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An Experimental Study on the Galloping of Inclined Cables

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Abstract

A series of wind tunnel tests was conducted to investigate the existence of the galloping instability of inclined dry cables and also to identify the influence of some parameters on it. These parameters are the structural damping and cable surface roughness, which may have significant impact on the vibration characteristics. The test results showed both the divergent type of galloping instability and the limited amplitude high wind speed vortex shedding excitation. Galloping instability was observed in only one case. Parametric study shows that the vortex shedding oscillation can be easily suppressed with an increase of structural damping. It was also shown that the instability criterion indicated by earlier research was too conservative compared to the results obtained from the present study.

키워드: *갤로핑, 회오리 바람, 감쇠효과, 표면현상효과*
Keywords: *Galloping, Vortex, Damping effect, Surface roughness effect*

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1. INTRODUCTION

The mechanical principle of cable-stayed bridges has been exhibited long through the human history. However, the prevalent use of cable-stayed bridges started only after the Second World War. About a half century ago, Dischinger built a bridge in Stromsund, Sweden, which is considered to be the first modern cable-stayed bridge.

Since then, cable-stayed bridges have been extensively developed in size and also in variation of structural arrangements. Cable-stayed bridges are not only sound and economical structures for medium-span crossings but they can also offer outstanding aesthetic qualities due to their small diameter cables and the wide variety of structural designs. In order to satisfy both structural aesthetics and economic conditions, it is natural that more slender and lighter structures have been developed.

At the same time, as a result, they developed a new problem of structural dynamics. The characteristics of cables, with their light weight and large flexibility, together with their small structural damping, make the cables easily excited by the dynamic action of wind.

2. AERODYNAMICS OF CABLES

2.1 General

The focus on the aerodynamic excitation of cables became important when electric power

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*** Professor, Ph. D, Division of Architectural Eng., Kangwon National University transmission lines and large scale cable supported structures emerged. One of the reasons why cable dynamics became a big engineering issue was because of its inherently low structural damping. The structural damping of cables is typically less than 0.1% of critical, which is at least an order of magnitude less in comparison to other types of structural members. This chapter gives a general description of the aerodynamic problems of cables by considering their dynamic characteristics, excitation mechanisms and possible ways to suppress their occurrence for practical purposes.

There are various types of cable vibration under aerodynamic excitations. They can be categorized as follows:

(1) Vortex-induced vibration, or Aeolian oscillation;
(2) Buffeting due to wind gust
(3) Classical galloping typically observed in iced cables
(4) Wake interference, or wake galloping and resonant buffeting
(5) Rain-wind vibration
(6) Reynolds number related drag instability
(7) Dry inclined cable galloping
(8) High-wind speed vortex excitation.

2.2 Control methods of wind-induced cable vibrations

Civil engineering structures including bridges, buildings and towers usually have an overall structural damping at the level of 1% of critical. Hence, if there is any possibility of serious dynamic excitations anticipated and yet damping is significantly lower than this level, there should be a warning flag. Cables, such as the ones used in cable-stayed bridges and other cable-supported structures, are prone to wind excitation because of their flexible characteristics and inherently low damping level, usually the order of 0.1% of critical or even less

Due to these unavoidable characteristics, there have been various attempts to control vibrations of stay cables of cable-stayed bridge and hanger ropes of suspension bridges Introduction of artificial dampers is a possible consequence. There have been various dampers developed and applied to power transmission lines and bridge cables. Some of them are referred to here.

2.2.1 Dampers commonly used for power lines

Past experience in this field is important since there have been so many types of relatively inexpensive, simple dampers developed. Aeolian vibration dampers widely used are typically as follows [1]:

The Stockbridge type damper (Fig. 2-1a) is one of the earliest commercial damping devices, consisting of two pear-shaped masses supported on a length of steel strand. When the end-masses vibrate in their natural frequencies, the steel strand is bent and friction is caused by slipping between wires dissipates vibration energy. Two masses and the strands' are sometimes made non-symmetric to make the damper more sensitive to different frequencies. A possible problem of this damper is fatigue failure of the steel strand, ironically particularly when the damper is effectively working. This damper has been also used for bridge cables.

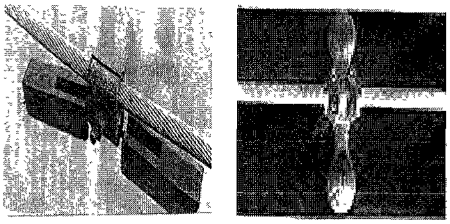
However, recent study [2] shows that Hydro-Québec has developed a new damper using two elastrometric articulations instead of messengers. This articulation, according to the reference [2], is based on elastomeric cylinders located in cavities in such a way that the arm rotation not only produces shear in the elastomer but also gives compression to minimize any risk of cracking. Such a technology allowed stoppers to be incorporated in the articulations to avoid damage to dampers under severe ice storm conditions. It has been further innovated to obtain multiple damper resonance frequencies.

Torsional damper (Fig.2-1b), which was invented in Canada, consists of an arm and a mass joined through a polymer disc system. When twisting vibration occurs, the polymer is shear loaded due to the inertia of the damper mass. However, it was subsequently abandoned because of inefficiency at most frequencies.

Impact damper invented by a Swedish inventor Elgra consists of a vertical stem having three cast masses loosely fitted to a vertical shaft and each mass rests on a polymer washer. When the conductor acceleration exceeds 1g, these masses do not follow the conductor motion any more and start rattling, which results vertical impacts and dissipates energy. Tests have shown that this type of damper works well for the acceleration of about 2*g*. However, it was discarded from service in Sweden and elsewhere because of excessive wear at the connecting rod joint.

There are a number of other types of Aeolian vibration dampers mentioned in the literature [1] together with the past experience and experimental observations. In comparison to the vortex shedding excitation case, wake-induced vibration of bundled conductors are often controlled by tilting the bundles, adjusting the cable separation, and staggering the subspan systems. Associated with the last methods, flexible spacer-dampers have been used but they are often structurally complicated and expensive. More serious vibration problems for power-lines are galloping and vibrations related to wake interferences.

However, most damping mechanisms or protection measures used to prevent these vibrations and their damages are not directly applicable to cable vibrations in general.



(a) (b)

Fig 2-1 Damper

2.2.2. Dampers used for stay cables of cable-stayed bridges

Various methods have been developed to suppress the vibration of stay cables and hanger ropes of suspension bridges. Several researchers have investigated the viscous damper attached transversely to damp the response of the cable structures, too.

Among the simplest ideas of artificial dampers are the use of viscous or visco-elastic materials particularly at the cable anchorage and the tie ropes in various ways. Tie ropes can be installed in horizontal, vertical, or diagonal ways depending on the case but the fundamental idea is much the same. The method has been applied to many bridges including Farø, Normandy, Meiko-Nishi, and others. The Normandy and Yokohama-Bay Bridges were equipped with spacer-dampers to provide the connectors or spacers with a simple damping mechanism. The use of the visco-elastic anchorage system, inserting the neoprene rubber washer into the anchorage socket, is installed in the stay cables, too. [3, 4, 5]

Complementary method of visco-elastic anchorage system is the use of the shock absorber or a dashpot, near the anchorage. Brotonne, Sunshine, Aratsu and some other bridges have these dampers and they seem to be quite effective. In order to make the installation of the damper most effective, the dampers damping can be properly designed by considering the overall modal damping. [3, 6]

However, cable connection using tie ropes and viscous damper have not proven to be well-balanced countermeasures from the structural aesthetics, installation and maintenance. Research on this problem has been extensively carried out all over the world, and led to solutions such as the passive magnetic damper and active control damper. The passive magnetic damper mechanism changes the vibration mode of cables. The active control damper uses the external force applied by the actuator to suppress the dynamic response. These methods also have some disadvantages for their commercial application because of production costs, reliability, and maintenance costs.

Another suppression method involves the application of the various surface treatments to the cables, particularly for controlling the rain-wind induced vibration. Actually, surface treatment methods were used to control other structures, too, such as chimney stacks, pipelines, towers etc. in prevention of vortex excitation and galloping instability. Examples of the stay cable vibration using the surface treatments methods are the Higashi-Kobe Bridge cables with longitudinal fins, the Yuge Bridge cables fitted with parallel grooves, and the Tatara Bridge cables given the surface indentations. [5, 6]

3. EXPERIMENT OF CABLE

3.1 Objective

In 1994, Japanese researchers (Saito et al.) reported that galloping instability could occur without deposition of ice or rain when the cables were inclined against wind. According to this report [7], the instability was possible when the angle between the cable axis and the wind direction was 30° to 60°. If this instability criterion is applied without any exceptions, many of the bridge stay-cables would be categorized as prone to galloping. However, in reality most of the existing bridge stay-cables have been surviving without any problem of this galloping instability. From this point, it is obvious that this criterion has to be examined carefully.

The objective of this study is to confirm the existence of the above-mentioned galloping instability of the inclined dry cables and also to identify the influence of some parameters such as the structural damping and cable surface roughness, which may have significant impact on the vibration.

To this end, a series of wind tunnel tests was conducted at the Propulsion wind tunnel, using a two-dimension sectional model of inclined dry cables. The wind tunnel belongs to the Institute of Aerospace Research (IAR), National Research Council Canada (NRCC). The spring system supporting the cable model was designed and manufactured by RWDI and installed in the wind tunnel in May 2001.

3.2 Model cable and its setup

A section of a full-size cable was used as the model. The properties of the model are: 0.16m in outer diameter, 6.7m in length, and the mass of 60.8kg/m. The model together with the springs are shown in Fig. 3-1.

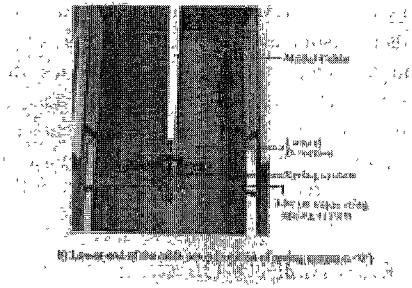


Fig. 3-1. Spring system and model

The cable model is a hollow steel pipe and there is a concentric internal cylinder fixed inside of it to adjust the weight and also to help the model installation. The inner cylinder is also a steel pipe of 0.1m diameter. The outer surface of the model is wrapped with a polyethylene sheet to make the surface smooth.

Each end of the cable is connected to four springs to allow movement in two perpendicular directions. The up-wind end of the cable was located above the ceiling of the tunnel and is connected to the axial wire to partially support the cable weight. The lower end of the cable is also supported by a four-spring rig, which is identical to the one at the upper-end, except the lower end rig is placed on two beams which were installed across the wind tunnel section. The same setup of the springs was used through the whole test series These springs have a total mass of 60kg, and have vertical and sway spring constants of 4.99kN/m and 4.78kN/m, respectively.

The vertical test setup angle and the rotation angle of the spring system are related to a combination of the vertical inclination angle and the horizontal yaw angle on the bridge stay-cables. The definition and the relationship between these angles are given in Table 3-1.

Table 3-1. The model setup angle

Model	θ	β	ϕ	α
Setup 1B	**45**	**0**	**45**	**0**
Setup 1C	**30**	**35.27**	**45**	**54.8**
Setup 2A	**60**	**0**	**60**	**0**
Setup 2C	**45**	**45**	**60**	**54.8**
Setup 3A	**35**	**0**	**35**	**0**
Setup 3C	**20**	**29.35**	**35**	**58.7**

* where, θ:cable inclination angle, β:wind attack angle, ϕ:cable-wind relative angle, and α:setup of rotation angle of spring system

3.3 Test results

Both divergent type of cable motion and the limited amplitude response of the cable were observed.

3.3.1 Divergent type response

Divergent type response of the cable was observed only in Setup 2C. This response has the characteristics of galloping instability. The galloping motion is characterized by a quick increase of amplitude with increasing wind speed at the natural frequency of structure. The amplitude response of cable and the response trace at the mean wind speed of 32m/s are given in Figs. 3-2 and 3-3

It is shown in the time trace that the amplitude was less than 20mm at the mean wind speed range of 10 ~ 30m/s but when the mean wind speed reached 32m/s, corresponding to the reduced wind speed *U/fD* 140, the amplitude increased from ± 20 to ± 80mm. Moreover, the sway amplitude also showed a tendency of increasing further. It had to be manually suppressed due to the clearance of the wind tunnel ceiling for the model setup. The maximum peak-to-peak response observed was about 1*D*, where *D* is the cable diameter.

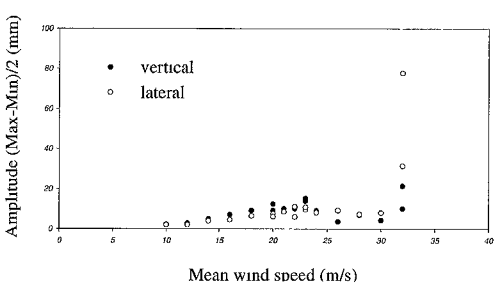


Fig. 3-2. Wind-induced response of setup2C with smooth surface and no additional damping

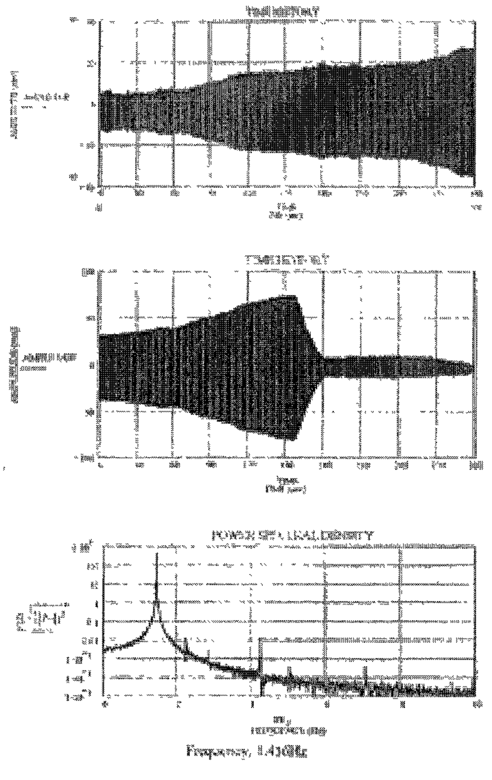


Fig. 3-3. Time trace and PSD of model setup 2C

3.3.2 Limited amplitude vibration

Limited amplitude vibration was observed with four different cases and they are shown in Figs. 3-4 through 3-7. Test results indicate that all of these have the characteristics of the high-speed vortex excitation.

The characteristics of the motion are summarized as follows:

(1) The amplitude of the motion is limited. The largest amplitude observed was with the setup 2A. When the wind speed is 19m/s, the amplitude of the cable motion reaches the maximum of 67mm. The amplitude response is shown in Fig. 3-4.

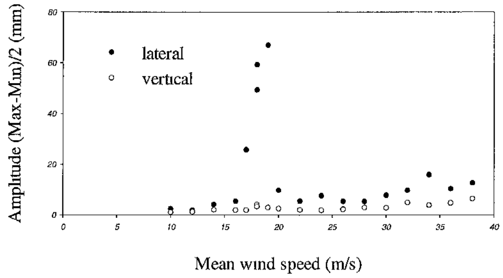


Fig. 3-4 Wind-induced response of setup2A with smooth surface and no additional damping

(2) The unstable motion was observed only in a limited wind speed range (10~20m/s).

(3) The maximum magnitude of the unstable motion depends on the orientation angle of the cable. It was larger with greater vertical inclination angle, as given in Table 3-2.

Table 3-2. Wind speed range of instability

Model	Wind speed(m/s)	**Amplitude(mm)**
Setup 2A	18~19	67
Setup 1B	24~26	31
Setup 1C	34~38	25
Setup 3A	22	20

In setup 3B, which is equivalent to the case of a cable with a very shallow vertical inclination angle of 20° and horizontal yaw angle of 29.35°, no unstable motion was found within the wind speed range of 8~34m/s The response observed was less than 5mm. Its amplitude response is in Fig. 3-5 and the time trace and PSD are given in Fig. 3-6.

(4) When the cable motion becomes unstable, there are two types of response: one is very organized harmonic motion and another is with the regular beating, which is similar to what Matsumoto described as the case of three-dimensional Karman vortex shedding. He explained that this regular beating is caused by the fluid interaction between the axial vortices along the inclined cable surface and the Karman vortices in the wake of the cable. The Karman vortex shedding is amplified intermittently as a result, according to his explanation [8,9], which induces the beating type motion of the inclined cable.

(5) In some of the setups, such as the setup 2A and setup 3B, an elliptical motion of the cable was observed, which correlates well with the field observation [10].

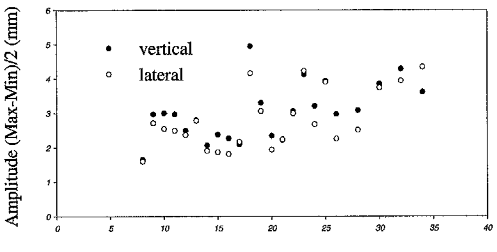


Fig. 3-5. Wind-induced response of setup 3B with smooth surface and no additional damping

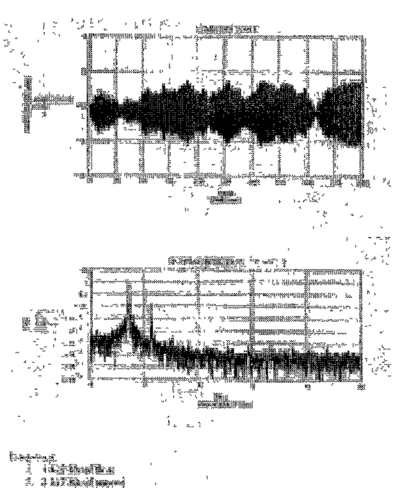


Fig. 3-6. Time trace and PSD of model setup 3B

(6) It is interesting to observe that all of these phenomena occurred more or less at the wind speed corresponding to the critical Reynolds number.

3.4 Test of surface roughness and damping

For this test, the cable surface roughness and the structural damping effects were considered to be the parameters that might have significant impact on the vibration of inclined dry cables.

3.4.1 Surface roughness effect

For the present test, the model was originally wrapped with the polyethylene sheet to give the smooth surface. However, for the rough surface, the cable was sprayed by liquid glue on its surface to examine if it would produce any differences in the cable response. Experimental results are given in Fig. 3-7.

The surface roughness is characterized by the roughness shape and the distribution of the roughness particles. This effect changes the flow separation points on the cable surface. In fact, the rougher surface is, the earlier the separation point occurs closer to the upstream of the cable surface, depending on the upstream flow speed. The major effect of separation is the large suction on the downstream of the cable, causing the wake to be much wider.

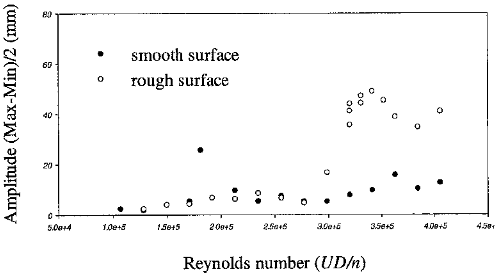


Fig. 3-7. Surface effect with setup 2A

3.4.2 Damping effect

Four different levels of structural damping (i.e. low, intermediate, high, and very high damping) were applied to examine the effect of damping on the cable response. The relationship between the damping and the response amplitude are given in Fig. 3-8.

Originally, it was intended to use a

commercially available dashpot type damper called Airpot to provide the system with the additional damping. However, the Airpot damper was found to have a sharp non-linearity as shown in Fig. 3-8.

Extremely high damping with small amplitudes is due to the friction between its piston and the cylinder wall. Because of this non-linearity, it was decided to use the Airpot damper only for the very high damping case, which is the order of 1% of critical. For the other levels, the additional damping was given to the system by adding several elastic rubber bands on the springs. These lower damping were from 0.03% to 0.5% of critical, covering the data range of the previous researchers.

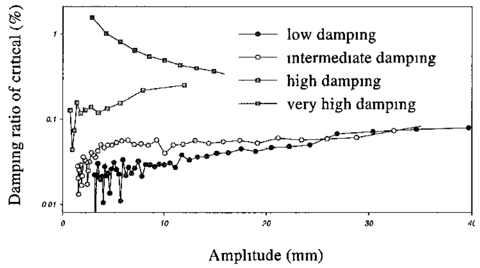


Fig. 3-8. Damping ratio versus amplitude at four different levels of damping

Fig. 3-9 gives the wind-induced response of the cable model with the setup 1B under all four levels of damping.

As clearly shown in the figure, when the damping is increased, the response is significantly reduced, but the position of the wind speed range where the vibration occurred did not change.

This set of results indicates that this limited amplitude motion can be suppressed by increasing the damping of the cable. Fig. 3-10 shows the wind-induced response with the setup 2C with high structural damping.

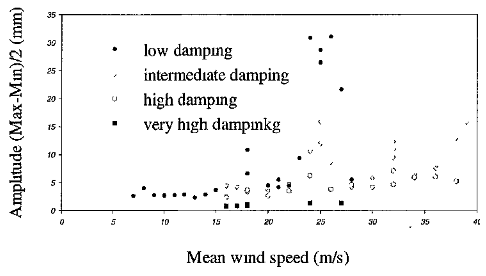


Fig. 3-9. Damping effect with setup 1B

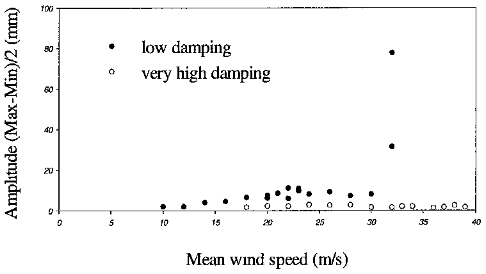


Fig. 3-10. Damping effect with setup 2C

3.5 Comparison with earlier studies

A limited number of experimental studies on inclined dry cables have been carried out particularly in Japan. Saito et al [7] defined an instability criterion for the inclined cable motion based on three different model setups. Two of them are exactly the same as the setups 1B and 2A in this study Miyata et al [11] investigated the inclined dry cable motion with one model setup. In order to make the comparison, these two sets of results, as well as the results obtained from this study are shown together in Fig. 3-11.

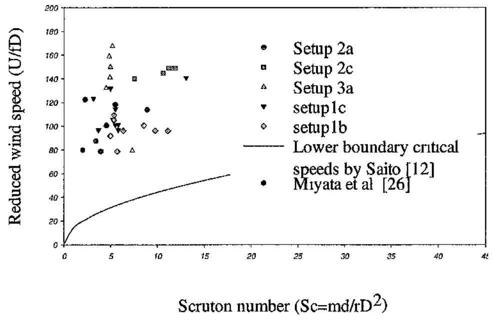


Fig. 3-11. Critical reduced wind speed versus Scruton number

Among the results from the present study, only the one corresponding to the setup 2C is the divergent galloping motion, whereas the others are high-speed vortex shedding excitation. As can be seen from the figure, the boundary for instability defined by Saito is much more conservative when compared with the results given by Miyata and this study.

Further to this, the similar instability criterion that could be defined by this studys findings would have a much steeper slope than that given by Saito, which implies that with the increase of the cable structural damping, the instability range of the inclined cable motion will be shifted to even higher wind speed level.

4. CONCLUSIONS

A series of wind tunnel tests were conducted to investigate the aerodynamic behaviour of inclined dry cable. Both the divergent type of galloping instability and the limited amplitude of high-speed vortex shedding excitation were observed.

(1) Galloping instability, which seems to grow into a large amplitude motion, was observed in only one case (Model setup 2C).

(2) The other vibrations observed in different setup cases and they seem to be categorized as high-speed vortex excitation.

(3) Parametric test shows that the vortex shedding oscillation can be easily suppressed with the increase of the structural damping. Increase of damping generally do not influence on the range of wind speed where the motion was detected.

(4) The instability criterion for the inclined dry cable vibration defined by Saito et al (1994) is found to give much lower critical wind speed in comparison to the present study.

In order to further clarify the problem of dry cable galloping, it is advisable to perform more study in future, particularly on the cause and mechanism of vibration and the Reynolds number effect on the inclined cable vibration.

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