22nd International Conference
ENGINEERING MECHANICS 2016
Svratka, Czech Republic, 9 – 12 May 2016

REDUCTION OF CABLE VIBRATIONS CAUSED BY WIND

I. Golebiowska[*], K. Peszynski[**]

Abstract: *The cables are important components of civil engineering structures. Due to their low internal damping, mass and rigidity, they are very sensitive to the dynamic action of the wind. Frequent and excessive cable vibrations are the cause of fatigue failure in the fixing location. Restricting the damage possibility caused by the wind is very important not only because of the safety of the construction, but also for economic reasons. The paper presents an analysis of experimental and theoretical research on ways to reduce the cables vibrations level and reviewing selected their application. Attention was drawn to merge the various methods in order to obtain the most effective way of damping.*

Keywords: Cable vibrations, damping methods, aerodynamic and mechanical methods

1. Introduction

With the development of innovative materials, technology, and advanced methods of calculations, people erect increasingly higher and longer constructions. Such structures as cable-stayed bridges, suspension bridges, masts, stacks, overhead power lines etc. are usually characterized by low rigidity and relatively low damping, and therefore are strongly affected by natural environment, such as wind. Cables are commonly used as structural components in such constructions. They have very low internal damping and are not capable of total dissipation of excitation energy, hence they can reach high amplitudes of vibrations. Damping coefficients of cables in serviced bridges range between 0.001 to 0.005 [Fujino Y., Kimura K, Tanaka H., 2012]. An increased span length of modern bridges requires longer cables, which leads to hazards related to their safety. High amplitudes of vibrations may induce excessive stress and fatigue damage in cables and in their connections to structural elements. Therefore, reduction of cable destruction possibilities caused by vibrations is very important not only in terms of economy but for structural safety as well.

Cables of bridges exhibit a variety of different aerodynamic and aeroelastic phenomena. In order to assume an effective and efficient method of lowering the level of cable vibrations, we need to have deep understanding of physical phenomena that take place under the influence of wind, such as: vortex excitation, vortex excitation at high velocity, rain-wind induced excitation, galloping, galloping of dry inclined cables, wake galloping for groups of cables, buffeting, etc.

This work is devoted to overview and analysis of the methods of damping the vibrations of bridge cables, as well as their application.

2. Vibration damping methods

General vibration damping methods are divided into passive, semi-active and active. Passive vibration control equipment are devices with fixed parameters (rigidity and damping). They do not require external power supply to work and are relatively cheap in comparison with active and semi-active control methods. These devices are relatively easy to design, manufacture, and service.

In comparison with the passive method, the active method of structure vibration damping is characterized by two basic features. The first one is the necessity to supply the required external energy to

[*]Assoc. Prof. Irena Golebiowska, PhD.: UTP University of Science and Technology, Faculty of Civil and Environmental Engineering and Architecture, Al. prof. S. Kaliskiego 7, 85-796 Bydgoszcz; PL, irena_golebiowska@wp.pl

[**]Assoc. Prof. Kazimierz Peszynski, PhD.: UTP University of Science and Technology, Faculty of Mechanical Engineering, Al. prof. S. Kaliskiego 7, 85-796 Bydgoszcz; PL, kazimierz.peszynski@utp.edu.pl

the control system. The second one is the need to implement feedback, as the process is based on real-time measurement data. Active control system is substantially a closed control system and it includes four basic components: structure treated as an object of control, measuring devices (vibration sensors), controller, and actuators. These devices are connected in a feedback loop. Measuring system is especially sensitive; it is composed of sensors carefully positioned on the structure, which primarily measure the structure responses to dynamic excitations. More complex active control systems may also measure external interference (such as wind velocity) and then the control system is a branched system with measurement of interfering value. After proper processing, measurement signals are input signals to the controller, which develops controlling signals for the actuators on the basis of a strictly specified algorithm. Practically, all the power supply is used for the actuators, which are responsible for counteracting the enormous forces of dynamic interference, hence their power of sometimes several dozen kilowatts.

A compromise between the passive control system and the active control system is semi-active control system. It combines advantages of passive and active systems, but it also has some of their drawbacks. In this system, external energy is used to set the parameters of the passive controller (damping and/or rigidity). Characteristics of such device must be modified during its operation. Energy requirements of the semi-active control system are low – several dozen watts. This type of control is substantially a passive control with an internal built-in controlling system.

Currently, passive dampers are divided into three categories: hysteresis dampers, viscous dampers, and mass dampers. The first category of dampers uses materials and systems with hysteresis damping features. The second category uses fluids whose resistive force affecting a body is directly proportional to its velocity. The most common are fluids with high viscosity, such as engine oil. Mass dampers use the inertia of additional mass added to the structure. Frequency of a damper's own vibrations is usually set to the value of basic frequency of the structure's own vibrations in order to transfer the energy of vibrations from the structure to the damper.

There are several possible methods of damping cable vibrations. They include: surface modification (aerodynamic methods), increasing rigidity of a cable system (structural methods), and increasing the damping level (mechanical methods).

2.1. Aerodynamic methods

The reference literature suggests numerous different cable surface modifications [Zdravkovich M.M., 1981]. One of the most common modifications are helical strakes and ribs (spiral turbulators). Helical strakes with a rectangular section and sharp edges break the vortex structures, help to avoid rain-wind excitations through preventing the forming of water rivulets, and induce three-dimensional flow interferences, which, as a consequence, helps in reducing the level of vibrations caused by vortexes,see Fig. 1.

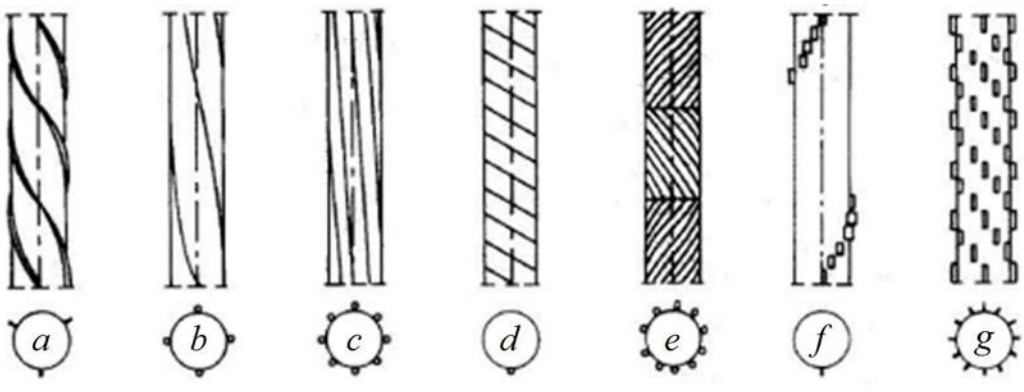

Fig. 1: Types of cylinder surface modifications: a), b), c), d), e) spiral turbulators; f) wing-like turbulator; g) fin turbulator.

The paper [Lee S.J., Kim H.-B., 1997] presents results of a test on a cylinder with three rods wound on it. It was established that surface ridges (wound structures) lengthen the area of vortex formation and their frequency and wake width are reduced. The publication [Novak M., 2001] proposes the installation of separate little rectangular plates (wing-like turbulator) on the cylinder surface, making a helical line.

This solution is based on the same concept as that described above, but the plates arranged helically do not block water rivulets. Another solution is to add extended rectangular plates to the cylinder surface by welding. This circumferential solution provides multi-directional efficiency of this surface modification, which is backed up by 70% reduction of vortex excitation in resonance [Alexandre M., 1970].

In order to reduce aerodynamic interactions between two parallel hanger cables on the Akashi-Kaikyo suspension bridge (Japan), wires were wounded around the hanger cables. Spiral turbulators proved to be effective in reducing the level of vortex-induced vibrations and wake-induced instabilities, see Fig. 2 [Fujino Y., Kimura K, Tanaka H., 2012].

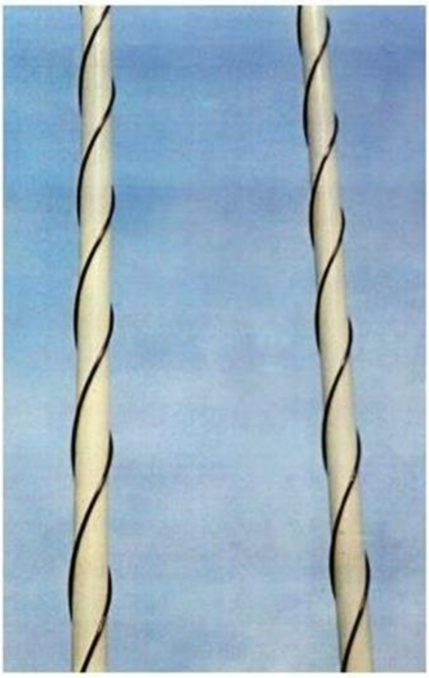

Fig. 2: An example of spiral turbulators used on the Akashi-Kaikyo suspension bridge

Another effective method of aerodynamic damping are channels made on the cable surface along the axis so that water can flow through this channels without the possibility of transverse movement. Such type of modification has been implemented on the Higashi-Kobe bridge (Japan), see Fig. 3.

Fig. 3: Cable surface modification on the Higashi-Kobe bridge.

This solution is very efficiently when it comes to reducing inclined cable vibrations at rain-wind excitation [Saito T., Matsumoto M., Kitazawa M., 1994]. The paper [Bearman P.W. and Harvey J.K. 1993] describes the results of tests on a cylinder with evenly arranged indentations within its entire circumference, with the proportion between the indentation depth and the cable diameter corresponding to the one in a typical golf ball. The cylinder with these indentations demonstrated a lower critical Reynolds number than a smooth cylinder, because the irregular surface made the boundary layer increase in thickness and led to earlier detachment of the flow [Holmes, J.D., 2001], see Fig. 4.

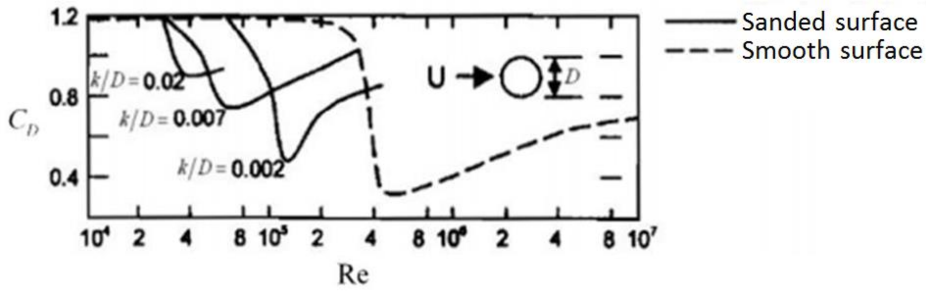

Fig. 4: Resistance coefficient for different values of k/D: k – indentation depth, D – cylinder diameter.

Another type of surface modification is making a regularly arranged pattern on the cable surface in the form of discreet indentations, which prevent water rivulets from forming [Miyata T., Katsuchi H., Tamura Y., 1999]. Such an indentation conduces to stabilization of flow separation from the cable surface. Cables of such type have been used on the Tatara bridge (Japan).

Fig. 5: The example of cable surface indentation used on the Tatara bridge

Cable surface can also be modified by applying proper perforated shrouds or longitudinal bars parallel to the cylinder axis or rods attached to a ring mounted on the cylinder. Paper [Wong H.Y. and Kokkalis A., (1982)] presents results of experimental tests carried out in an aerodynamic tunnel on selected types of cylinder surface modifications. The tests demonstrate that all the modifications were effective in reducing the level of vibrations induced by vortexes; the highest reduction of aerodynamic resistance coefficient was observed in the case of the perforated shroud, although it was not the most effective method of vortex damping.

2.2. Mechanical methods

There are many various solutions for reducing vibrations of cables in cable-stay bridges and hanger cables in suspension bridges. The simplest solution, often used, are additional lines that tie the cables; they can be installed vertically, horizontally or diagonally, as needed, which increases the rigidity of the cables within their plane (structural method). This damping method has been used in many bridges around the world, e.g. in the Normandie bridge (France), see Fig. 6, Second Severn (Great Britain), and Yobuko (Japan).

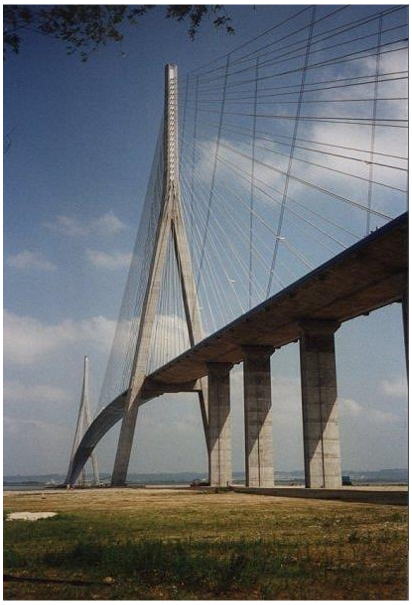

Fig. 6: A system of additional tying cables on the Normandie bridge (France).

Many cables of cable-stay bridges are equipped with passive internal dampers at the point where the cables are connected with the deck (inside the stay pipe of the anchorage area). This method shows highly-effective passive internal dampers (VSL), see Fig. 7, which can be also used as external dampers.

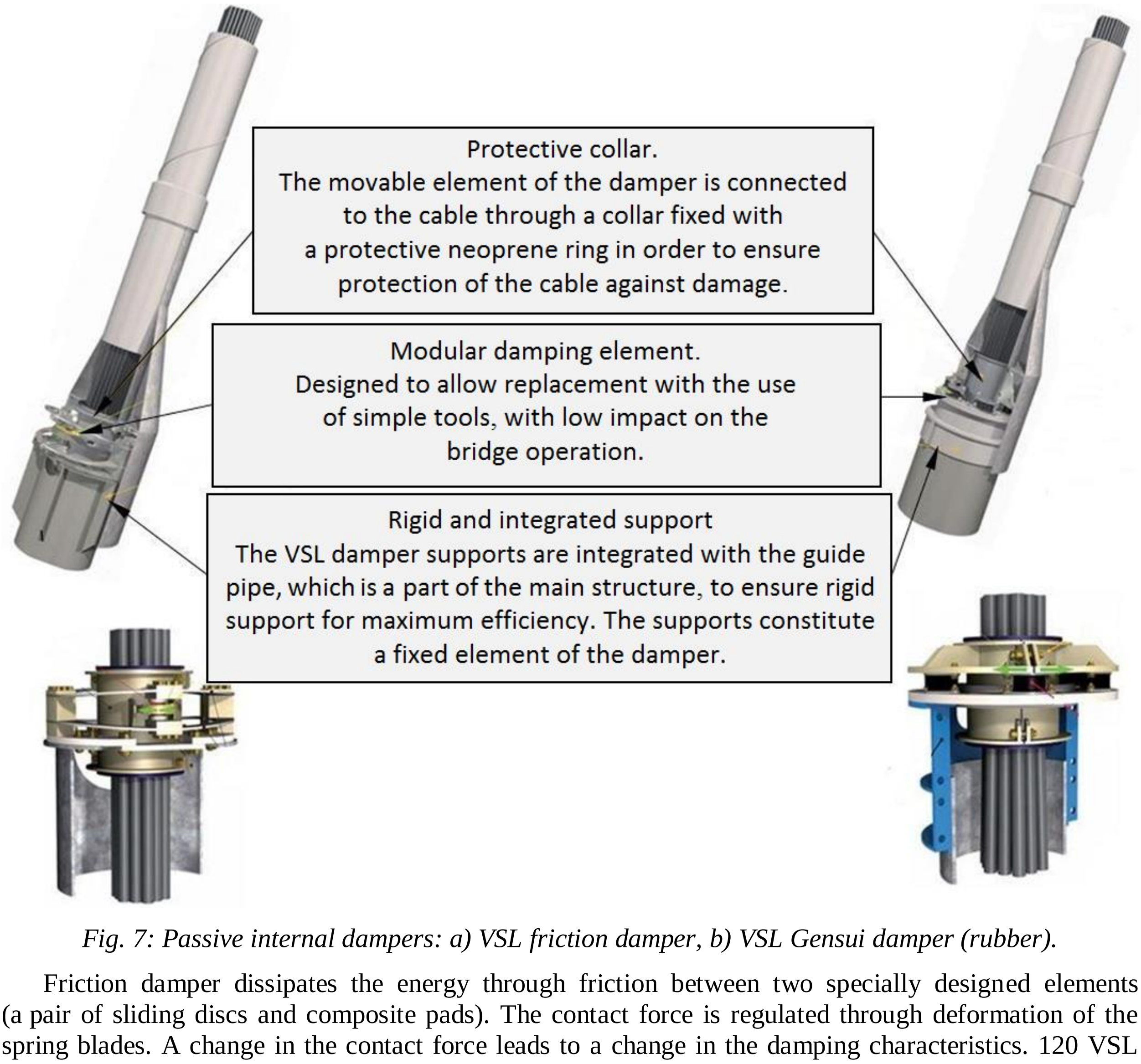

Fig. 7: Passive internal dampers: a) VSL friction damper, b) VSL Gensui damper (rubber).

Friction damper dissipates the energy through friction between two specially designed elements (a pair of sliding discs and composite pads). The contact force is regulated through deformation of the spring blades. A change in the contact force leads to a change in the damping characteristics. 120 VSL friction dampers have been used for the cables of the Udevala bridge (Sweden). Optimum damping of the friction damper is independent from the type of vibrations, i.e. the friction damper will be effective for any type of vibrations.

VSL GENSUI damper dissipates energy through deformation of elastic elements made of high-durability rubber with high fatigue strength. Several damping elements are placed between two discs, one of which is rigidly attached to the stay cable and the other to the guide pipe. In this case, the characteristics of the damper is determined by the number and type of damping elements used.

If cable damping is still insufficient, using the above damping method, external dampers are used that are placed within a short distance from the cable anchoring point. External oil dampers have been applied to cables in, for example, the Normandie bridge (France) and the Aratsu bridge (Japan), see Fig. 8.

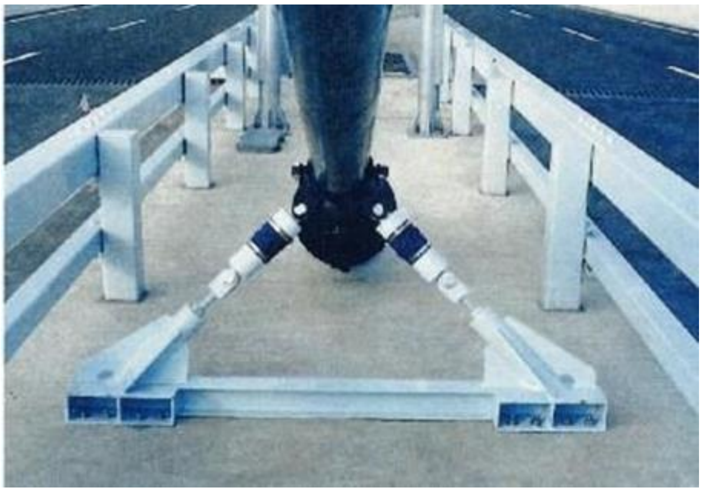

Fig. 8: Oil damper installed on the Aratsu bridge.

Advantages of oil damper: wide range of damping capabilities, low costs, simple technology. Oil damper may provide axial damping force along the direction of its cylinder. In order to control the cable vibrations in both planes (in the cable plane and beyond it), installation of two oil dampers transversely to the cable axis at a specific angle of inclination is required. Passive viscous dampers (oil, hydraulic) can be effective, providing optimum damping level only for a chosen type of vibrations, while for the other types the added damping will be lower than optimum. It is commonly known that vibrations induced by the rain-wind excitation are dominated by the first several types of vibrations, mainly by the second type. That is why, these dampers designed to damp the first type of vibrations will be less effective in minimizing vibrations induced by the rain-wind excitation. Damper effectiveness is higher when it is mounted at the anti-node (maximum amplitude) point of the cables; however, due to practical and aesthetic reasons, external dampers are mounted near the anchoring point of the cable, i.e. within a distance of 2-6% of the cable length [Gimsing N., Georgakis Ch., 2012].

Today, semi-active dampers of MR type (magnetorheological) are also widely used to damp cable vibrations. MR dampers are filled with MR fluid controlled by a magnetic field with the use of an electromagnet, which allows a continuous control of damping characteristics through the change of energy. Its rheological characteristics will change in the presence of a magnetic field: without a magnetic field, MR fluid acts as a Newtonian fluid; if a magnetic field is applied, MR fluid acts as a Bingham fluid. MR fluid consists of three basic components: base fluid (carrier fluid), metal particles, stabilizing additives.

The base fluid serves as a carrier in which magnetic particles are suspended. Hydrocarbon oils, mineral oils, and silicone oils are commonly used as carrier fluids for manufacturing MR fluids. If there is no magnetic field, an MR fluid has similar characteristics to those of the carrier fluid, but upon applying a magnetic field, the rheological characteristics may change rapidly. Thus in a matter of milliseconds, a fluid may change its properties into properties similar to a solid body [Kciuk M, Turczyn R. 2006].

There are three types of MR dampers: mono-tube, twin-tube, and double-ended MR dampers [Ashfak A et al., 2009]. Mono-tube MR damper is the most commonly used MR damper to control cable vibrations. It consists of only one MR fluid reservoir and an accumulator to compensate changes in volume caused by piston rod movement. MR damper may ensure optimum or sub-optimum damping for any type of vibrations and any type of cable through the change of input voltage.

Fig. 9: An MR damper installed in the Doingting Lake bridge.

In 2002, 312 semi-active MR dampers were used to control rain-wind-induced vibrations in the Doingting Lake cable-stay bridge (China), see Fig.9. That was the first time in the world that MR dampers had been applied to bridge cables. Thanks to their mechanical simplicity, low energy requirements, and ability to produce high damping forces, MR dampers are one of the most promising devices used in mechanical control of cable vibrations. The only problem is related to the requirement of an external energy source.

3. Conclusions

High amplitudes of cable vibrations may lead to their destruction, and thus a shorter service life. Therefore, reducing the level of cable vibrations is so important with regard to the safety of an entire structure. Common methods of minimizing cable dynamic response are: additional tying cables, appropriate external surface finish, and the use of mechanical passive and semi-active dampers. A combination of particular methods seems to be a more effective solution. As opposed to passive dampers, semi-active dampers applied to cables offer permanent optimum level of effectiveness, even when various different types of vibrations are to be damped. What is more, there is a low energy requirement to power a semi-active damper and the energy can be supplied for example from solar cells.

References

Alexandre M., (1970) Experimental study of the action of vortex shedding on cylinders with longitudinally welded fins. Euromech Colloq. 17, Cambridge (U.K.), 1970.

Ashfak A et al., (2009) Design, Fabrication and Evaluation of MR Damper, University of Kerala, India. World Academy of Science, Engineering and Technology 53, pp 358-363.

Bearman P.W. and Harvey J.K. (1993) Control of Circular Cylinder Flow by the Use of Dimples. AIAA Journal, Vol. 31, No. 10, 1993, pp. 1753-1756.

Fujino Y., Kimura K, Tanaka H., (2012) Wind Resistant Design of Bridges in Japan, Springer.

Gimsing N., Georgakis Ch., (2012) Cable Supported Bridges: Concept & Design, Wiley, 3rd Edition.

Holmes, J.D., (2001) Wind Loadings of Structures, Spon Press, New York.

Kciuk M, Turczyn R. (2006) Properties and application of magnetorheological fluids. Journal of Achievements in Materials and Manufacturing Engineering, Volume 18.

Lee S.J., Kim H.-B., (1997) The Effect of Surface Protrusions on the Near Wake of a Circular Cylinder. Journal of Wind Engineering and Industrial Aerodynamics 69-71, pp. 351-361.

Miyata T., Katsuchi H., Tamura Y., (1999) Comprehensive Discussions on Structural Control for Wind- Induced Responses of Bridges and Buildings, Wind Engineering into the 21st Century. Balkema, Rotterdam, 1999, pp. 487-494.

Novak M., (1966) The Wind Induced Lateral Vibration of Circular Guyed Masts, Tower-Shaped Steel and Reinforced Concrete Structures, Symp. Int. Ass. Shell Struct., Bratislava, 1966.

Wong H.Y. and Kokkalis A., (1982) A Comparative Study of Three Aerodynamic Devices for Suppressing Vortex-Induced Oscillation. J. Wind Eng. Indust. Aerodyn., 10:32-29.

Zdravkovich M.M., (1981) Review and Classification of Various Aerodynamic and Hydrodynamic Means for Suppressing Vortex Shedding. Journal of Wind Engineering and Industrial Aerodynamics 7/1981, pp. 145-189.