

AN EXPLANATION OF THE RAIN-WIND INDUCED VIBRATION OF INCLINED STAYS.

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***Abstract :** After some years of research and various full scale observations the excitation of bridge stays by the so called "rain-wind induced vibration" is still not well explained. It seems clear today that some different phenomenon have been identified, acting separately, exhibiting different kind of instability. The vibration of "quasi-vertical" hangers, for instance, must be considered apart from the excitation of inclined stays as well as the parametric excitation of stays by the deck. In the same way the vibration of tubes without any rain, that has been observed during laboratory experiments but never reported on actual bridges, must be treated separately.*

In the present paper a series of wind tunnel experiments recreating the excitation on in wind descending inclined cables is described. A model is developed and its results compared to recent experiments on the Rion Bridge stays.

1 INTRODUCTION

In 1992 the aerodynamic studies on the Normandie bridge included the design of a cable cladding avoiding the rain-wind excitation. The phenomenon was successfully reproduced in the CSTB climatic wind tunnel, at full scale, with 7.4 m long sectional model of the actual stay [1]. It was then proved that a small helical string stretched around the cladding was disorganising the excitation phenomenon in such a way that the cable remained stable without an important increase of the drag coefficient. This principle has been applied on numerous cable stayed bridges afterwards.

Some further experiment have been conducted in 1994, 1995 and 1996, the aim of which was to explain the origin of the excitation. In collaboration with the aerodynamics laboratory, University of Poitiers, the pressure field around the PE pipe and the water height on the cable during excitation were measured, studied and compared with CFD calculations. This method proved successful for the elimination of some hypothesis.

At the same period a number of actual vibration of bridge stays were reported, leading to series of experiments all over the world. The vibration of quasi vertical hangers of suspended bridges was discovered [2], [3] and studied. It is now clear that this particular excitation does not have the same characteristics as the rain-wind induced vibration of inclined stays which is the subject of the present paper.

Some wind tunnel studies [4], [5] yield new cladding design, with a dimpled surface. The early assumption of Hikami [6], that a moderate rain is necessary to the excitation, was confirmed. A recent full scale study [7] also proved that, for this excitation of inclined cables, lapped with smooth PE cladding, leading to high amplitude vibration, the presence of a light rain is needed and that this excitation is restricted in wind direction and wind speed.

It is therefore obvious that the different model of excitation proposed that do not respect these characteristics must not be applied to describe this peculiar excitation. This is the case of all the models based on the galloping of a 8 like shape that are not restricted in wind speed.

2 WIND TUNNEL EXPERIMENT FOR THE MEASUREMENT OF WATER THICKNESS AND INSTANTANEOUS PRESSURE FIELD

2-1 General layout

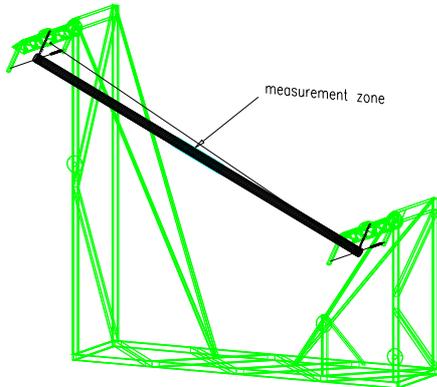


Figure 1 : principle of the test rig



Figure 2 : test rig in wind tunnel.

The principle of a full scale rigid model of the cable suspended in the Jules Verne climatic wind tunnel was kept on from the previous series of tests. The model is composed of a 6m long iron tube that is fitted inside a PE pipe 160 mm external diameter. The test rig supports the model at each edge trough iron helical springs and the model is laterally guided by the mean of cables. The frequency of the vertical oscillation is 1.08 Hz, the damping related to critical $\xi=0.08\%$, the weight of the model 20 kg/m. The higher suspension point can be lifted such as the inclination angle α can be varied from 20 to 45 degree. The yaw angle β can be tuned from 0 to 90 degree (figure 1).

The whole is subjected to a smooth flow and a light rain. This rain, like the genuine drizzle, is composed of small water droplet carried out by the wind, the mean size of which is 600 μm .

The wind tunnel tests had to overcome a major difficulty : the instantaneous and simultaneous measurement of a pressure field and a water thickness on a moving model, without additional structural damping or flow disturbance, under rain fall. No sensor exists on the market for such a purpose, we designed it.

2-2 The waterproof pressure sensor.

The very low pressure level, the typical speed range being 7 to 12 m/s, don't allow to use classical surface mounted membrane transducers, the sensitivity of which is not high enough.

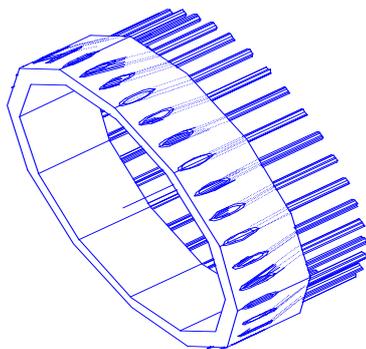


Figure 3 : the pressure ring

The early design of the sensor was based on this principle of a LDPE membrane interposed between the outside wet air and a small inner volume in which the pressure was measured by a classical differential pressure scanner. It was rapidly shown that the high dilatation coefficient of PE transformed the device in a temperature sensor instead of a pressure one.

The second design of the pressure sensor used 32 special pressure taps that don't fill with water. To achieve this, we used one characteristic of the model that is always inclined with an angle α ranging from 20 to 60°. The pressure tapes were machined in an

aluminium ring as 3 mm diameter coincident drillings. The interaction with the surface gave an ellipsoidal hole, the inner side of the drillings was covered with silicone grease to avoid a water meniscus. The instantaneous pressure field was measured on the 32 points at the same time, with a rate of 200 Hz.

This pressure sensor was calibrated, without water, by comparison with the instantaneous pressure field of another pressure tapes ring, with classical tapes 0.8 mm diameter normal to the surface, situated 250 mm apart on the same suspended model. The mean pressure values were the same with the two rings, the “waterproof” tapes had a transfer function flat up to 30 Hz. Therefore the instantaneous pressure signal measured by the 3 mm tapes was low path filtered, but correct in the frequency range concerned by this study.

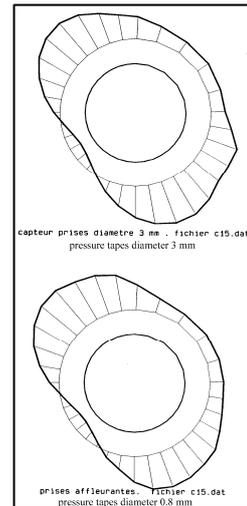


Figure 4 : comparison between the two rings

2-3 The water thickness sensor

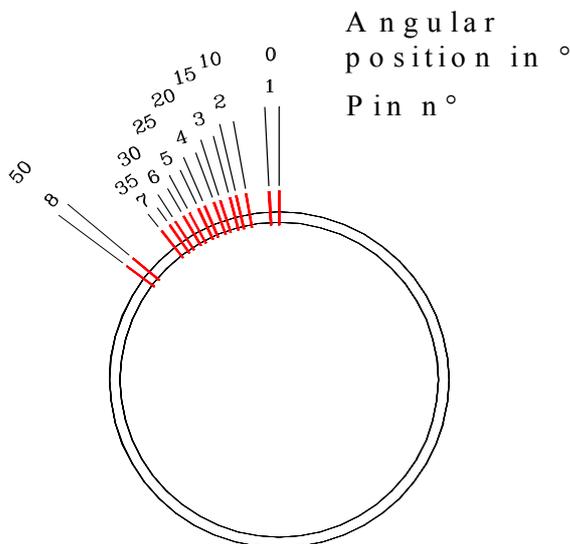


Figure 5 : twined pins location on the water sensor

The water level on the PE tube was measured, at the same time as the pressure field and the model acceleration, by the use of small twined metal pins 5 mm long connected to an AC high frequency generator : the resistivity measured between each pair of pins was linearly dependent from the water thickness.

The 8 twined pins, arranged on a ring at the location of the moving upper water rivulet, were placed on the model, 250 mm apart from the pressure sensor ring.

The small diameter of the pins (0.3 mm) did not disturb the air and water flows, the upper rivulet was shown to be unaffected, in its location and oscillation, by the sensor.

3 RESULTS

The parameters [1] conducting to the rain-wind induced excitation were reproduced and the data from the water and pressure sensors recorded when the excitation was established. A small video camera fixed on the lower edge of the model showed the rivulet.

- A) The water thickness varied, when the model oscillated, between 0.2 and 0.7 mm . This value was the same order than what has been reproduced in experiments using an artificial rivulet [8] but the rivulet shape was radically different : the actual rivulet covered all the upper part of the moving cylinder, sliding like a carpet on it. The upper rivulet mean position could be deduced from the 8 twined pins signal and its mean value indicated that the rivulet “climbed” on the top of the cylinder when the wind mean speed increased. The phase shift of this mean position with the model acceleration was close to 30°. The rivulet movement to the top of the cylinder was sudden and didn’t last more than 1/3 of the period. The spectral analysis of the rivulet movement did not show any other noticeable

frequency than the one of the model movement. When the movement was established and the rain supplier cut off the movement clearly increased before a slow decrease. This shows that the more favourable state is a very thin (0.2 mm ?) water film.

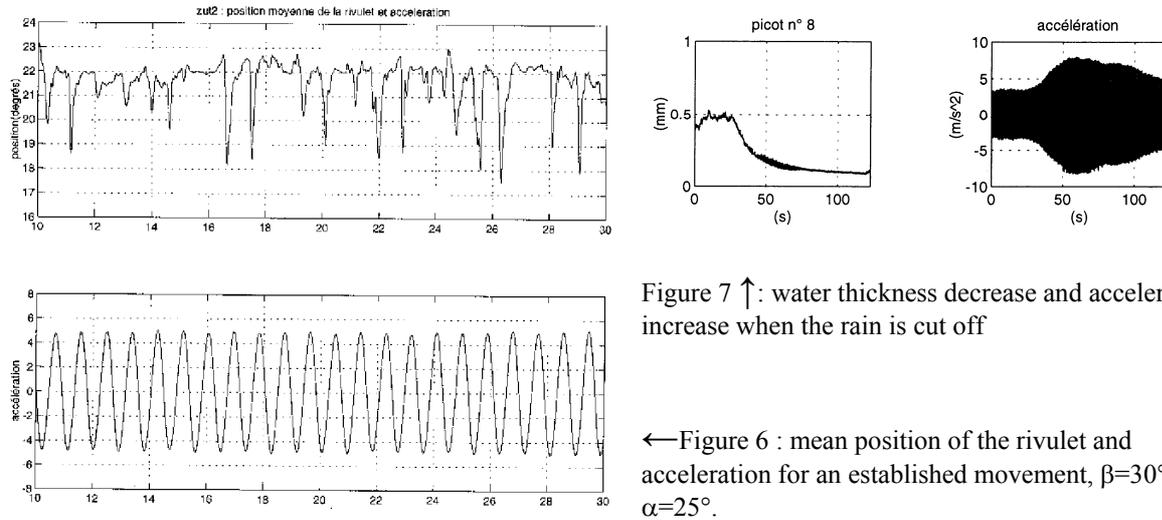


Figure 7 ↑: water thickness decrease and acceleration increase when the rain is cut off

← Figure 6 : mean position of the rivulet and acceleration for an established movement, $\beta=30^\circ$, $\alpha=25^\circ$.

B) The integration of the pressure field gave the vertical (lift) fluctuating forces on the stay. The spectral analysis showed a peak at the stay displacement frequency, but the time signal was not sinusoidal at all on the time history drawing. Some very high and narrow peaks appeared every 1, 2 or 3 period of the movement. Some very high negative peaks were also shown on the lift force, coming just before the positive ones, but their phase shift with the movement was not favourable to lower the excitation.

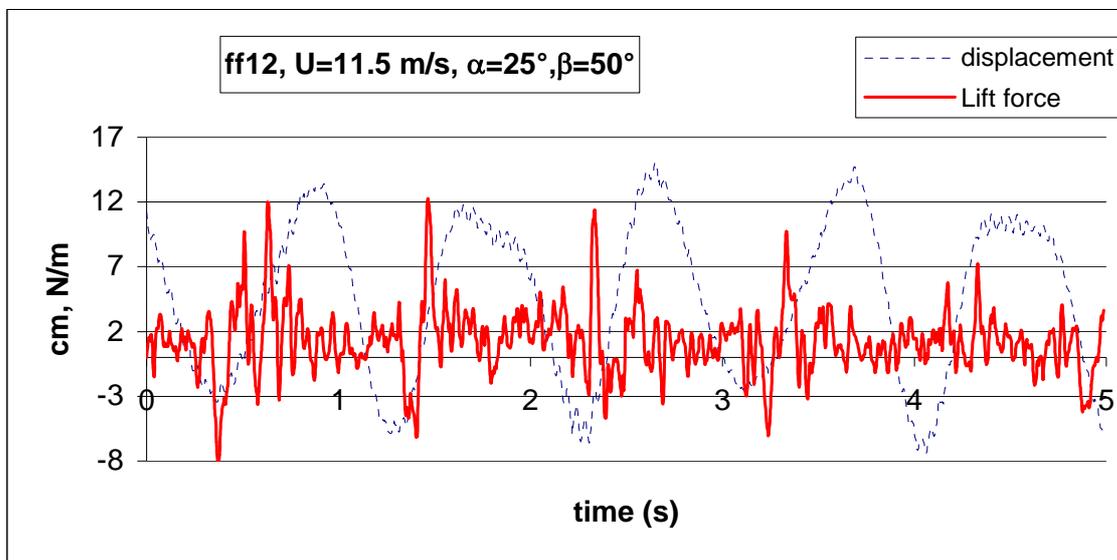


Figure 8 : time history signal of the integrated lift force and vertical movement

The positive lift peaks, on the opposite, were perfectly situated, in the movement time history, to increase the model movement. The value of this phase shift, measured on a series of well established rain-wind excitation for various wind speed and yawing angle, through the phase of the inter-spectra, varied between 30° and 50° .

The instantaneous pressure field was drawn, like a pressure movie, with a step of 1/100 second. It showed that these lift force peaks can be related to a sudden pressure field oscillation, first on the lower part, then on the upper part were. It seems that the upper

separation point only moved. The flow, separated from this point, reattached on the cylinder for a period of about 0.10 second, creating a negative lift force peak. Then the reattachment point disappeared and a strong suction zone was created, in not more than 0.03 s, on the top of the cylinder, yielding a positive peak of lift force.

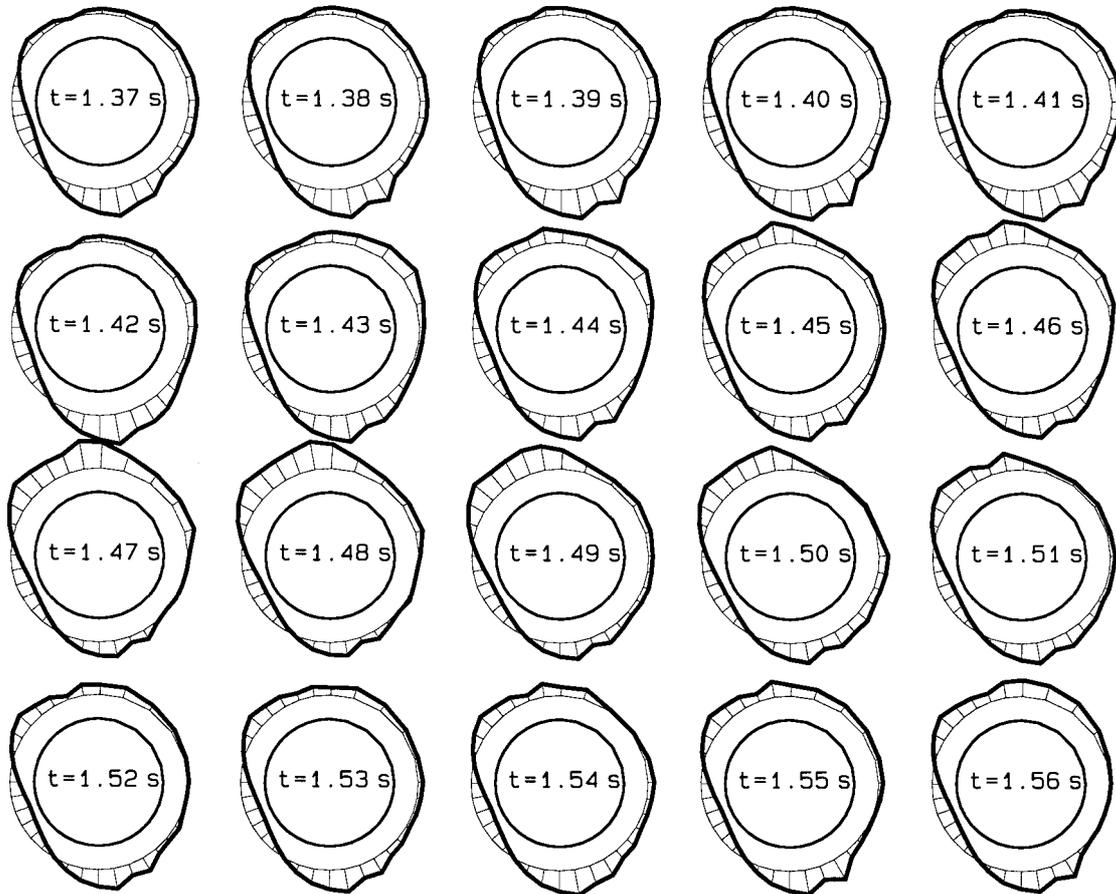


Figure 9 : time history signal of the pressure field corresponding to figure 8, ff12 file, $U=11.5$ m/s, $\alpha=25^\circ$, $\beta=50^\circ$

- C) The upper water rivulet existed and moved but without any excitation acting on the model for some set of parameters. The set of parameters for which the model was excited is the same as previously published .

4. ANALYSIS

A number of physical models have been tried as explanation and compared to these new experimental data. Three dimensional vortex shedding and galloping were said to be different from this excitation, even if the oscillation of the pressure field creating the lift force peaks had a period close to the vortex shedding one.

A CFD calculation showed that the Reynolds number related to the dry surface roughness was close to critical ($Re \approx 0.7 \cdot 10^5$ with the cylinder diameter and $Re \approx 2.5 \cdot 10^5$ with the length of the current lines) and that the water surface could cause the jump of Reynolds number value to critical, giving a sliding speed on the lower part of the boundary layer.

A model of the rivulet was developed that gave a relaxation time for this thin water film moving on the PE surface close to the cable model frequency. If the frequency changes, the rivulet movement amplitude also changes.

The equilibrium of the rivulet relies on the gravity force (1 N/m^2), the model acceleration (2 m/s^2), the sliding force of the air boundary layer (2 N/m^2) and the sliding force on the PE cylinder. In this model the boundary conditions of air flow are set by the water speed, that is linearly dependent from the rivulet thickness (0.5 mm/s for a 0.1 mm film). Any change in the water thickness can them be responsible for a change in air speed, changing the boundary layer and the pressure field.

The phenomenon can be described by the following events : when the cylinder begins to go upwards, the upper rivulet goes down after a given delay. The water accumulation in the lowest part of the rivulet creates an acceleration of the running water surface, transmitted to the boundary layer wall speed. When this local speed increase fits with the transition to turbulence, a quick change in the pressure field around the cylinder creates lift forces that can create, if the mechanical behaviour is favourable, the excitation.

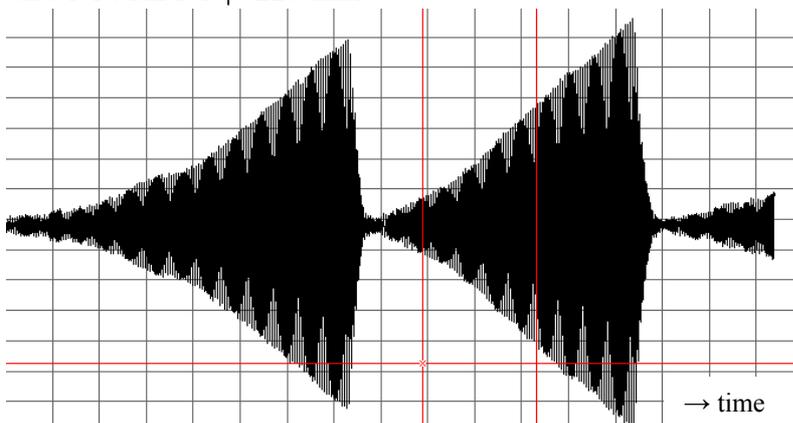
From this model it can be derived that :

- i) The rain-wind excitation can affect a wide range of cable diameter, especially the great ones, any time in a narrow band of wind speed.
- ii) The frequency range of the excitation is related to the relaxation time of the rivulet (governing the delay between the cable movement and the rivulet displacement). For this reason the different cables of a bridge can be excited on different modes, but with close frequencies.
- iii) The excitation is created by an initial cable displacement. Additional structural damping will help avoid the excitation.
- iv) The efficiency of discreet surface processing on the cable surface can be calculated. It does not act directly on the air flow, as it is covered by water, but on the water flow conditions. The marked surface processing, that is not covered with the water film, is also efficient as directly acting on the air flow to keep a high Reynolds number. But the result is an obvious loss in aerodynamic properties, like the increase of drag force.

5 VALIDATION BY NEW SERIES OF WIND TUNNEL TESTS

The model developed was based on experimental data on a 160 mm diameter model. The very comprehensive wind study realised for the RION-ANTIRION bridge, under construction in Greece, included the design of a cable covering shape avoiding the rain-wind induced excitation, for two cable diameter, 180 mm and 225 mm .

The study was performed in an open jet wind tunnel (6 m wide, adjustable height from 3 to 5 m) with a 8 m long model weighting 20 kg/m . The inclination angle α was varied from 17° to 30° , the yawing angle β from 0° to 90° . The wind speed went from 0 to 30 m/s , the turbulence intensity was less than 5% , the temperature 14°C , the rain intensity about 10 mm/hour . The model structural damping was $\xi=0.06\%$ of critical, the model frequency 1 Hz for $\phi=180 \text{ mm}$ and 1.14 Hz for $\phi=225 \text{ mm}$.



The first series of test was performed with smooth PE tubes. The excitation was characterised by the negative damping calculated from the increasing movement signal.

Figure 10 : negative damping measured from the amplitude increase.

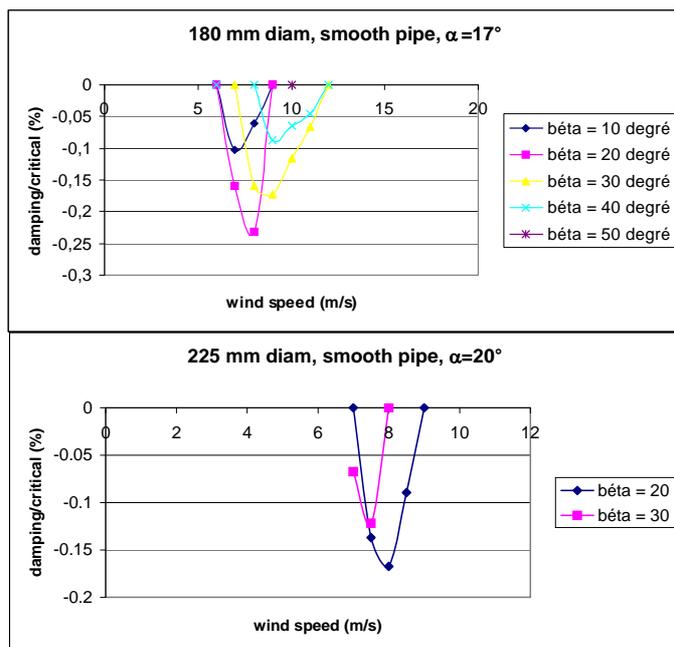


Figure 11 : negative damping for a model covered with smooth pipes

The excitation was very strong for the 180 mm diameter pipe at 8 m/s and did not exist for wind speed out of the 5-12 m/s range. This results were close to previous one with a 160 mm pipe, the excitation being stronger.

The wind speed range was different for the bigger diameter smooth pipe. This was due to the upper rivulet equilibrium for which a higher wind speed was necessary. For this pipe diameter the parameter range (inclination and yawing angle) corresponding to excitation was narrower than for the 180 mm pipe.

Then model was afterwards equipped with pipes surrounded by an double helical thread 3x3 mm at a step of 250 mm (for $\phi=180$ mm) and 350 mm (for $\phi=225$ mm).

With this pipe neither the rain-wind excitation, nor any other galloping, were observed in the range 0-25 m/s for all angle combination.

The total damping, measured after an artificial excitation, always increased with the increasing wind speed.

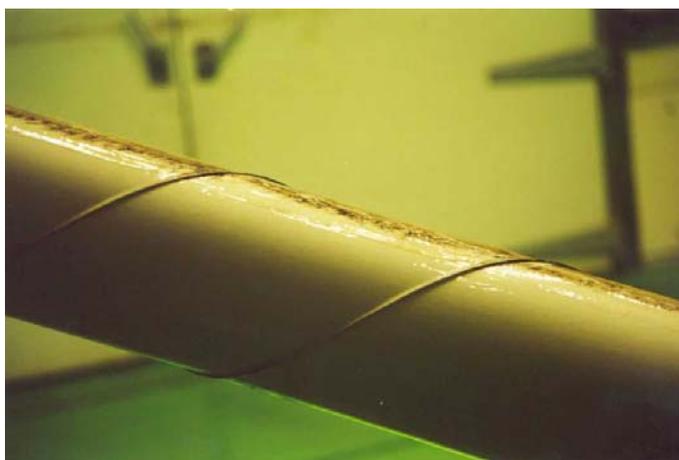


Figure 12 : pipe with helical thread

6 CONCLUSION

A physical model of the excitator responsible for the rain-wind induced excitation of cables has been derived from wind tunnel experiments. This model proved useful to explain and forecast the condition of the excitation.

The excitation dependence on water thickness was then explained by the link between this thickness and the water surface speed. With a thin water film, the water run speed increase due to the tube vertical acceleration is much more important than with a thick water film.

The parametric studies of the excitation conditions have been extended to 180 mm and 225 mm smooth surface cylinders. It was then confirmed that the excitation occurs for a wide range of pipe diameter, the most sensitive one being 180 mm.

The RION-ANTIRION bridge cables surface has been designed using these data. The double helical thread pipes, that have been tested successfully in the CSTB Jules Verne wind tunnel, proved to be efficient in suppressing the rain-wind induced excitation, keeping the drag forces on the stays at a low value.

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