentioned above the selected type of the cable damping device developed is an elastomeric damper using a material with high energy-absorbing properties and special damping characteristics.

REQUIREMENTS AND OBJECTIVES

Stadium roofs, towers and in particular bridge structures are designed more and more venturously and the span widths are increased by means of increasingly long cables. Due to more frequent application, the big span widths, the slenderness and in particular the low internal damping more or less problematic cable vibrations were observed frequently in the last few years. The reasons for these cable vibrations are not mentioned in more detail in this paper as they have already been frequently and comprehensively described in literature.

Usual means for the reduction of cable vibrations are so-called "disturbance ropes" (connection cables or wires which link the cable lines with each other and therefore put the cables "out of tune") and "vibration dampers" (increase of internal damping). There are numerous and various technologies and systems, in particular regarding vibration dampers, with the trend that each of the "big" stay cable system suppliers develops systems of his own. Familiar technologies include frictional dampers, rubber dampers as well as passive, active and semi-active (adaptive) damper systems which are attached to the cable and are usually supported at the bridge deck or the penetration tube. Apart from the frequently very high costs for these vibration dampers other disadvantages like energy demand for active and semi-active solutions and impairment of the optical appearance of cable-stayed bridges may arise as well.

The present paper describes the development process of a passive vibration damper based on polyurethane materials (type "rubber damper"), which can be simply adapted to each application and every individual cable.

The following objectives were defined for development work:

- Cost-efficiency
- Optimum effectiveness
- Easy customization
- Easy installation and suitability for subsequent mounting
- No maintenance required
- Long duration of life

- Little optical impairments (installation in penetration tube)

HIGH DAMPING ELASTOMER DAMPER

The efficiency of a cable damper depends on many parameters which have to be considered for the development and design of a new damper.

- Cable tension
- Cable sag
- Cable stiffness
- Rigidity of cable anchorage
- Free vibration length
- Rigidity of damper support
- Number of dampers
- Dynamic porperties of the cable
- Damper position (distance to the cable anchorage)
- Stiffness of the damper
- Non-linearities in damper characteristics

The behavior of a high damping elastomer damper is described in the following section based on the extensive theoretical research work of Fujino, Asce and Hoang [3].

For determination of the damper parameters to maximize the cable damping, empirical formulas or numerical results of solving complex eigenvalue problem are typically adopted. For the damper model, due to the hysteretic properties of the elastomer material, the damping force is independent of frequency and expressed as

$$f_c(t) = K(1 + i\varphi)v(x_c, t) \tag{1}$$

from which

$$F_c = K(1 + i\varphi)\tilde{v}_c \tag{2}$$

where K ist the spring factor of the damper and φ ist the loss factor of the material. This leads to

$$\frac{\xi_n}{x_c / L} \cong R_{sn} R_f \frac{\varphi \eta_f \overline{K}}{(1 + \eta_f \overline{K})^2 + (\varphi \eta_f \overline{K})^2} \tag{3}$$

where

$$\overline{K} \equiv x_R K / H$$

is a dimensionsless parameter of the spring factor.

If the damper is concealed in an anchor tube the effect of the anchor tube stiffness can be added. Starting from the damping force expressions

$$f_c(t) = kv_k(t) = K(1 + i\varphi)[v(x_c, t) - v_k(t)] \quad \text{or} \quad F_c = \tilde{v}_c \frac{K(1 + i\varphi)}{1 + K(1 + i\varphi)/k} \tag{4}$$

the cable modal damping is readily obtained as

$$\frac{\xi_n}{x_c / L} \cong R_{sn} R_f R_k \frac{\varphi \eta_k \overline{K}}{(1 + \eta_k \overline{K})^2 + (\varphi \eta_k \overline{K})^2} \tag{5}$$

where $\bar{k} \equiv x_c k / H$ and $\eta_k \equiv \eta_f + \dfrac{1}{\bar{k}}$ and $R_k \equiv \dfrac{\eta_f}{\eta_k} = \dfrac{\bar{k}\eta_f}{1+\bar{k}\eta_f}$.

Given the loss factor φ the optimal spring factor K which maximizes modal damping ξ_n can be determined. If the symbols are defined as

$$\eta_\varphi \equiv \sqrt{1+\varphi^2} \quad \text{and} \quad \mathrm{R}_\varphi \equiv \frac{\varphi}{1+\sqrt{1+\varphi^2}} \qquad (6)$$

then the maximum modal damping ratio in the cable is

$$\frac{\xi_n^{\max}}{x_c / L} = 0.5 R_k R_f R_{sn} R_\varphi \quad \text{for} \quad \bar{K}^{opt} = \frac{1}{\eta_k \eta_\varphi} \qquad (7)$$

Therefore for a damper with a given loss factor the spring factor $\bar{K}$ is a key parameter. In this case $\bar{K}$ is modified by the cable flexural rigidity η_f, the damper support stiffness η_k and the loss factor η_φ. Note that the modal damping for an elastomer damper is associated with the modal index n only by the factor R_{ns}. Thus for a taut cable the same damping level ξ_R can be achieved fort he first few vibration modes of interest. A typical modal damping curve ξ_R versus $\bar{K}$ of an ideal taut non-flexural cable ($\eta_f = R_f = 1$) with a elastomer damper of rigid support ($\eta_k = R_k = 1$) and given $\varphi = 0.25$ is shown in Figure 1. The maximum damping in this ideal case is

$$\xi_R^{\max} = 0.5\, R_\varphi x_c / L = 0.0616\, x_c / L \qquad (8)$$

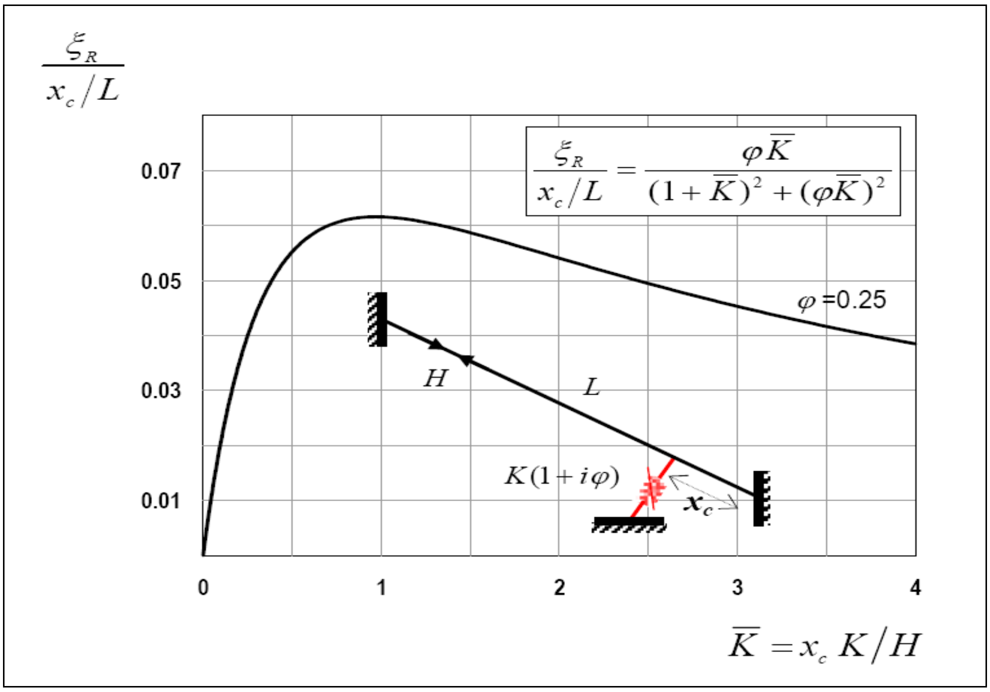

Figure 1: Cable with elastomer damper (Fujino, Asce and Hoang 2007)

CONCEPT AND LABORATORY TESTS

Starting point for the development is the heavily damping material Sylomer® HD by Getzner Werkstoffe GmbH, which was modified for the cable damper. An elastomer generally has elastic, ductile and damping properties. For the application in the damper defined elastic and damping quotas are required.

The working principles of dampers are generally always based on physical processes which can be described by physical effects. Damping can be reached by the following physical effects by means of an elastomer:

- Strain / compression
- Bending
- Shear
- Torsion
- Transverse contraction

Considering the functional requirements of a cable damper, the maximization of effect and under the aspect of durability and reliability the physical effect of shear is most promising (Figure 2). In order to be able to damp all vibration directions of transversal cable vibrations in equal measure, the shear unit must be designed symmetrically to the cable axis.

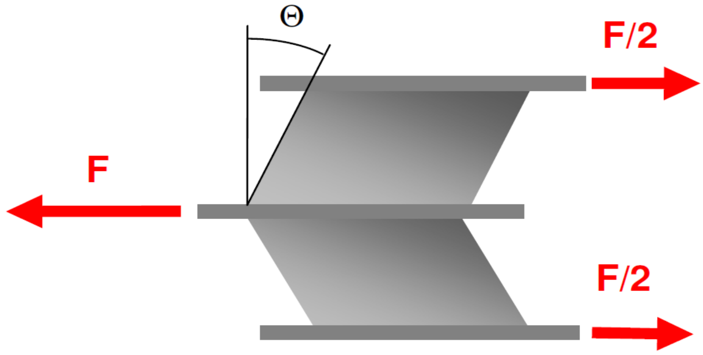

Figure 2: Action principle of the shear unit

In the next step the requirements were described in detail:

- The damper shall be composed of several independent damper elements
- The elements shall be easily exchangeable
- The failure of an element shall affect the impact of the other elements as little as possible
- The damping elements shall be exclusively stressed by shear force
- The impact shall be effective in all directions
- The dimensions shall be as compact as possible in order to enable the installation in the penetration tube
- The volume of elastomer shall be as great as possible and be fully used at the given dimensions
- The damping elements shall be designed in such a way that no tensile stresses arise in any load case
- The whole damper shall be designed free of clearance so that the damper is effective even with very low vibration amplitudes
- All connections, in particular those between steel and elastomer, shall be designed for great durability.
- The removal of dissipation heat shall be guaranteed.

DESING AND CONSTRUCTION

The mentioned requirements led to the damping element shown in Figure 3. The thickness and geometry of the damping element is designed in such a way that no tensile stresses arise in case of maximum shear deformation and therefore maximum shear angles. This can be reached on the one hand by prestressing the element in the course of installation and on the other hand by a geometric shape. The joining surface of steel and elastomer is maximized by the shape.

The connection itself is performed by direct injection of sole of the elastomer at the pre-treated steel parts in the course of casting. The mechanical resistance was optimized in the course of the project by improving the composition, the manufacturing process and the pre-treatment of steel. The durability was verified at the servo-hydraulic test stand by long-term tests with up to eight million load cycles.

The achievement of the structural element parameters respectively favoured could be checked by means of the test device:

- Dynamic stiffness [N/m] (real and mathematical part)
- Damping coefficient [Ns/m]
- Heat loss work [N/m]
- Loss angle [°]

In the course of the development work elements with most diverse parameters were produced and tested in order to enable later customization regarding the properties for every cable.
The tests also proved heat dissipation by the steel parts which prevents overheating of the damper in case of continuous stress.

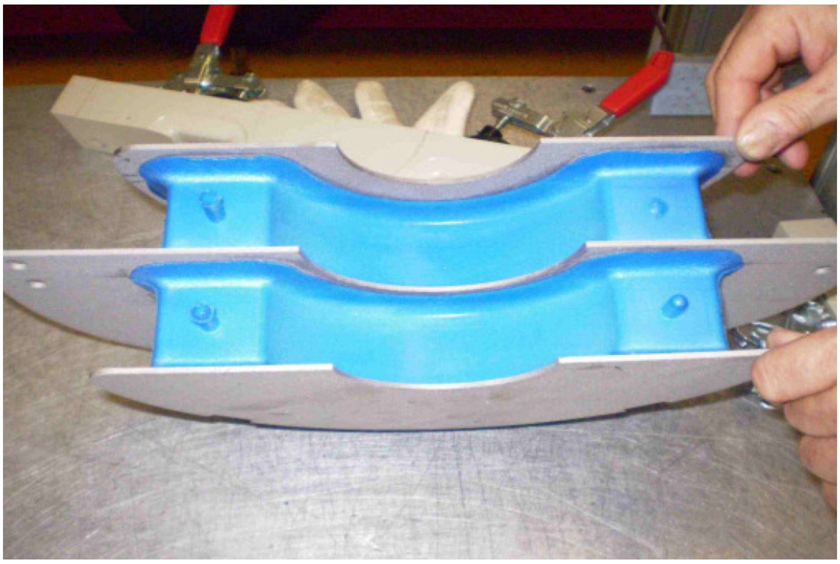
Figure 3: Damping element

PROTOTYPE TEST AT THE TEST STAND

After the construction and assembly of the respective fixing units for cables and support structures prototype tests were carried out at the 1:1 test stand at ELSA in the JRC in Ispra / Milan.

The test stand was established in the course of the EU research project IMAC and consists of four different cables. As a basis for the design of the damper prototype measurements and analyses were performed at the cables, which resulted in very low damping rates of approx. 0.1 % for the first and second natural frequencies of the cables. A target value for the damping ratio of 0.5% (logarithmic decrement ~3.15%) was defined.

Figure 4 shows the expected damper action dependent on the damping coefficient and the loss factor for the selected damper position. It is clearly visible that already relatively slight deviations of the damping coefficient from the target value strongly affect the damper impact. Previous laboratory tests showed loss factors ranging from 0.35 to 0.60 % for the elastomers used.

Corresponding to Figure 5 the test set-up was arranged in such a way that test arrangements from one to eight damping elements placed in one to four panels are possible.

The cables were manually excited to vibration in the 1st and 2nd eigenfrequencies for the tests. The cable vibrations were measured with several accelerometers and displacement transducers. The damping was respectively determined from the decay process by means of a curve-fitting algorithm.

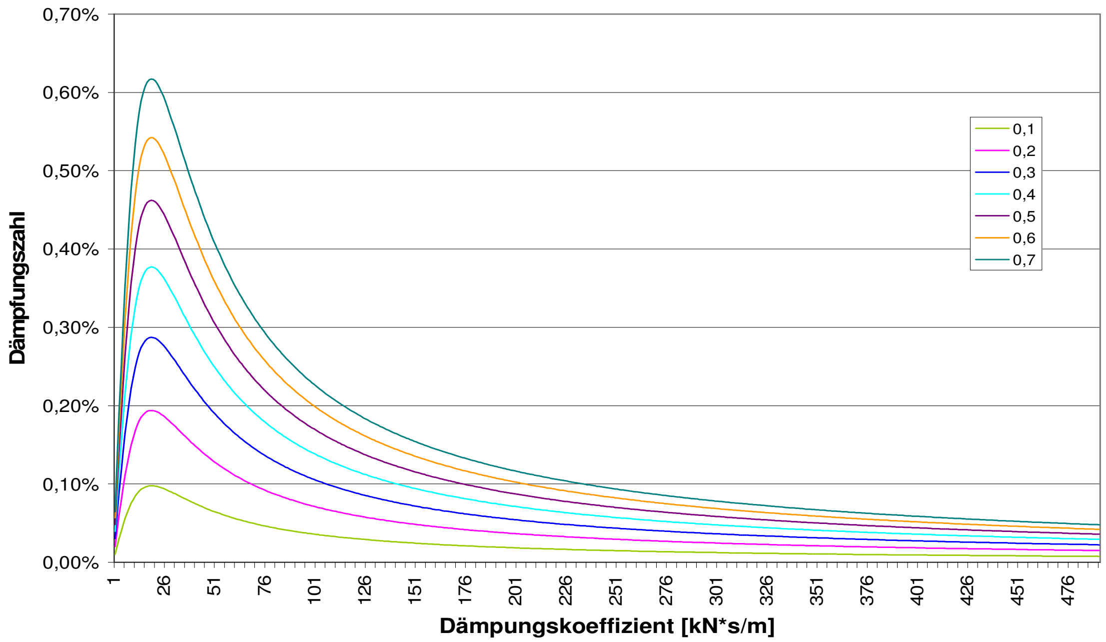

Figure 4: Damper impact dependent on damping coefficient and loss factor

Depending on the configuration and the natural frequency damping rates of up to 0.89 % could be determined. The tests also showed that greater bending stiffness of the cable close to anchorage and the slightly damping effect of the anchorage configuration have a negative effect on the effectiveness of the damper.

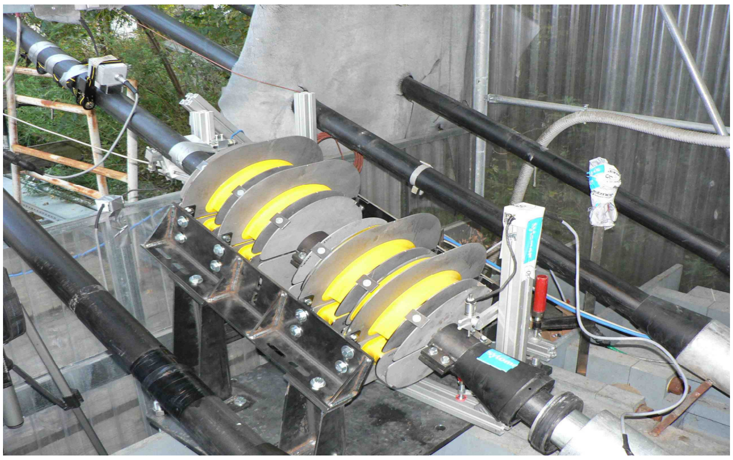

Figure 5: Test set-up at the test stand at ELSA (JRC)

FIRST APPLICATION OF THE PROTOTYPE

Prototypes where applied at the four stay cables of the transmission mast at the top of the Schöckl mountain/ Austria (Figure 6) for the first time. Considerable cable vibrations are frequently observed at these stay cables.

Figure 6: Transmission mast at the Schöckl and stay cable with installed damper

In the course of mounting extensive measurements and analyses were carried out and a permanent measurement system for the monitoring of vibrations was installed at two of the four stay cables.

The goal of the prototype installation was the increase of the damping ratio form 0.19 % to at least 0.50 for the vibration modes of interest. The analysis of the measurement data shows results in the range between 0.50 and 0.60 % for the first 3 modes of all four cables.

OUTLOOK

Extensive experience with regard to the interactions between cable damper, vibrating cable and influence of the anchoring structure could be gained during the development work of the presented passive cable damper, in particular during the tests at the test stand. The development process and the tests have corresponded to the expectations up to now. However, further analyses regarding the influence of environmental conditions, in particular of very high and very low temperatures, on the effectiveness of the damper are required. In addition long-term observation by measurements and analyses for a minimum cycle of one year is planned. Due to the exposed location regarding environmental influences the transmission mast Schöckl is especially suitable for this purpose.

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