ON THE PERFORMANCE AND DURABILITY OF STAY CABLES

Dr. H. WENZEL
Managing Director
VCE – Vienna Consulting Engineers
Diesterwegasse 1, 1140 Vienna, Austria
Tel : +43 1 894 60 21 – Fax : +43 1 894 61 70 – e-mail: vce@atnet.at

Summary

The number of cable stayed bridges with large spans is growing fast. Computational skills and improvement in materials have led to longer and more slender elements. These more and more flexible structures are characterized by low structural damping and low natural frequencies. Other additional conditions, such as the special arrangement of multi-cables, ice accumulation on cable surfaces, water rivulet by rain on cable surfaces, show at the cables different aerodynamic vibration patterns, such as rain wind induced vibration, galloping instability, flutter instability vortex induced vibration, wake galloping and similar or combinations of the mentioned phenomena. Therefore a careful design has to take cable vibrations into account at very early design stages. The precise evaluation of the vibration risk, the expected amplitude and if necessary an appropriate vibration control method becomes essential.

1. Introduction

This paper is concentrated on the state of the art of cable vibrations, referring to recent works of Prof. Matsumoto, Claude Dumoulin, George Magonette, Peter Irwin and others.

In order to find out the relevant excitation mechanisms a large number of tests in wind-tunnels and in the field have been carried out. Direct measurement of the response characteristics of cables have been performed to identify the driving exiting forces. However the behavior has been turned out to be so complex, that closed solutions of the actual generation mechanism and proper vibration control could not be established yet. This contribution therefore concentrates on the state of the art to date and refers to proposed or applied methods to control the wind-induced cable vibration.
2. Excitation Mechanisms

2.1 Rain Wind induced Vibrations
Cable Vibrations induced by Wind and Rain have been observed on a number of Cable Stayed Bridges. Prominent examples are the Erasmus Bridge in Rotterdam, which has been closed for 5 days and the Meiko Nishi Bridge in Japan, where the amplitudes reached several meters in seize. Damages at cables and connectors have been observed. In many cases the joint occurrence of Wind and Rain has been recorded.

The Phenomena of Cable Vibration can be divided into several categories out of which the following are the most important:

- Rainstorm induced Vibrations
- Galloping

Rainstorm induced Vibrations normally occur on cables with an inclination of 20° to 30° against the horizontal and at wind speeds from 8 to 12 m/s combined with a moderate rainfall. Other factors that influence the behavior are the type of cable (i.e. locked coil cable or grouted strand cable), the roughness of the surface (at HDPE Pipes the age of the cable) and the frequency match between cable frequency and deck frequency.

Cable galloping occurs only at rather high wind speeds, which are normally above 18 m/s.
VCE has developed a method to assess the cable vibrations through measurement of critical damping. For this the BRIMOS method is used. It consists of a monitoring system which records the vibrations and a Software that extracts the damping from the readings.

An important parameter in aerodynamics is the Scruton Number [14], which is defined in the following formula:

\[ S_c = \frac{m \cdot \xi}{\rho \cdot d^2} \]  \hspace{1cm} (1)

In this formula \( m \) is the mass of the cable per meter, \( \xi \) is the critical damping of the cable, measured and calculated by BRIMOS, \( \rho \) is the density of air (in general 1.25 kg/m\(^3\)) and \( d \) is the diameter of the cable. High numbers for the Scruton Number tend to suppress the oscillation and bring up the start of instability at high wind speeds. As can be seen from the formula damping is the main factor for the Scruton Number. Most vibration problems at cables are subject to low damping values. The situation can be improved by the improvement of damping through devices which are fixed to the cables.

Following a proposal by the PTI (Post Tentioning Institute) [15] the critical wind speed against galloping can be calculated from the following formula.

\[ V_{krit} = k \cdot f_n \cdot d \cdot \sqrt{\frac{m \cdot \xi}{\rho \cdot d^2}} \] \hspace{1cm} (2)

In case that the actual frequency and the critical damping of a cable is known, any cable can be assessed against vibration problems. In case that the Scruton Number is greater then 10 the cable should be save. This applies mainly for the first 3 frequencies, for which the energy input for activation of the vibration mechanism is reasonable. In fact most of the recordings found vibrations in the second or third order.

The above mentioned items suggest that the treatment of cable vibration problems can be handled by an increase of the frequency. Out of the formulas for any given cable a target value can be calculated. Based on that a suitable damper can be dimensioned.

At Cable Stayed Bridges normally only 1 or 2 cables out of many are subject to vibrations (for the Tulln Bridge 1 out of 60, for the Donautadt Bridge 1 out of 20). It is therefore advisable to carry out these test after erection and to find damping only for the few cables in question. This will minimize the cost.

The type of damper to be used can be individually decided. Recently used have been:

- Connection Cables between neighboring cables (Normandy Bridge)
- Spring dampers at the cable ends (RAMA IX Bridge)
- Elastomeric Ring Dampers near the anchors (applied in most of the bridges)
- Tuned Mass Dampers (Severn Bridge)
No dampers have been applied on some of the bridges due to the fact that the vibration has activated additional damping by the cracking of the grout and the cable force adjustment. After a new measurement it showed, that the damping has increased considerably for the effected frequency and cable.

### 2.2 Vortex induced Vibration

At high reduced wind velocity, i.e. 20, 40, 60, 80 cable vibrations have been observed frequently. The generation mechanism has not yet been explained satisfactory. Works by Matsumoto et alia [12] it noted that these reduced wind velocities are higher than the resonance wind velocities for Karman vortices. It is explained using observation data of prototype cables (Temposan Bridge) and the results from wind-tunnel tests are explained. It the wind-tunnel tests the unsteady aerodynamic lift-force on the cable and the unsteady pressure distribution along the cable were measured and the vortices around the inclined cable have been visualized.

As an example of the aerodynamic response of inclined cables Figure 2 is shown. The longest cable ($L_0$ 183.5 m) of the Temposan Bridge, which is a cable stayed bridge in Osaka with the main span length of 350 m. The vibration occurs at the particular high reduced wind speed of 40 (2nd mode) and 80 (1st mode) approximately. The table shows that these aerodynamic instabilities are velocity restricted response at high reduced wind velocity.

An observation at the Meiko West Bridge (Main span 405 m) it became clear that single mode vibrations are rather rare, but multi-mode vibrations are observed often. Especially vibrations consisting of 2 modes are frequently observed and these modes generate typical beat phenomena. Therefore it is likely that some important mechanisms of the aerodynamic cable vibration might be hidden in the interference between vibrating modes.
Fig. 4 Visualized Karman vortex and the axial vortex (without end plates, $\beta = 45^\circ$, in smooth flow), Foto by Prof. Matsumoto

The wind-tunnel test carried out to study these phenomena revealed that in addition to Karman vortices axial vortex has been experienced. These are vortices developing along the cable downwards. The combination generates the fluid interaction between Karman vortex and axial vortex. This can explain the occurrence of vibrations at the reduced wind velocities of 20, 40, 60 and 80. The wind-tunnel tests also suggests the existence of 3dimensional characteristics of vortex shedding, which seems strongly be dependent on the end conditions and the properties of the cable. The observed beat phenomena might also be explained by this interaction of vortices in future.

2.3 Parametric Excitation

The scientific community has accepted that singular reasons for cable vibrations are rare. It is most likely that a number of phenomena collaborate when actually cables start to vibrate. Parametric excitation may well be the starting point for many of the phenomena observed. It multi stay cable systems almost any frequency is represented. With changing loads cable frequencies are also subject to change, this means parametric excitation can emerge almost on random basis.

In practice it has been observed that particular those frequencies in the range of the predominant vehicle frequencies are excited. In concrete bridges this is the range from 6 to 10 Hz. This means that frequencies of rather high order are excited. This will not lead to resonance phenomena, but the chance that the vibration is reduced to lower orders is realistic. In practice it was observed that in none of the cases measured clear single frequencies where present. More or less all frequencies have been identified in any of the cases. This suggests that parametric excitation starts from a high order of vibration triggered by traffic, which excites one of the lower modes progressively. As long as there is sufficient damping no major problem will develop.

It is therefore advisable to measure damping of all modes up to 10 Hz and compare the values for the identification of suspicious frequencies. These may be compared with predominant frequencies of the deck as well.
2.4 Galloping

Galloping of cables occurs particular at high wind-speeds and turbulent wind-condition. There are a number of different mechanisms explained so far. Cables are vibrating due to the fact that out of plain forces are recorded in the wind environment. This may be as simple as wake turbulence at a Pylon or closely spaced cables. The most dangerous phenomenon is a very uniquely characterized wind regime showing frequencies in the order of the cable frequencies. Such observations have mainly be made in Japan under Typhoon conditions.

Attempts to predict the critical wind-speed depending on the Scruton number and the frequency of the cable have been made by Saito and Irvine [14] but it does not consider important factors such as aerodynamic damping or the excitation mechanism.

When galloping phenomena are observed ordinary dampers situated close to the end of the cables are not effective. Only cross ties will help to deal with the problem.

3. Damping Technologies

In order to achieve reasonable artificial damping it is crucial to understand the excitation mechanism first of all. Many different solutions have been proposed and applied on various bridges world-wide. To prevent the vibration passive measures like cross ties, interconnecting the stay cables, have been used. But some problems have occurred with this systems. The initial tension of the cross ties must be selected with care in order to avoid detensioning and shock effects in the cable system. Another popular solution is the installation of shock absorbers at the bridge deck. Viscous dampers located near the cable anchorage have a limited damping effect, in particular in case of parametric excitation.

Successful attempts to increase the critical wind-speed for vortex induced vibrations have been particular taken in Japan, where the cables were fabricated in a shape deviating from the ideal round configuration. To suppress the rain induced vibrations helical wires or rivulets on the HDPE tubes have been successfully used. The successful development of shape memory alloys has finally introduced another option into the technique.

For long cables the active damping strategy may be applied.

The relevant literature provides sufficient material on the conventional methods. The following chapter will therefore concentrate only on the two most innovative approaches.

3.1 Active damping

The aim of the active control system is to upgrade the damping of the complete structure and consequently to mitigate the induced vibrations of both the stay cables and the deck structure. The methodology is based on an active tendon consisting of an actuator collocated with a force Sensor. The active damping is based on the control of the displacement of the cable anchor-point. This technique developed at the University de Brussels [1] carried out within a project in the 4th framework program of the European
Union (Active Control of Engineering structures, ACE, BE-3334) [2,3]. It has a strong physical support and its effectiveness has already been confirmed experimentally by tests performed on small scaled mockups.

![Image](image1.png)  ![Image](image2.png)

**Fig. 5** Sketch of the bridge mock-up with measurement locations  **Fig. 6** Sinusoidal excitation test in the vertical plane at 1.04 Hz. Displacement at the right free edge of the bridge

The mockup used for the experimental analysis is a unique large scale cable stayed bridge especially designed to improve knowledge of the controlled structure dynamics. While substantial progress has been made in the study of components of active damping systems, little attention has been paid to the overall performance of the system applied to a realistic structure. This large experiment became possible at the Joint Research Center (JRC) of the European Union in Ispra, Italy, where a large reaction wall enables the installation of a cable stayed bridge with 30 m cantilever.

The structural control system consists of a number of important components such as Sensors, controllers, actuators and power generators that must be part of an integrated system. Moreover, a number of implementation aspects must be addressed such as intermittent and fail save operation, integrated safety, reliability and maintenance. This issues require experimental verification under realistic conditions and the validation of the active control system prototype on a large scale mockup gives us a better knowledge of the non-linear dynamic behavior of the cables and of the real loads in the cables and the anchorage.

The specific objectives of the testing campaign where [4]

- To improve the understanding of induced vibrations
- To validate the numerical tools for prediction of dynamic behavior of cables
- To verify the capability of the active system to mitigate the effects of induced vibrations
- To evaluate in detail the performance and the reliability of the hole implementation

In Figure 6 we get the result of a forced excitation test in the vertical plain at 1.04 Hz. The immediate reduction of amplitudes is clearly visible also the exciter is still active. Looking at Figure 7, showing the same signal at a very close look the function of the system is
clearly visible. The insertion of the control induces a phase lag in the tension applied on the cable.

Fig. 7 Sinusoidal excitation in the vertical plane at 1.04 Hz. Displacement and force of the piston at the right end of the bridge P10

Fig. 8 Sinusoidal excitation in the vertical plane at 1.04 Hz. Force vs. Piston displacement when control is inserted (63 - 69 sec)

Over a hundred different tests have been carried out under an extensive test program completed in December 1999. It was successfully demonstrated that the technology works. Questions to be answered are the economic impact and the durability of such a system. The costs of such a system can be traded of against savings from particular simple, but less aerodynamic structural solutions. The reliability of the system is supported by the producer of the hydraulic devices (Mannesmann Rexroth, Germany) who guaranties the performance of such systems as used in steel water structures over a minimum period of 30 years.

3.2 Smart materials

Shape memory alloys (SMA) combine very high yield strength with extreme elongation capabilities. This helps to absorb almost any form of energy in the vibration field. The conception is to provide very thin wires between cables that fulfill the following functions:

- Change in the boundary conditions of the cable
- Allow limited vibrations
- Absorb energy in case of excessive vibration
- Restore the system into its original position

It is anticipated that the energy to be suppressed in the starting phase of a vibration is very small. In this stage the wire acts in the normal elastic range. In case that the cable is excited to violent vibrations with high amplitudes the SMA wire will be able to absorb huge amounts through its hysteric performance. It is estimated that 8 to 12% damping can be introduced into the system. SMA wires are able to perform numerous cycles with elongation of around 8%. Breaking shall occur over an elongation of 15%. The material properties make sure that there will be no corrosion or any other attack from environment. This makes the application rather simple.
The first application has been provided at a cable stayed bridge in Austria (Figure 9), where rain induced vibration have been observed already several times.

4. Practical approach

It is a fact that in multi stay bridges always only a few cables are effected. The provision of damping devices at all cables would be a very uneconomic solution. This applies mainly to medium span bridges, where the risk of a catastrophic failure is small. The reasonable approach in these cases would be to built the bridge first of all with a provision of later installation of damping measures only. After erection all cables shall be measured by a monitoring equipment, providing the frequencies and damping capacity. From the evaluation of damping the critical cables can be found. It will be necessary to carry out tests also during operation to catch eventual parametric excitation phenomena triggered by traffic. For example at the Tulln West Bridge in Austria out of 60 stay cables only 4 have been identified to be critical. Measures have been implied on these 4 cables only.

To gain deeper knowledge of the phenomena involved permanent monitoring of cables is desired. For this purpose several cables have been equipped with accelerometers. Due to the rare occurrence of vibrations with a magnitude of interest no bad incidence records have been obtained yet. Anyhow the environmental influence on the cable properties could be demonstrated.

An innovative approach to learn more about these phenomena has been implemented in Norway [16], where the vibration of power lines creates major problems. The possibility of remote monitoring technology featuring video and image processing seems to be a promising option for the future. Commercial GSM telephones and video compression technologies provide options for installations of such system anywhere where the necessary operation power can be provided. The system can be operated online and by the use of image processing and scene analysis can automatically generate sequences of movements of the cable whenever something important happens. This system introduced by ASTRAGARD has performed well at power transmission lines. Right now the algorithms for scene analysis are further developed to stabilize the automatic recognition and recording of events. The new concept called SCOUT (Self Contained Observation Unit) is under
development. It contains a PC for image processing and data handling purposes. For power generation a wind turbine or solar sells are provided. 4 to 8 video cameras can be mounted separately and might be even remotely operated if necessary.

The use of such a system at a cable stayed bridge would be of highest interest. Anyhow the costs involve did not allow this operation yet.

5. Conclusion

Also problems with vibrating cables are a wide spread fact, the knowledge on the mechanisms is only partly available yet. The basic phenomena have been well understood, but in practice the situation is much more complex. It is very rare that simple singular mechanisms are observed. This makes the prediction of the behavior extremely complicated. It has therefore been proven to be more economic to treat the problem of cable vibrations after erection of a structure, where due measurements can provide a good basis for local problem treatment. This approach should apply to bridges with a span up to 600 m. The success of active control further allow the treatment of extra-ordinary difficult problems so that the risk of the above mentioned approach remains relatively small.

For better understanding of the excitation mechanisms it would be desirable to receive real data of incidences for analysis. Future research project should be mainly focused on this task.

6. References


