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RAIN-WIND INDUCED VIBRATIONS IN STAY CABLES

Response Characteristics, Excitation Mechanisms and Modelling

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ABSTRACT: The strongly nonlinear phenomenon of rain-wind induced vibrations of stay cables is discussed, focusing on issues related to their exciting mechanisms, the cable response characteristics and the adequate modeling. Numerical results obtained are compared to wind-tunnel test data as well as to full scale measurements on cable-stayed bridges.

KEY WORDS: Rain-wind induced vibrations, stay cables, bridges.

1 INTRODUCTION

Large amplitude Rain-Wind-Induced-Vibrations (RWIV) of stay cables are a challenging problem in the design of cable-stayed bridges. Such phenomena were first observed on the Meikonishi bridge in Nagoya, Japan [1] and also later on other such bridges, as for instance on the fully steel Erasmus bridge in Rotterdam, the Netherlands (1996) and the Second Severn Crossing, connecting England and Wales [3]. It was found that the cables, which were stable under wind action only, were oscillating under a combined influence of rain and wind, leading to large amplitude motions, even for light-to-moderate simultaneous rain and wind action. The frequency of the observed vibrations was much lower than the critical one of the vortex-induced vibrations, while it was also perceived that the cable oscillations took place in the vertical plane mostly in single mode; for increasing cable length however, higher modes (up to the 4th) appeared. Most importantly, during the oscillations a water rivulet appeared on the lower surface of the cable, which was characterized by a leeward shift and vibrated in circumferential directions [1,8,10].

More detailed field measurements – observations, as well as wind-tunnel tests, which were realized at a later time, showed that there were in fact two rivulets formed: one on the upper cable surface and another on the lower surface. This formation and corresponding motion is illustrated in the contents of Photo 1, courtesy of wind tunnel tests conducted in the Hong-Kong Polytechnic Institute, simulating wind-rain action on a cylinder.

Both rivulets were oscillating in circumferential direction at the same frequency as that of the cable, with their point of formation depending on the wind velocity. Their presence and movement alter significantly and in a random manner on the cross-sectional profile of the cable, as acted upon by wind, and hence complicate interaction occurs.

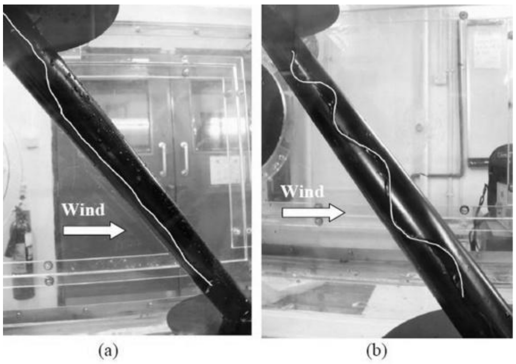


Photo 1. Water rivulets (white curves) on cylinder surface: (a) leeward and (b) windward rivulet

Measurements of the aerodynamic forces as the rivulets formed separately showed the negligible role of the lower rivulet (a fact still not accepted by all relevant studies), and it is generally believed that that the upper rivulet is dominant in inducing cable dynamics, and it is postulated that the instability phenomena observed are ought to either the point of formation or the oscillation of this rivulet itself [2,4]. Moreover, further studies have also indicated that there might be an additional factor triggering the RWIV, namely an axial flow generated at the near wake of the inclined cable and associated with 3D-flow characteristics.

Since the first observation of the foregoing phenomenon, numerous attempts, for modeling these extremely nonlinear (and quite stochastic in nature) vibrations have been made, and reported in the literature. These range from simplified one and two degree of freedom systems of standing and moving rivulets on an idealized cylinder to sophisticates simulations. The latter are based on strip-theory or on approaches coupling unsteady aerodynamics to thin-film models based on lubrication theory for the rain water. None of these however have yet gained any general justification, since to a smaller or larger extent they cannot predict the majority of measured RWIV on either real structures or wind tests.

To this end, and since the exciting mechanisms of RWIV of stay-cables is still under debate in the Engineering Community, the present work aims to clarify all the aforementioned issues by (a) offering an overview of existing scientific knowledge regarding various response characteristics and underlying exciting mechanisms and (b) summarizing the most important models proposed.

The references given at the end of this work are kept to a strict minimum and are only indicative (note that a vast literature is related to the subject), while a strong effort has also been undergone by the authors to keep theoretical analyses and quantitative results as short as possible.

2 RAIN-WIND-INDUCED-VIBRATIONS OF STAY- CABLES

2.1 Major response characteristics and basic principles

These along with the fundamental mechanism of RWIV of stay-cables were thoroughly investigated by Matsumoto et al [2], via a series of wind tunnel tests. Their results indicated that rain-wind-induced vibrations of cables can be classified in three types, i.e.

1) the “galloping type”, which includes both divergent galloping and velocity restricted galloping, related to a negative slope of the lift force caused by an “upper water rivulet” and/or “axial flow”,
2) the vortex-shedding type with long period and
3) their mixed type.

In particular, it was found that this velocity-restricted response caused by vortex-shedding is excited by the three-dimensionality of conventional Karman vortex shedding along the cable axis. More details concerning the test setup and the whole galloping-based analysis can be found in the contents of the paper cited above. These general characteristics are closely related with the basic principles governing these oscillations [4], which are summarized in what follows:

a) The effective cross-section of the cables during motion is permanently changing. (At this point it should be noted that other studies, mainly of the Japanese School [1, 2] and others not cited herein, explain that the motion of the rivulet leads to *a periodic change of cable cross-section* for the flow).
b) The shape of the cross-section made of the cable and the rivulets depends on the adhesion, on the wind forces and on the momentary acceleration of the cross - section. Because of this dependency the frequency of the variation of the shape is the same with the frequency of its oscillation,
c) As a consequence of the momentary accelerations, the rivulets oscillate on the surface of the cable in the circumferential direction,
d) If the resulting wind force, which acts on the entire cross – section, is oscillating in the same frequency and with the same sign as the oscillation velocity, positive work is produced and the vibrating system receives an energy input, and large amplitudes occur. Their magnitude depends on the structural damping and on the retaining elastic forces due to second-order effects, and
e) The exciting frequency is conditioned by the motion and is identical to the natural frequency. Hence, the rain-wind-induced vibrations are *a self-excited oscillation* that may occur over a wide range of frequencies.

Moreover, in a very interesting work concerning the phenomenology, the mechanical modeling and the numerical simulation of RWIV [13], it was deduced that the major reason, that these vibrations are not fully understood and satisfyingly determined, is that the flow around an inclined cable with rivulets is very complex and the cable aerodynamics of these phenomena depend on various parameters like the inclinations and the diameters of the cable, the geometrical shape and the position of the rivulet as well as the velocity and the angle of the incidence of the flow.

In general, strongly nonlinear multi - parametric dynamic instability phenomena characterize the response of stay – cables under simultaneous rain and wind action [10], and their analysis and simulation is extremely complicated.

2.2 Excitation mechanisms

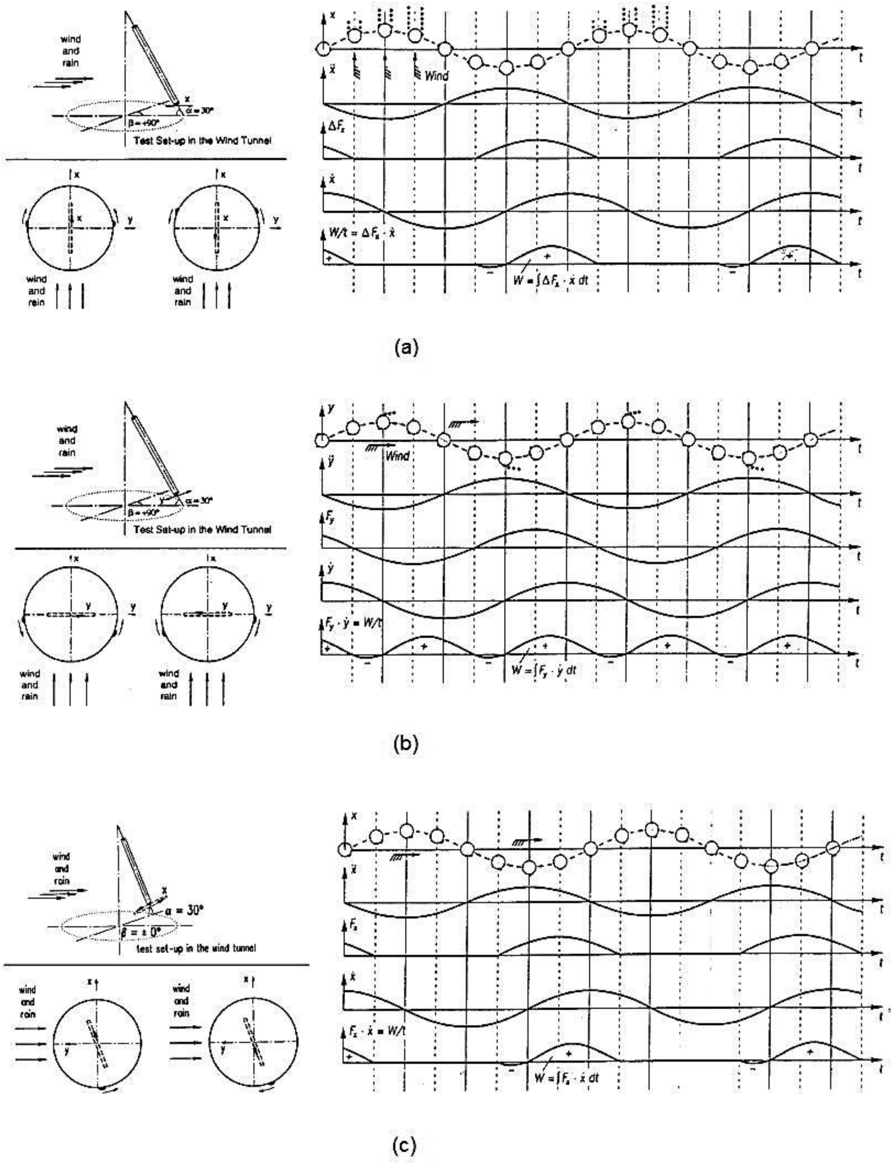
In accordance with the contents of the previous sub-section, various different approaches – fluid mechanical phenomena are discussed in the literature, in an attempt to identify, describe and validate the exciting mechanisms of RWIV.

According to [1], the instability does not seem to be caused by vortex induced vibrations, because the Strouhal number, the amplitudes and the frequency differ from those of RWIV, while standard galloping effects are also not suitable, since the surface of the cylindrical cable is too smooth without any rigid edge. Wake galloping can be excluded too, because the distance between stay-cables are in most cases very large. It was also concluded, by the above study (and others of similar content) that the dimensions of the rivulets forming on the cable surface are negligible compared to the cable cross-section dimensions, and therefore RWIV are unlikely to be generated by the change of the effective cross – section.

Besides of the explanation of RWIV as a special kind of galloping, many scientists (for instance [2]) discuss that rain-wind-induced vibrations represent a new type of instability phenomena. The excitation mechanism described is caused by the three-dimensionality of Karman vortex shedding, while it was deduced that the oscillations are additionally enhanced by the axial flow in the wake of the cable and by the geometrical shape of the upper rivulet.

On the other hand, as also mentioned earlier, it was assumed [4] that, as a result of the rivulet motion, the effective cross – section undergoes a permanent change and as a result of wind tunnel tests three different excitation mechanisms were reported, parallel and perpendicular to the wind directions in dependence of the rivulet motion at the cable surface. These mechanisms are depicted in Figure 1.

Another possible mechanism of excitation was derived by Seidel and Dinkler [13], based on the phenomena of the Prandtl tripwire, considering the rivulets as a movable disturbance. Following this approach the occurrence of the lower and upper limit of the critical velocity may be explained and all kinds of observable vibrations can be described.



(a)

(b)

(c)

Figure 1. Exciting mechanisms of RWIV [Verbiede and Ruscheweyh 1998]: (a) Vibration in the wind direction, symmetrical motion of the rivulets on the cross section, (b) Vibration in the cross-wind direction, antimetrical motion of the rivulets on the cross section, (c) Vibration predominantly in the cross-wind direction, mainly caused by the motion of a rivulet at the underside of the cable.

2.3 Modelling

A variety of different mechanical models have been proposed in the literature for simulating RWIV. These may be divided into two main types, namely simplified discrete ones, with one or two degrees of freedom, and sophisticated ones based on strip and lubrication theory. Among the former, the most significant recent ones, to the authors' opinion, are, in chronological order of appearance, the following:

- Stochastic model by Cao et al. 2003 [5, 11]

In this spring-dashpot model, shown in Figure 2, a single rivulet moving on the upper of a cable, under the influence of the wind, gravitational and friction forces is considered.

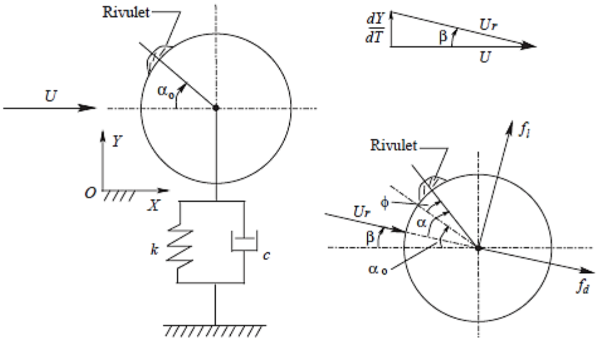


Figure 2. Stochastic mechanical model of Cao et al. 2003

The motion is described by the response of a band-pass filter. If φ(t) is the fluctuation angle describing the motion of the rivulet on the cable perimeter, and after determining the lift and drag forces on the model, a stochastic process is adopted for φ, while the static angle α_0 of the rivulet is taken as a function of the mean wind speed U, as reported by wind tunnel tests. Results based on linearized aerodynamic forces showed that a stochastic resonant phenomenon can be induced depending on the location of the rivulet, while also a stationary stochastic state regarding the cable may also be observed.

- Single-degree-of-freedom models [7-10]

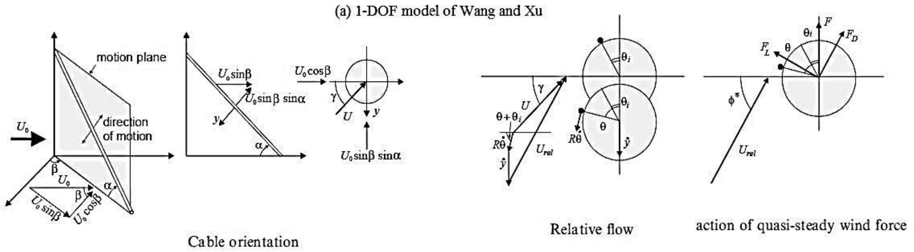
Several simplified 1-DOF models have been reported, with each of them possessing some merit, but none capable of fully modeling RWIV of stay-cables. Three representative such models are shown in Figure 3, while others also exist, not discussed herein for reason given earlier as well as for brevity.

Detailed features of each individual model can be found in the full length papers cited above, but it should be noted that assumptions related to each model restrict their wider applicability and hence only limited wind tunnel test results and real measurements are captured by their response.

orientation of inclined cylinder

relative velocity of cable and moving

(a) 1-DOF model of Wang and Xu

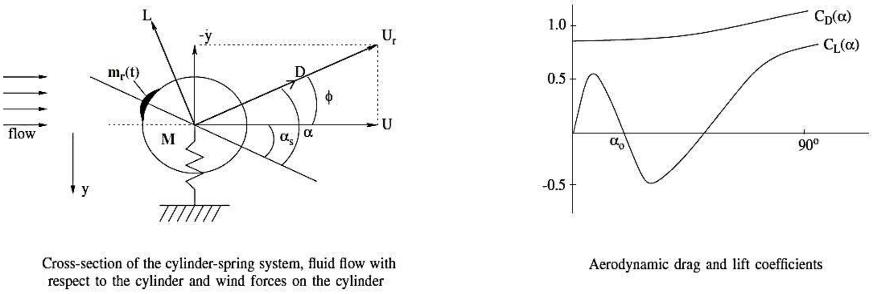


Cable orientation

Relative flow

action of quasi-steady wind force

(b) 1-DOF model of Wilde and Witkowski



Cross-section of the cylinder-spring system, fluid flow with respect to the cylinder and wind forces on the cylinder

Aerodynamic drag and lift coefficients

(c) 1-DOF model of van de Burgh et al.

Figure 3. Single-degree-of-freedom models

The second kind of models, the sophisticated ones [6, 14], are more precise by nature, but based on very complicated theories that cannot be easily understood and their results still remain controversial. Further discussion relies far beyond the scopes of the present work.

3 CONCLUSIONS

According to the above overview it is clear that the problem of rain-wind-induced vibration of stay cables remains an open scientific issue, since neither the exciting mechanisms are fully explored nor adequate modeling has been achieved till now. The authors believe that the stochastic nature of these oscillations should be tackled accordingly, but further theoretical research is required, accompanied by large scale experiments and consistent in-situ measurements on cable-stayed bridges worldwide.

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