DESIGN SPECIFICATIONS FOR A NOVEL CLIMATIC WIND TUNNEL FOR THE TESTING OF STRUCTURAL CABLES

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Introduction

The newly proposed Femern fixed link between Denmark and Germany will push the limits in engineering design. The selection of a cable-stayed or suspension bridge will lead to one of the longest bridges of its type in the world. The challenges of designing a bridge are many and the prospects of cable vibrations already preoccupy both the owners and designers. In this connection, the Danish owners/operators Femern Bælt A/S, together with Storebælt A/S, are funding a collaborative research project to examine the ways of reducing the risk of cable vibrations on a bridge solution. A novel climatic wind tunnel facility, dedicated to the testing of structural cables, is being developed as part of this research project. This paper describes the specifications and considerations for the construction of such a facility.

CABLE VIBRATIONS AND THE SPECIFICATIONS FOR A TESTING FACILITY

Wind-induced vibrations of cables are predominately due to buffeting, vortex shedding, galloping, wake galloping or some form of rain-wind interaction. Cables can vibrate under all meteorological conditions, particularly due to their large exposure and their low inherent damping. However, the largest amplitudes of vibration are usually attributable to rain, ice or sleet. A review of the known vibration mechanisms and the available mitigation measures is provided by Kumarasena et. al [1].
Experimental research on the wind-induced vibrations of cables has been hampered by the lack of suitable facilities that can simulate true meteorological conditions. Furthermore, wind-tunnel testing of cables needs to be undertaken at appropriate Reynolds numbers and preferably at full scale, as certain forms of wind-induced vibration are highly dependant on this number and on the correct formation of rain or ice. Smaller low-speed wind-tunnels are often unable to achieve the necessary Reynolds numbers without significant levels of blockage. Apart from wind-tunnel blockage, the physics of ice accumulation including thermodynamic effects and rivulet establishment for rain conditions are significantly biased at reduced scale. As several of the most dominant wind-induced vibrations occur within the *subcritical* and *critical* Reynolds number regions (Fig. 1a), it is desirable that a wind-tunnel test facility should be able to test up to at least the *supercritical* range. The *supercritical* range for circular cylinders (cable sheathing) can be assumed to start at approximately 3×10^5 for smooth flow. The Reynolds number for a circular cylinder of diameter D is:

$$Re = \frac{V \cdot D}{\nu} \tag{1}$$

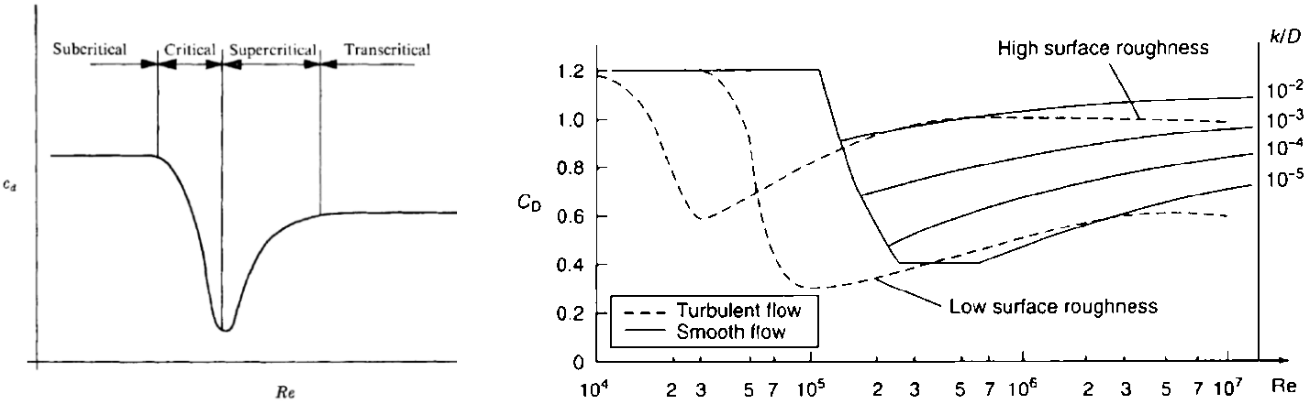

FIGURE 1a (left) - Definition of Reynolds number regions for a circular cylinder [2], 1b (right) - Reynolds number-dependant drag coefficient of a cylinder for varying surface roughness and flow turbulence [3]

where the kinematic viscosity of air is approximately $\nu = 1.5 \times 10^{-5}$ m^2/sec at 20°C and V is the velocity of oncoming air.

Neglecting suspension bridge main cables, the largest structural cables in use are suspension bridge hangers and the stay cables on cable-stayed bridges. The Great East Belt suspension bridge (second longest span in the world) has a largest hanger diameter of D = 115mm, whilst the longest and second longest span cable-stayed bridges (Sutong and Stonecutters, respectively) have longest cable diameters of 158mm and 169mm, respectively [4]. The largest known cable diameters used to date are in the order of 250mm (e.g. Øresund Bridge, Denmark-Sweden). Therefore, an appropriate wind-tunnel testing facility will be able to test cables with a diameter of up to approximately 200mm. By solving Eq. (1) for *V*, it can be found that the required wind tunnel velocity to reach the *supercritical* Reynolds number region will be:

$$V = \frac{3\times10^{5}\cdot1.5\times10^{-5}\,\mathrm{m}^{2}/\mathrm{sec}}{0.2\mathrm{m}} = 22.5\,\mathrm{m/sec} \qquad (2)$$

The maximum allowable blockage in a wind-tunnel, before result correction leads to doubt in test accuracy, is approximately 10% of the total test section. According to Simiu and Scanlan [5], this will result in a necessary correction in force coefficients of about 15%. As such, it is proposed that the test section of a generic wind-tunnel testing facility for cables have a minimum cross-sectional area of $2.0\times2.0m^2$.

Most structural cables are subject to both smooth and turbulent wind. Large terrain roughness or a heavily built-up environment can produce wind turbulence intensities of up to 20%. An appropriate wind-tunnel testing facility will be able to create a near full-frequency spectrum flow with a turbulence intensity of between 1% and 20%.

For the simulation of rain and ice, a test facility will be able to reproduce rain flow with a range of liquid water content (LWC) at varying temperatures down to -5°C. Temperatures below this level would not allow for the adequate transfer of precipitation to a cable surface. The maximum required rain flow will have a LWC of 0.4gr/m^3, as water contents above this level would not result in any further water or ice accumulation on the surface of a cable [6], [7].

Finally, a suitable wind-tunnel test facility will be able to test cables for varying wind angles-of-attack. An examination of the existing cable-stayed bridges reveals that bridge cables with angles of inclination of less than 22.5° would start to become structurally inefficient [8]. Consequently, a test section of 2m height would result in a section length of approximately 5m (length = 2m/sin22.5).

This leads to the basic specifications for a climatic wind-tunnel testing facility of Table 1.

TABLE 1 - Basic specifications for a climatic wind-tunnel facility for the testing of structural cables

Minimum wind velocity	25 m/sec^2
Test section cross-sectional area	2.0×2.0m^2
Turbulence intensity	1% - 20%
Temperature range	-5^{o}C - 40 ^{o}C
Rain flow	0.4g/m^3
Test section length	5m

DESIGN CONSIDERATIONS FOR THE FORCE/DTU CLIMATIC WIND TUNNEL (CWT)

A closed-curcuit wind tunnel with the basic specifications of Table 1 is being constructed at FORCE Technology (formerly the Danish Maritime Institute) in Denmark. It is currently referred to as the FORCE/DTU Climatic Wind Tunnel (CWT).

The performance of a wind tunnel depends primarily on the achievable airflow velocity and flow quality. Both aspects need to be considered simultaneously and may lead to several iterative steps before reaching the desired aerodynamic performance level. The design of the CWT is primarily based on existing wind tunnel designs and tunnel design "know-how" ([9],[10],[11],[12],[13],[14]).

According to the basic specifications in Tab. 1, the flow rate for a maximum wind tunnel velocity of 25m/sec will have to be 100m^3/s. The magnitude of the overall resistance to the air circulation, expressed as the pressure loss Δp, depends heavily on the aerodynamic design. The aerodynamic design, in turn, is dependant on the overall dimensions of the tunnel. The overall dimensions of the CWT are approximately 8m (vertical) height × 4m width × 20.5m long. An overview of the proposed climatic wind-tunnel with its main features is provided in Fig. 2.

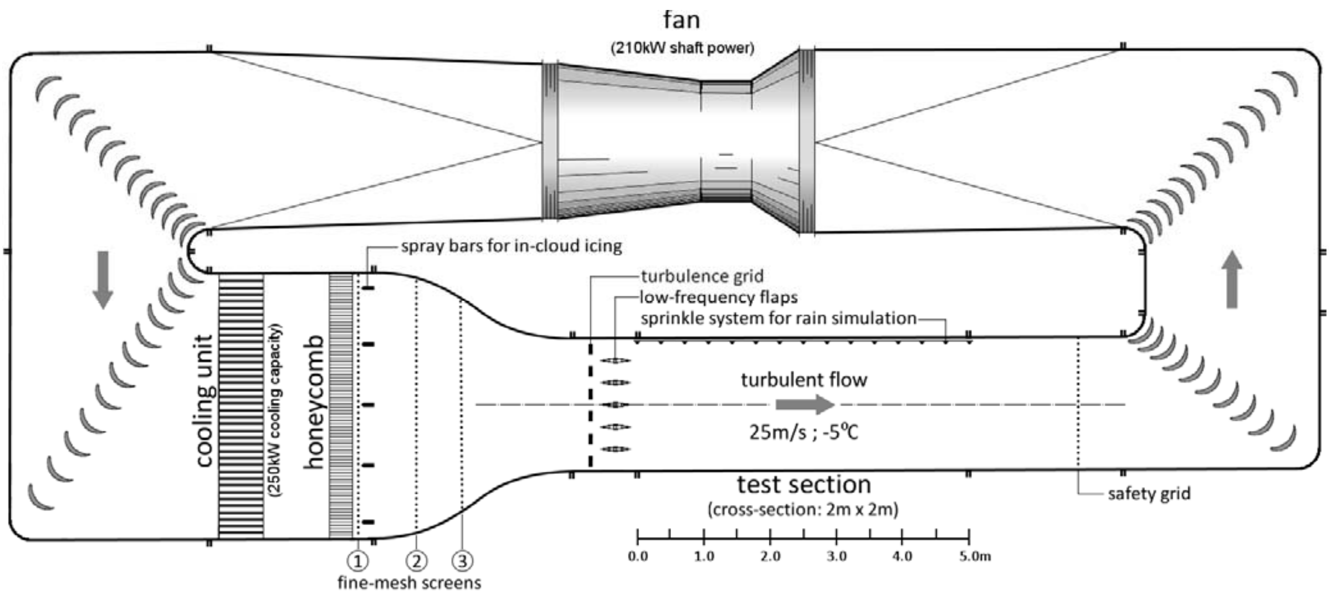

FIGURE 2 - Elevation of the Climatic Wind-Tunnel facility for bridge cable testing.

CWT concept

A closed-circuit type wind tunnel allows for a controlled establishment of the different climatic test conditions. Due to constraints of the available space, the conventional design of a slow cross-section expansion behind test section towards the fan (allowing for optimal pressure recovery) needed to be abandoned - resulting in an increased power requirement. The CWT cross-sections are rectangular

except for the transitions before and behind the fan. The closed circulation is established through four 90° turns. Each turn is equipped with profiled guide vanes arranged with progressive spacing as described by Idelchik [11].
To modulate the airflow characteristics with as low a pressure loss as possible the settling chamber cross-section is set at 4.0m × 4.0m. The chamber houses the cooling unit, which contributes significantly to the overall pressure loss.

Fan power and cooling capacity

The present CWT design of Figure 2 requires a 210kW motor for the fan. This shaft power is needed to circulate the air with $100m^3/s$ at maximum drag configuration, i.e. all flow generating devices (turbulent flow) and model setup included. The cooling unit has a capacity of 250kW to compensate for heat due to air friction and motor waste heat and to heat transmission from ambience.

Flow modification

Two flow conditions have been considered for the tunnel design: smooth and turbulent flow. Both impose different requirements on the design.
To generate smooth flow or actually flow with a turbulence intensity below 1%, the vorticity in the approaching flow is eliminated with a honeycomb grid (approx. 19mm cell pitch) and three successive wire meshes. The design and dimensions are largely taken from the wind tunnel facilities at FORCE Technology. The initial meshes consist of 0.6mm wire and a porosity of 50%. All meshes are designed to be easily exchangeable.
For turbulent flow generation three methods are considered: grid bars, pivoted flaps and fan RPM control. The need to test with full-scale turbulence imposes the application of unconventional methods. The usage of grid bars allows for the generation of a limited range of vortex dimensions. i.e. the grid bar generated turbulence covers mainly the high-frequency range of the wind turbulence spectrum. To generate contributions from the middle and low-frequency range, the CWT is fitted with computer-controlled pivoted flaps. Actuated individually or in a cluster, the effect of larger turbulent structures passing the cable shall be simulated. Finally, very low frequency turbulent fluctuations can be achieved by varying the fan RPM.

Rain and ice accretion

Recreating rain and ice accretion on the cables as observed in nature requires the capability of correct liquid water content generation in the airflow and the ability to generate low air temperatures (-5°C or below). The design of the CWT spray bars and peripheral equipment is based on the Altitude Icing Wind-Tunnel at the National Research Council (NRC) in Canada [15]. The CWT spraying system consists of five spray bars with nozzles, directly behind the wire mesh at the honeycomb. The total number of spray bars can be changed and the optimal distribution of the spray nozzles across the flow can be chosen according to the need.
Ice accretion tests on circular cylinders performed at NRC showed that particularly at air temperatures around -1°C to -2°C the accretion of water droplets on a cylinder surface and the transition to solid or spongy ice depends heavily on the flow and heat transfer conditions in the surface boundary flow. These observations substantiate the approach of including turbulence in the ice accretion simulation since significant effects in the liquid phase of the accumulated water are expected.
A second system for rain simulation is installed under the ceiling of the test chamber. The rain system can be adjusted in position to account for the driving effect of the airflow on the droplet trajectory.

WIND TUNNEL TESTING OF CABLES UNDER DIFFERENT CLIMATIC CONDITIONS

As mentioned, cable vibrations are known to be associated with a number of phenomena, each occurring under different geometric and meteorological conditions. A basic requirement for a wind tunnel facility aimed at cable testing is that of being able to reproduce as many as those conditions as possible. In particular, the CTW is specifically designed for the testing of dry, wet or iced vertical and inclined/yawed cables. In addition, the facility allows for static, passive dynamic and active dynamic setups. Due to the large number of possible testing conditions the test chamber design is inspired by modularity. This allows elements (panels) of the test chamber to be interchangeable, with the aim of obtaining numerous model support conditions, together with different geometric arrangements. In Fig. 3 a cross section of the Climatic Wind Tunnel is shown. The test chamber is connected to the rest of the tunnel through elastic joints, to prevent any external mechanical vibration transmittance to the setup.

Fig. 4 shows preliminary drawings of the test chamber. Based on the basic specifications, presented in Table 1, the chamber is 5m long, with a cross section of 2m x 2m. The chamber is made of four plane frames constructed of box profiles, connected longitudinally with T profiles and is divided into three areas. Two areas, each 2.05m long, are characterised by having floor, wall and ceiling panels that can be interchanged. The central area of the camber, 0.9m long has fixed floor, ceiling and walls. The interchangeable panels are 1.8m x 1.8m, with different specifications for each.

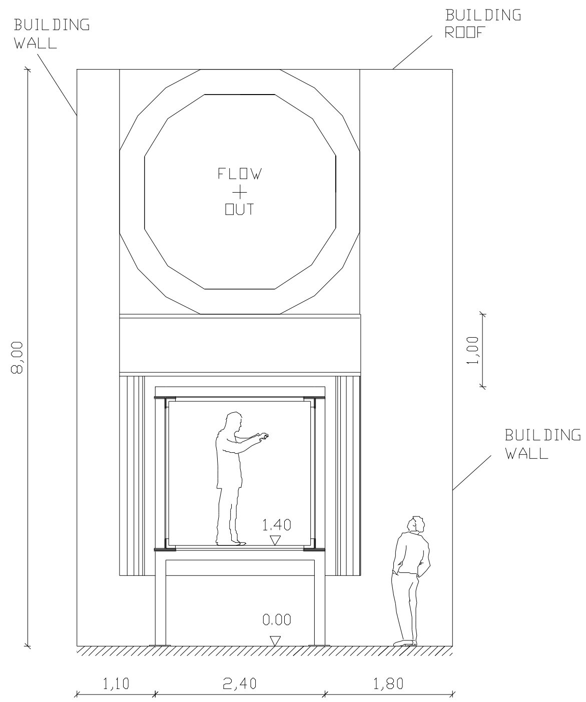

FIGURE 3. Cross section of the Climatic Wind Tunnel

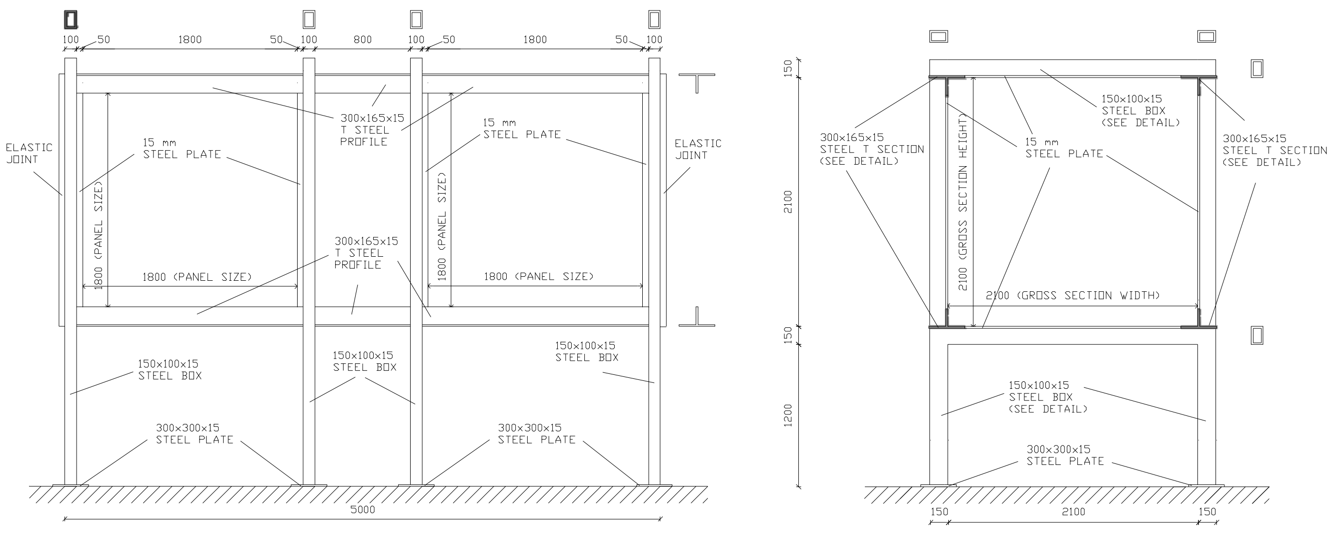

FIGURE 4 - Side view and cross section of the test chamber

Static setup

For static tests the cable model is rigidly connected to the test chamber floor and ceiling (or to the chamber walls, where necessary), placed entirely inside the wind tunnel. Static setups will be obtained using two fixed mount panels, whose position in the test chamber depends on the particular angle arrangement. Standard arrangements are those in which the vertical direction in the wind tunnel coincides with the vertical direction in the field. Such coincidence is mandatory when rain and ice are reproduced in the wind tunnel. It is optional for dry cable testing.

In Fig. 5, a section of the fixed mount panel is shown, together with a view indicating the location of the threaded holes for the attachment of the model. Each panel is provided with 289 threaded holes, arranged in 17 arrays of 17, with a centre to centre distance of 100mm. This allows the alongwind distance of the attachment points to vary from 0 to 4.50 m and the crosswind distance to vary between 0 and 1.70m, both with a step of 0.10m (see Fig. 3).

Fig. 6 sketches the cable geometry, showing the angle of inclination θ and the angle of yaw β of the cable. When the point of attachment of the axis of the model is located 150mm from the tunnel floor and ceiling, then it is found that the inclination angle can vary from 19.4° to 90°, and the yaw angle from 0° to 90°, even though not all combinations will be possible. The connection of the model to the mount panel is made through either ball or Cardan joints.

The static setup allows pressure and force measurement on dry and wet cables and force measurement on iced cables, as well as PIV and flow visualisation tests.

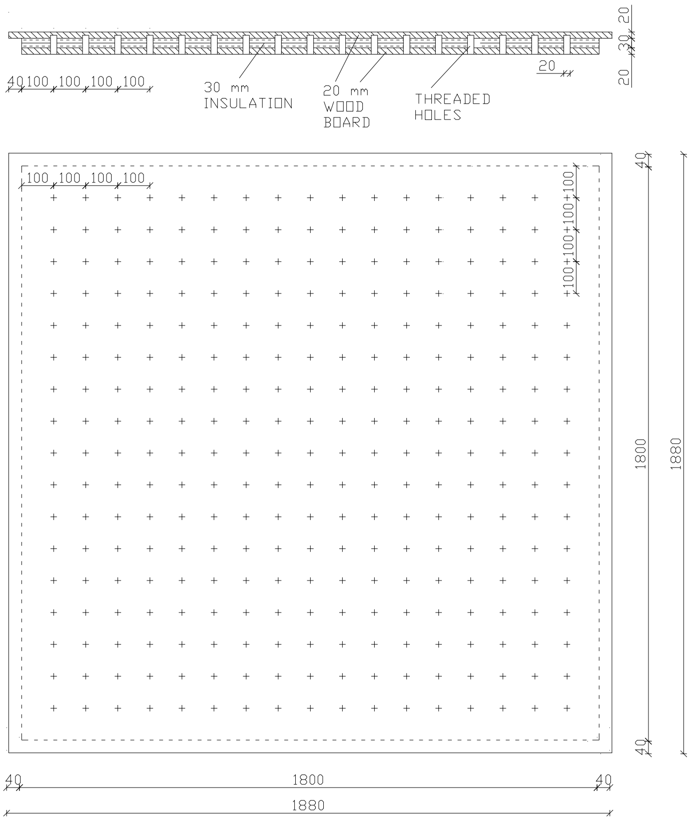

FIGURE 5 - Fixed mount panel

Passive dynamic setups

In passive dynamic setups the model is supported on springs, therefore is free to vibrate under the wind action. For a dry cable, i.e. in the case in which gravity does not play any role in shaping the geometry, the inclination and yaw angles of the prototype can be combined into one single angle. This allows for the placement of the model longitudinally in the wind tunnel, using the inclination angle in the wind tunnel to reproduce both the inclination and the yaw angle of the prototype. In particular, the inclination angle φ in the wind tunnel is obtained as [16]:

$$\cos\varphi = \cos\theta\cos\beta \qquad (3)$$

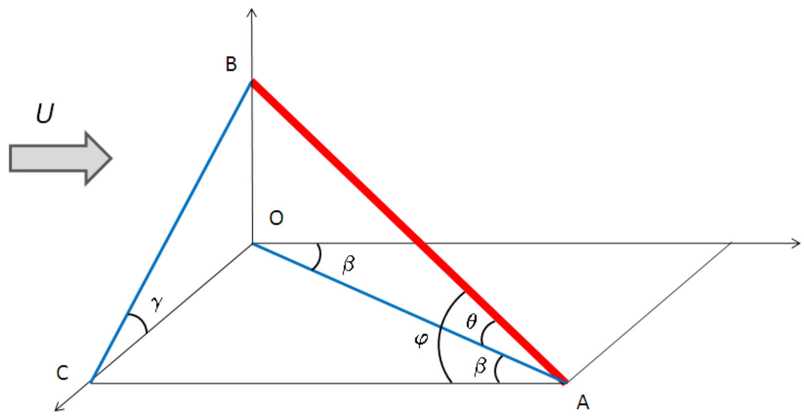

FIGURE 6 - Cable geometry

Taking advantage of this relationship, with φ varying from 21° to 90° it is possible to obtain several combinations of the cable inclination and yaw angle, and have the model vibrate in a plane orthogonal

to its axis. When the model is placed longitudinally in the wind tunnel, it is then possible to locate the suspension rig outside the test chamber, with the model going through special slotted panels. This configuration allows for the reproduction of some features of the axial flow which naturally develops on inclined cables. This is done by properly shaping the panel slots, in order to let the correct amount of air through. In addition the axial flow can be controlled by imposing a pressure difference at the two ends of the model, located outside the test chamber. To this aim, the two supporting rigs are located in two pressurised volumes, one above the test chamber ceiling and the other below its floor. The two pressurised volumes are connected through a ventilation duct, in which a fan is installed. The propeller creates a pressure difference, which is translated into a pressure difference between the two pressurised volumes. This setup is mainly designed for dry cable testing and it does not allow for the investigation of rain-wind vibrations, except for the particular case in which the wind is parallel to the bridge axis (β=0). On the other hand, it does allow for tests on iced cables, as long as the ice accretion is obtained on the actual geometric configuration of the cable. Again, when the wind is parallel to the bridge axis, then ice accretion can take place on the cable already located in the passive dynamic rig. However, when the cable is yawed, then ice accretion should take place on the model mounted on the static setup. Once ice accretion is complete, then the model is moved to the passive dynamic rig for testing. By doing so, the cable can also be rotated with respect to its axis, therefore reproducing changes in the wind direction after ice accretion. These changes are believed to be responsible for most ice-wind induced vibrations. For the purpose of changing the model position in the test chamber, this has to be of variable length. This can be achieved through a modular model, i.e. a model made of a number of segments which can be easily added or removed.
When using the setup above, one has to pay attention to the Froude scaling of the model. Froude scaling requires that:

$$Fr_m = \frac{V_m}{\sqrt{g_m L_m}} = \frac{V_p}{\sqrt{g_p L_p}} = Fr_p \tag{4}$$

where L is a characteristic length, g is gravity and where the suffixes p and m refer to the prototype and to the model, respectively. When the vertical direction in the wind tunnel does not coincide with the vertical direction in the field, but is rather rotated of an angle γ (see Fig. 5) then:

$$g_m = g_p / \sin\gamma \tag{5}$$

and:

$$\lambda_V = \frac{\sqrt{\lambda_l}}{\sqrt{\sin\gamma}} \tag{6}$$

λ_l and λ_V being the length and velocity scales. This can be easily taken into account in the calculations. However, an unrealistic acceleration component arises in the setup, orthogonal to the vertical direction in the field, whose magnitude is:

$$a_h = g_p / \cos\gamma \tag{7}$$

A second passive dynamic setup will be possible, in which the model is placed wholly inside the tunnel, and with the same inclination and yaw angles as the prototype. This setup allows testing of rain- and ice-wind induced vibrations and is not subjected to acceleration distortion above. It, however, does no allow for the reproduction of an axial flow.

Active dynamic setup

Finally, a third possibility is that of performing tests with active dynamics, i.e. imposing an external motion to the model and measuring the driving forces. After subtraction of the inertia force, the aerodynamic force exerted by the flow on the cable in that particular vibratory state is found.
This setup has similar characteristics as the first passive dynamics setup described, i.e. the model will be placed longitudinally in the tunnel, with the suspension rig located outside the test chamber. Therefore it does not allow for testing of rain-wind vibrations. It does, however, allow for testing of ice-wind vibrations, following the same procedure described for the passive dynamics tests. The model will be driven in a sinusoidal motion in a plane orthogonal to the model axis, with prescribed frequency and amplitude. The dynamic rig is also designed for the application of “substructuring”.

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