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PONTE SULLO STRETTO DI MESSINA

PROGETTO DEFINITIVO

EUROLINK S.C.p.A.

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INDICE

1 Executive summary

This report elaborates on the potential galloping instabilities found during the wind tunnel sub-tests C1.

Based on wind tunnel tests and quasi-steady analysis it is found that the twin back stays of the Messina Bridge are likely to be prone to classical den Hartog galloping as the individual cable elements of the twinned back stays experiences negative lift slopes for horizontal wind. A second type of galloping instability, interference galloping, is found for the downwind cable element when the wind is at quartering angles with the bridge line. Paired with available wind statistics the conditions for onset of galloping of the back stays are likely to be encountered for about 0.15 % of the year if mitigating measures are not taken.

The preferred mitigation measure for the galloping instabilities constitutes a perforated plate inserted in the gap between the twin back stay cables. The plate will prevent flow in the gap between the cable elements and thus eliminate the flow switching mechanism leading to den Hartog and interference galloping.

2 Sub-tests C1

Wind tunnel tests carried out in the pressurized wind tunnel at DLR, Göttingen, Germany [1] have demonstrated the existence of an interference galloping instability for a model of the twin cable system, Figure 1. Here it is noted that a vibration instability is encountered at inflow angles in the range of approximately 4 deg < α < 12 deg for Re = $5.6 \cdot 10^6$ corresponding to the SILS condition at z = 250 m level. For wind speeds less than 28 m/s (Re < $2.4 \cdot 10^6$) the critical inflow interval is decreased to 8 < α < 12 deg where the lift slope is estimated as $\partial C_{L2}/\partial\alpha = 5.01$. Adjacent to the instability range the lifts lope is negative indicating classical den Hartog galloping. In the inflow angle range -2 < α < 4 deg where the lift slope is estimated as $\partial C_{L2}/\partial\alpha = -2.87$.

The probability of encountering wind speeds larger than 28 m/s is very low according to the available wind data [3]. The critical inflow interval considered here is therefore 8 deg < α < 12.

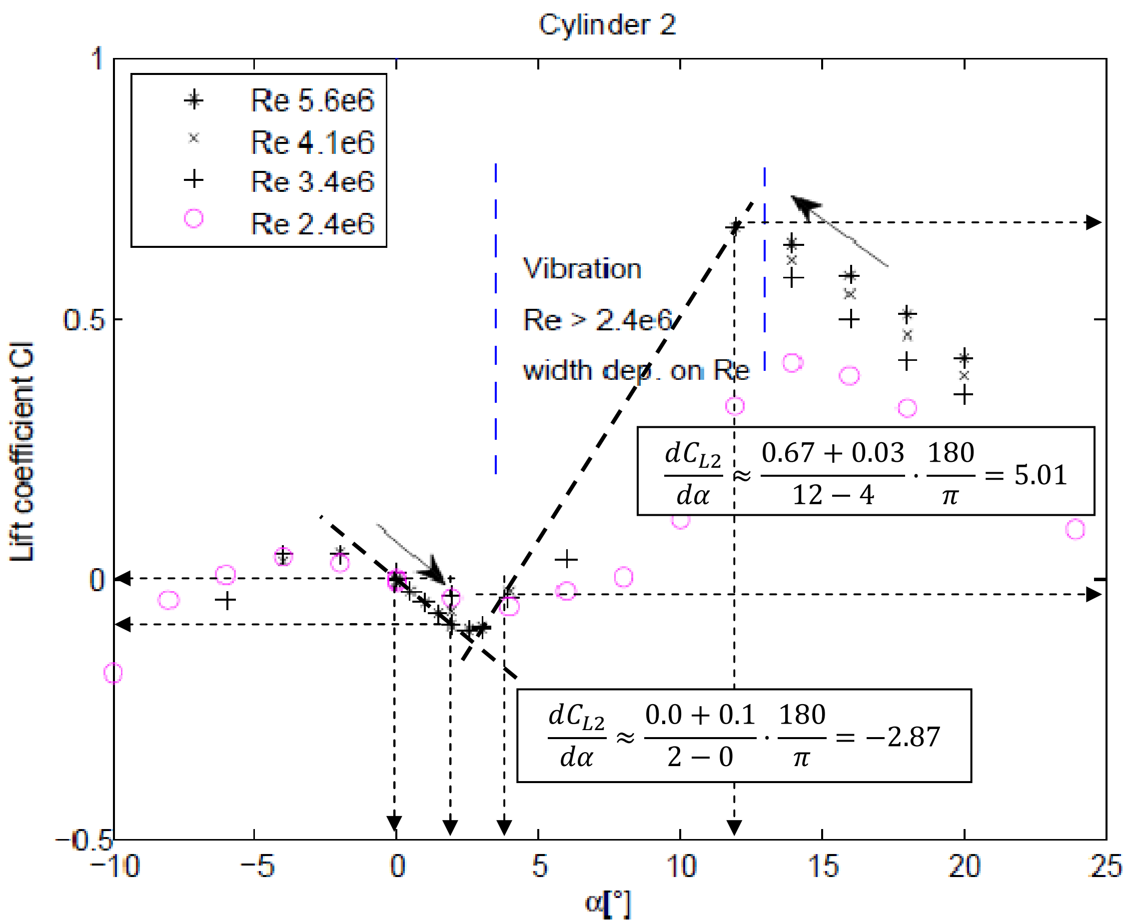

Figure 1 Lift coefficient of downwind cylinder as function on inflow angle α, having Reynolds' Number as parameter and estimation of lift slopes $\partial C_{L2}/\partial\alpha$. High Reynolds Number fit.

Also the wind tunnel tests demonstrated a risk of potential den Hartog galloping for the upwind cylinder of the cable model, Figure 2. Here it is noted that the lift coefficient C_{L1} displays a negative slope in the range of inflow angles of approximately $-6 < \alpha < 6$ deg for Re = $2.4 \cdot 10^6$

The lift slope for the upwind cylinder around α = 0 deg. is estimated as $\partial C_{L1}/\partial\alpha$ =-1.7. The den Hartog criterion for galloping is thus fulfilled: $\partial C_{L1}/\partial\alpha + C_{D1} = -1.7 + 0.4 = -1.3 < 0$.

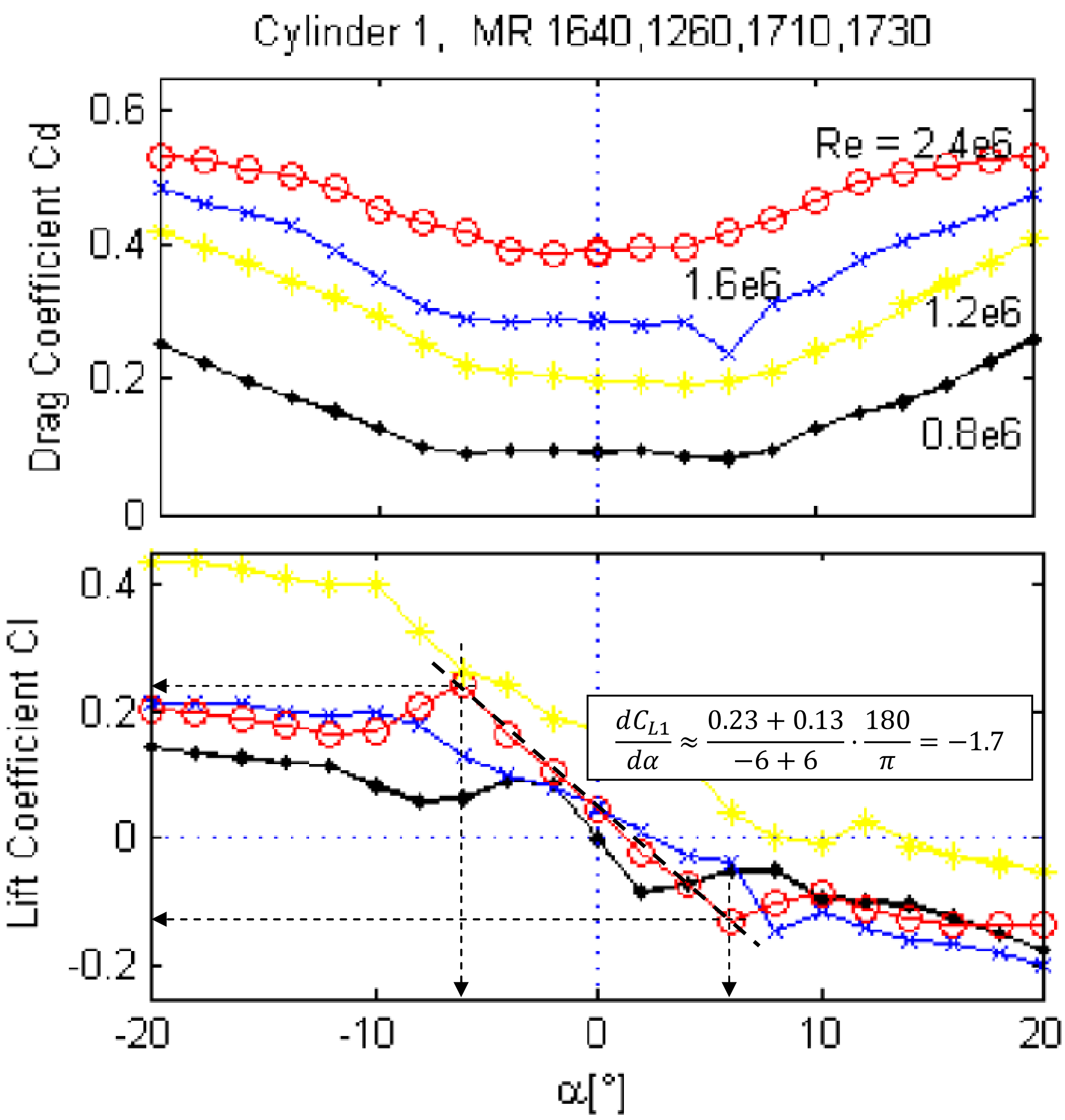

Figure 2 Drag and lift coefficient of upwind cylinder as function on inflow angle α, having Reynolds' Number as parameter and estimation of lift slope $\partial C_{L1}/\partial \alpha$.

2.1 Inflow angle

In Figure the relationship between the inflow angle, β, in the horizontal plane and the inflow angle in the cable normal plane, α, is illustrated. The angle between the back stay and the horizontal plane is here denoted θ. An inflow angle in the horizontal plane, β, perpendicular to the bridge alignment ($\beta = 0$) leads to an inflow angle in the cable normal plane, α, equal to zero. The function

$\alpha = f(\beta, \theta)$ is derived using vector projections. By use of this function it is found for which angles, β, the inflow angle, α, will be in the critical interval 8 deg < α < 12 deg.

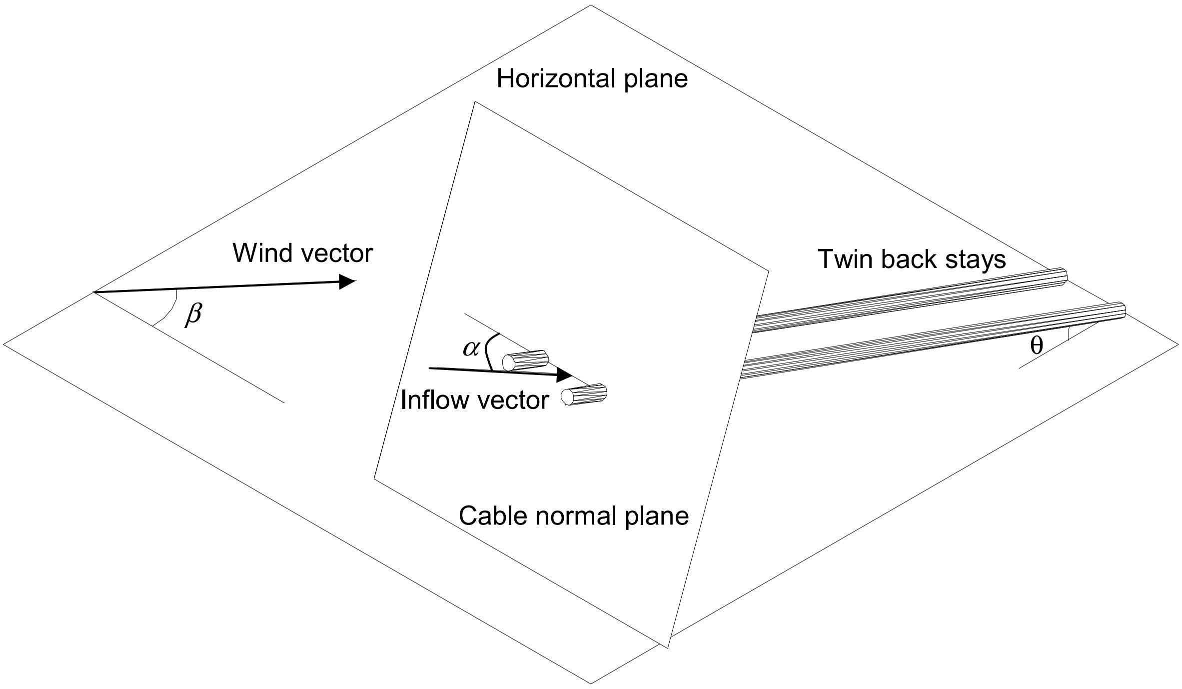

Figure 3 Relationship between wind in the horizontal plane and wind in the cable normal plane.

The horizontal angle intervals *(β-angles),* leading to inflow angles*, α,* in the critical interval is listed in Table 1. The critical β–intervals are illustrated in **Errore. L'origine riferimento non è stata trovata.** Figure 4 relative to the bridge alignment.

Table 1 Critical wind intervals in the horizontal plane (β-angles). Intervals 1 - 4 are associated with interference galloping of the downwind cable element, whereas intervals 5 and 6 are associated with classical den Hertog galloping of the upwind cable element.

Intervals	β_{start}	β_{end}
1	20	29
2	331	340
3	151	160
4	200	209
5	355	5
6	175	185

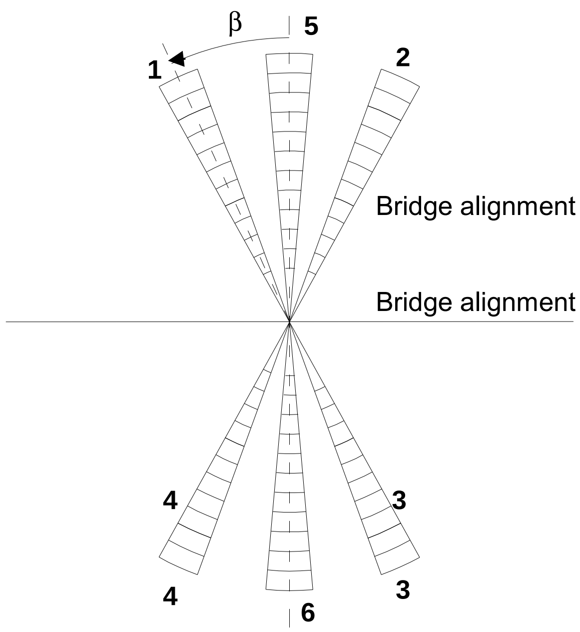

Figure 4 Critical wind intervals in the horizontal plane.

2.2 den Hartog galloping wind speed

Den Hartog galloping is a well known phenomenon linked to the eigenmodes of the structure.

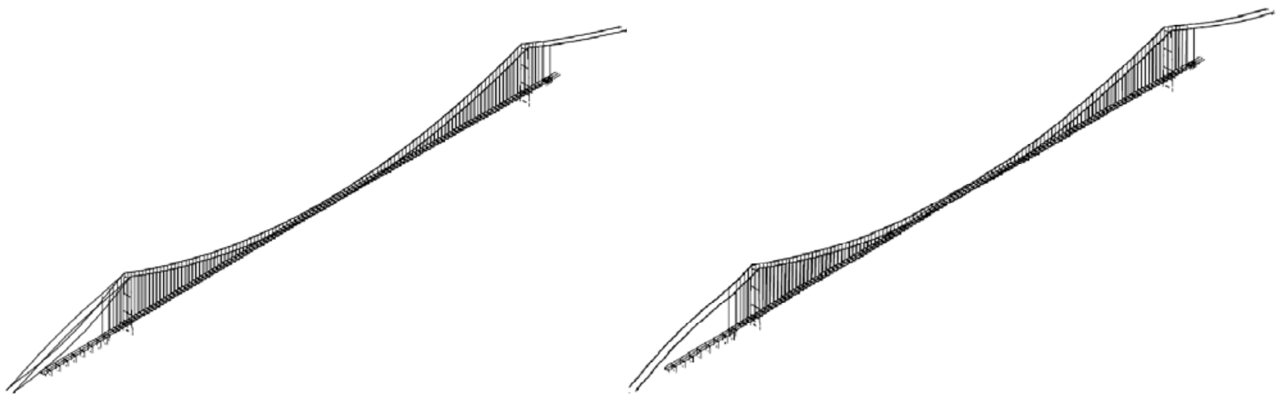

Figure 5 Lowest eigenmodes displaying back stay cable motion. Left: twist or out phase movement of the cable elements, f = 0.166 Hz. Right: vertical or in phase motion of the cable elements, f = 0.168 Hz.

The wind speed for onset of vertical den Hartog galloping can be predicted as [4]:

$$U_{g\_dH} = -\frac{4M\delta f}{\rho d} \cdot \frac{1}{\frac{\partial C_L}{\partial \alpha} + C_D}$$

Where M is section mass of cable element, δ is structural damping decrement, ρ air density, f is cable frequency of vibration, and d is cable diameter. In case of the back stays of the Messina bridge where the individual cable elements are identical and clamped together at 30 m intervals, the above equation is rewritten as:

$$U_{g\_dH} = -\frac{8M\delta f}{\rho d} \cdot \frac{1}{\left(\frac{\partial C_{L1}}{\partial \alpha} + C_D\right) + \left(\frac{\partial C_{L2}}{\partial \alpha} + C_D\right)}$$

Inserting the relevant structural data: M =8500 kg/m, δ = 0.02, ρ = 1.25 kg/m^3, f = 0.168 Hz, d = 1.27 m, $\partial C_{L1}/\partial\alpha + C_{D1}$ = -1.3, $\partial C_{L2}/\partial\alpha + C_{D2}$ = -2.8 yields and estimated galloping wind speed U_{g_dH} = 35 m/s

For the twist or out of phase mode the critical wind speed for on set of galloping can be estimated according to [4] as:

$$U_{g\_dH} = -\frac{4I\delta f}{\rho d^2 R} \cdot \frac{1}{\frac{\partial C_M}{\partial \alpha}}$$

Where the new variables are: I mass moment of inertia / unit length, R is characteristic radius defining relative velocity and $dC_M/d\alpha$ is the moment slope. Assuming $I = 2 \cdot M \cdot (a/2)^2$ where a is the centre-to-centre cable spacing, R = a/2 and $dC_M/d\alpha = dC_{L1}/d\alpha \cdot a/2d + dC_{L2}/d\alpha \cdot a/2d$ the above equation can be rewritten as:

$$U_{g\_dH} = -\frac{8M\delta f}{\rho d} \cdot \frac{1}{\frac{\partial C_{L1}}{\partial \alpha} + \frac{\partial C_{L2}}{\partial \alpha}}$$

Inserting the relevant structural data yields a galloping wind speed in the inflow angle range $-6 < \alpha < 6$ deg. yields a critical torsion galloping wind speed of approximately U_{g_dH} = 30 m/s for twisting of the twin cable assembly.

2.3 Interference galloping wind speed

Rusheweyh [2] have studied the phenomenon of interference galloping of closely spaced elastic cylinders and have developed an expression for the critical or onset wind speed U_g for the onset of the phenomenon:

$$U_{g\_in} = \sqrt{\frac{2M\delta}{\rho d^2}}\, 2fd \sqrt{\frac{-\pi \frac{a}{d}}{\frac{dC_{L2}}{d\alpha} sin(\varphi)}}$$

All quantities is the above equation refers to the downwind cylinder where: d is cylinder diameter, a distance from centre of the upwind to the downwind cylinder, M is mass / unit length, δ structural damping log-dec., f eigenfrequency, $dC_{L2}/d\alpha$ lift slope and φ phase angle between the cylinder motion and the exciting force. It is noted that φ must assume negative values in order for the aerodynamic forcing to drive the motion.

The lift slope for the downwind cable element is estimated as $dC_{L2}/d\alpha = 5.01$ in Figure 1. The remainder of the input data necessary for making an evaluation of the wind speed for onset of interference galloping of the Sicily side span are as before: M =8500 kg/m, δ = 0.02, ρ = 1.25 $kg/m^{3,}$ f = 0.166 Hz, a = 2.0 m, d = 1.27 m, φ = [-2 deg; -90 deg]

The result of the evaluation is shown in Figure 6 as the onset galloping wind speed as function of phase angle. It is noted that the galloping wind speed varies in the range 20 m/s - 4 m/s depending on the phase angle. It is likely that the motion is only lagging the excitation force by a small amount hence an onset galloping wind speed above 20 m/s is most likely.

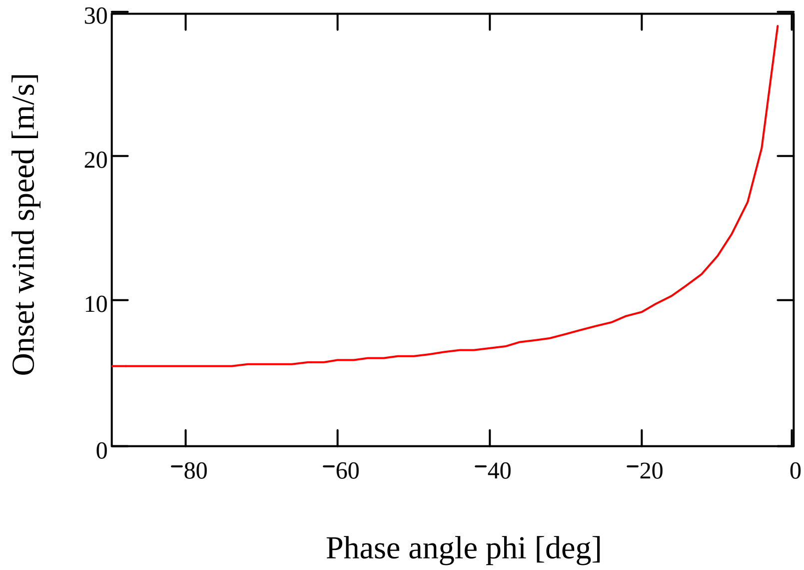

Figure 6 Onset wind speed for galloping $U_{g\text{-}in}$ as function of phase angle φ.

Vertical interference galloping of the downwind cable element is not strictly possible as the individual cable elements are clamped together at 30 m intervals. Ideally the interference galloping model should have been developed to predict torsion galloping as was the den Hartog model, but this is not pursued due to inherent model uncertainties which can not be eliminated unless calibrated against an aeroelastic wind tunnel test. For the present purpose it is assumed that the galloping wind speed for the twist motion is identical to that of the vertical motion.

2.4 Probability for occurrence of interference galloping

In **Errore. L'origine riferimento non è stata trovata.**a wind rose for wind speeds above 0 m/s for the Calabria side is shown [3], together with the bridge alignment and the wind directions where interference galloping instability can occur.

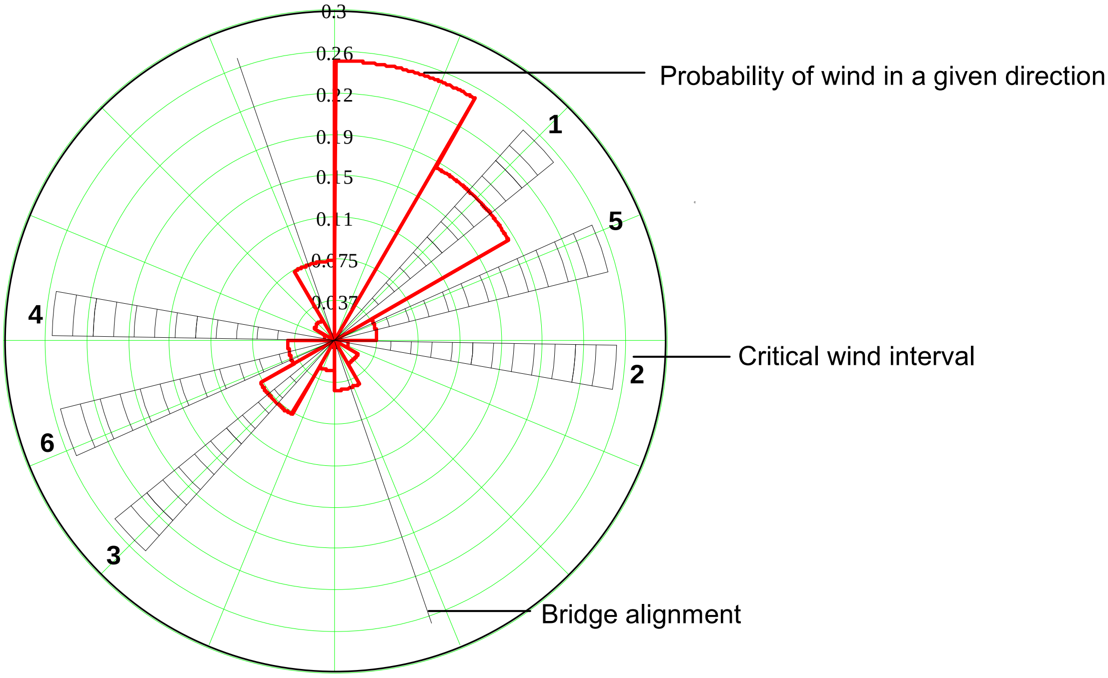

Figure 7 Wind rose for all wind speeds and wind intervals where galloping can occur.

The probabilities for wind speeds above 20 m/s in the four critical wind intervals are listed in Table 2. It should be noticed that Table 2 contains probabilities for wind speeds above 20 m/s, while the wind rose in Figure 7**Errore. L'origine riferimento non è stata trovata.** illustrates probabilities for all wind speeds.

Table 2 Probability of occurrence of interference (interval 1-4) and den Hartog galloping instability (interval 5,6) of individual cable elements.

Interval	Probability
1	0.036 %
2	0.014 %
3	0.064 %
4	0.007 %
5	0.005 %
6	0.023 %

Total	**0.15 %**

3 Conclusion

The present analysis has identified a small risk of galloping of the back stays. Interference galloping as well as den Hartog galloping has been identified as potential instability mechanisms which likely can be suppressed if air flow in the gap between the cable elements is prevented by inserting a porous plate between the cable elements. A sketch showing a possible practical arrangement of such a plate is show in Figure 8. The estimated weight of the aluminium grating including fixtures is 25 kg/m or 0.1% of the main cable weight.

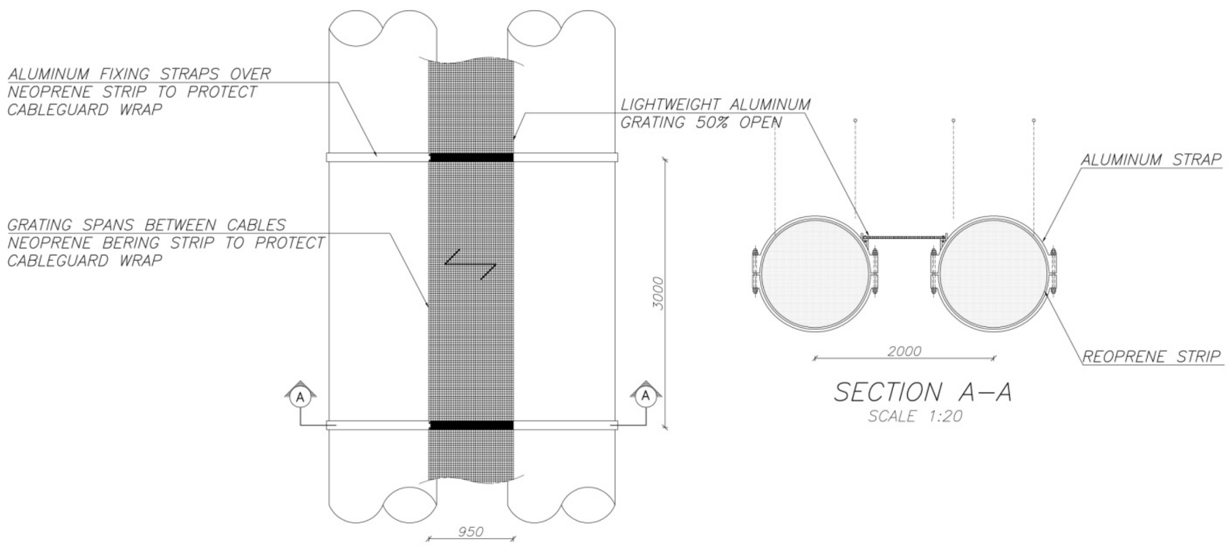

Figure 8 Sketch showing possible arrangement of grating between main cables

In view of the fact that the estimated galloping wind speeds are much lower than the flutter wind speed for the deck, it is recommended to investigate the galloping phenomenon and the proposed mitigation measure further in a high Reynolds Number aeroelastic test to be carried out either prior to or during the Progetto Esecutivo phase.

In case the proposed wind tunnel tests demonstrates that den Hartog or interference galloping can not be suppressed by the aluminium grating, a back proposal relying on mechanical damping is proposed as shown in Figure 9. Here a hydraulic damper is inserted in parallel with a mechanical spring between the individual cable elements and tie down cable anchored to the approach viaduct structures or ground.

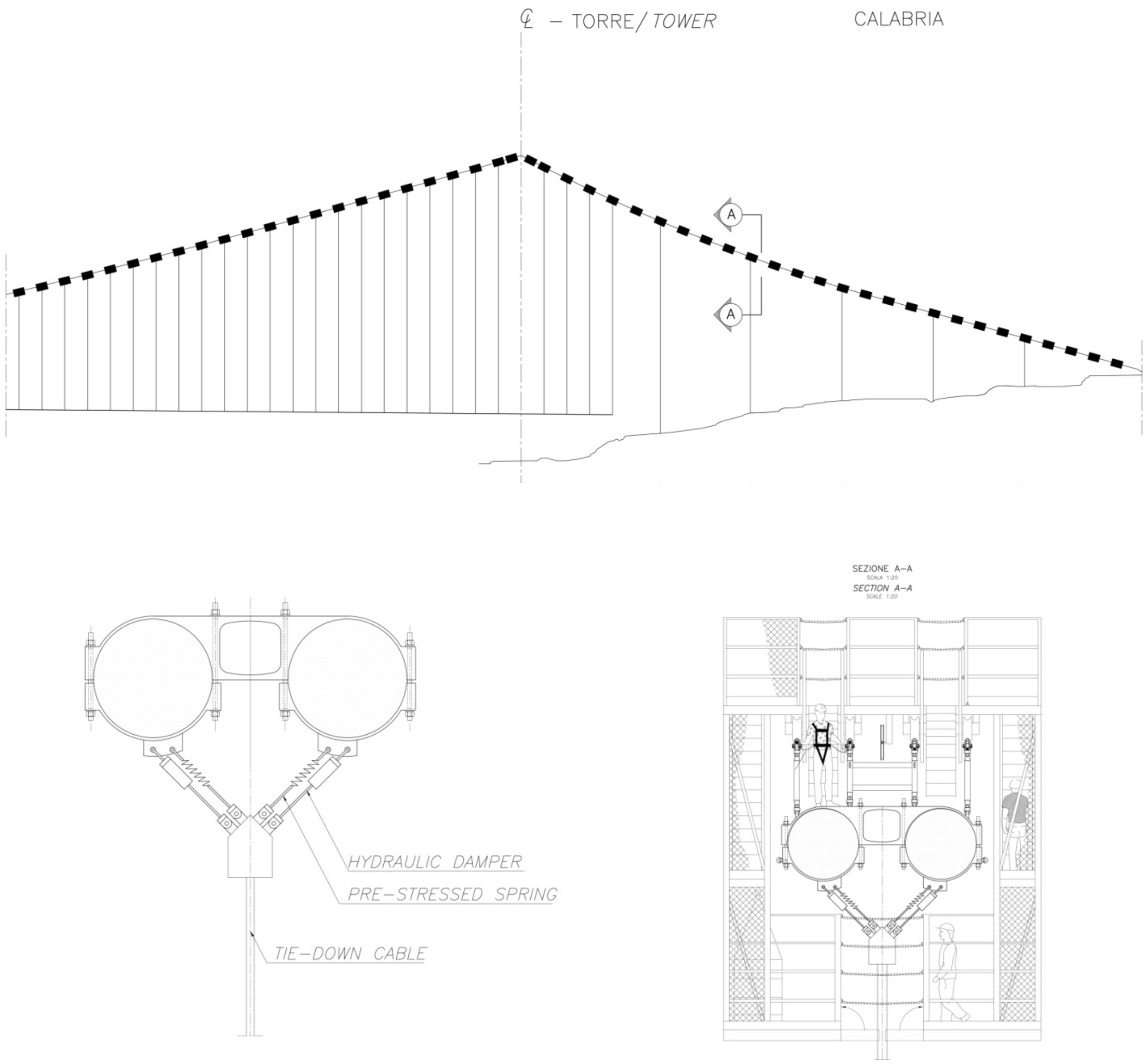

Figure 9 Sketch showing possible arrangement of pre-stressed springs and hydraulic dampers connecting the back span main cable elements to vertical tie-down cables

4 References

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4 Blevins, R.D.: Flow-induced Vibrations. Van Nostrand Reinhold, New York, 1997.