Study of aeroelastic interference effect among four cylinders arranged in rectangular configuration

S. Hračov[a], M. Macháček[a], P. Michálek[a]

[a] Institute of Theoretical and Applied Mechanics, Czech Academy of Sciences, Prosecká 76, 19000 Prague,, Czech Republic

1. Introduction

The hangers used for supporting the large civil engineering structures as, e.g., roofs or bridge decks represent the flexible structural elements susceptible to excessive vibration due to wind excitation. In the case of closely-spaced individual hangers, the significant wake-induced oscillations leading to significant reduction of their lifetime can occur, see [1-5].

This abstract deals with an analysis of the aerodynamic vibration of a group of four existing hangers supporting the hangar roof and creating in cross-section the rectangular array, see Fig. 1. It is especially concentrated upon the determination of the cause of the violent vibration of one of the hangers. In particular, the excessive vibration of the bottom downwind hanger in the across wind direction was observed, while the rest of hangers remained nearly stationary. The dominant vibration mode of the hanger was characterized by a one node in the middle of the length and by frequency $f = 5.85$ Hz. It corresponds to the second resonant frequency identified from the spectrum of the response related to hammer impact test. All four hangers in the form of tension rods have the same diameter, $D = 84.1$ mm, mass per unit length $\mu = 43.6$ kgm^{-1} and almost identical length 21 m and modal properties. The normalized distance between hangers in horizontal and vertical directions is equal to 3.15 D, and 3.8 D, respectively. The relatively high Scruton number of the hanger, $Sc = 59.2$, was determined for the expected very low logarithmic decrement of structural damping, $\vartheta = 0.006$.
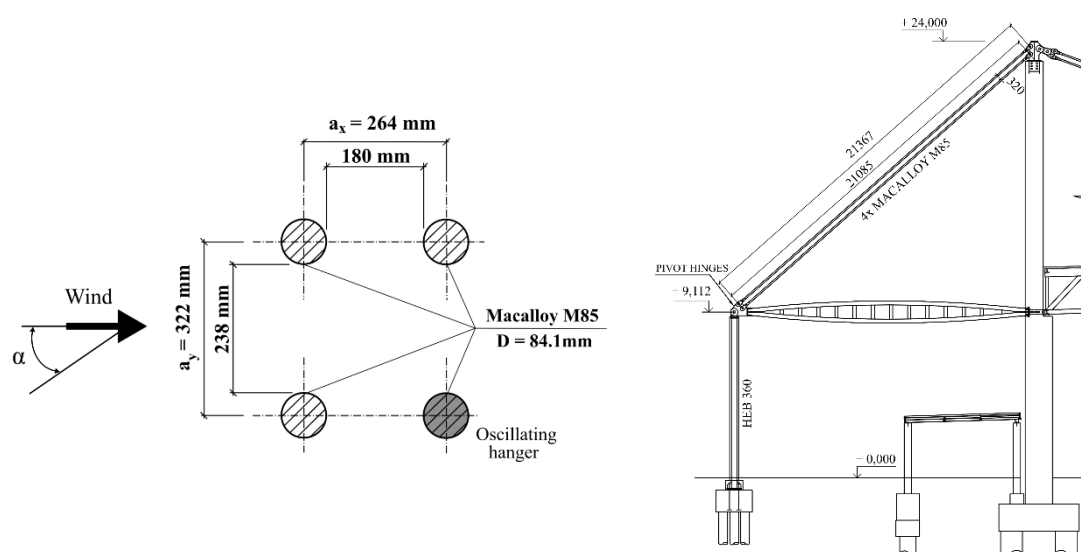

Fig. 1. Layout of hangers (left) and scheme of the part of roof supporting structure with hangers (right)

2. Theoretical analysis of wind-induced vibration

At first, the theoretical analysis of possible causes of the violent vibrations of the hanger was carried out. The calculations of critical wind speeds for vortex shedding and galloping of isolated one hanger according to Eurocode [2] confirmed the assumption of origin of excessive vibration in the wake induced vibration. In addition, the analysis of a pair of hangers did not reveal the significant increase in the response of the downwind hanger due vortex shedding effect on the upwind hanger. The theoretical analysis identifies the interference galloping as one of the possible causes of the serious vibrations. The formula for calculation of critical wind speed related to this type of aero-elastic instability can be found in the code [2] in the form:

$$v_{CIG} = 3.5 \cdot f \cdot D \cdot \sqrt{\frac{\frac{a}{D} \cdot S_c}{a_{IG}}}, \tag{1}$$

where f is natural frequency of hanger; D is diameter of hanger; a is distance between hangers; Sc is Scruton number and a_{IG} is a combined stability parameter with a value of 3. In our case, the formula (1) gives for the observed resonant frequency the estimations of critical wind speed equal to 13.6 m/s, which is realistic to be present at site. It must be noted, that this formula is related to only a pair of hangers and can be adopted only up to ratio $a/D = 3$. Nevertheless, the code [2] does not provide the solution for both, the higher ratios, a/D, even though the interference galloping can occur for ratio up to 4 [1] as well as for more complex arrangements of hangers as, e.g., analyzed tetrad of hangers. Thus, in our case, where the ratio in the wind direction is very close to the boundary value in [2] the above mentioned formula was used only for rough estimate of critical wind speed and the real interaction effect among four hangers needed to be investigated experimentally.

3. Procedure of wind tunnel testing

Aero-elastic stability and dynamic behavior of the bottom downwind hanger as a vibrating member of the tetrad of the rods were investigated experimentally in the wind tunnel of ITAM AS CR in Telč in the Czech Republic. The experimental model of each hanger was represented by 1.3-meter long plastic cylinder with the real cross section. Thus identical flow conditions around the cylinder as in reality i.e. same Reynolds number was reached. The cylinders were fixed horizontally to a specially designed experimental stand, see Fig. 2.

Fig. 2. Experimental set-up with mounted cylinders represented a real configuration of hangers

The bottom downwind hanger was placed into the special mechanism of this set-up allowing only the vertical (cross wind direction) movement. The stand enabled to analyze the influence of two values of Scruton number ($Sc = 44$ and $Sc = 79$) on aeroelastic instability of the cylinder, while its natural frequency ($f = 2.6\ Hz$) and the damping ratio ($\zeta = 1.5\ \%$) remained fixed. The lower natural frequency than in the real case was chosen due to mechanical restrictions of the stand. The low value selected in this way allows also to reduce the influence of vortex shedding emerging at wind velocity below 3 ms^{-1} on the instabilities occurring at higher wind speeds. The other three cylinders from tetrad were assumed as stationary, i.e. non-vibrating and were fixed between two plastic end-plates of the stand. Two positions of these fixed hangers were investigated in order to simulate two basic wind direction, i.e. $\alpha = 0°$ and $\alpha = 10°$, respectively, see Fig. 1. The latter case represents the critical wind incidence angle for the interference galloping [2]. In addition, behavior of an isolated hanger and a pair of hangers in the horizontal row were tested to compare the susceptibility to the aero-elastic instability with the full rectangular array configuration.

All tests were performed in the smooth flow conditions and consisted from incremental increases of the wind velocity from 2 ms^{-1} with the step approximately equal to 0.7 ms^{-1}. The maximum reached velocity was determined by the mechanical vibration limit of the set-up. Subsequently, the wind speed was decreased by the same step in order to identify the expected hysteresis effect. The steady-state response of the bottom downwind cylinder was measured for each velocity step using the rotary transducer connected to one of the moving lower arms of the set-up.

4. Results of experimental testing

At first, the hanger in rectangular array, in a pair of hangers and as an isolated element was tested in the smooth flow for angle of attack $\alpha = 0°$. The results of the dynamic response in all did not indicate any loss of the dynamic stability of the cylinder or an occurrence of high level oscillations as observed in reality. In particular, the RMS value of the vertical displacement did not exceed the value of *0.06 D*.

The experiments of all analyzed groups of hangers under the wind flow incidence angle $\alpha = 10°$ revealed sudden and significant increase of the cross-wind vibration response of the bottom downwind hanger at certain critical wind speed. By reaching the critical velocity, the harmonic response with high amplitudes was observed. Increase of the velocity above the critical one leads to the further increase of the response amplitude. It is documented in Fig. 3 in terms of RMS value of measured relative displacement for both the pair and the tetrad of hangers possessing the same and different Scruton numbers, Sc. For identical Sc, the outset of vibrations with high amplitudes for the rectangular array was detected at approximately two times lower reduced wind speed than for the pair of hangers. This implies on a significant influence of the upper row of hangers on interference galloping of downwind hanger in the bottom row. When comparing two groups of 4 hangers for different Sc, the initiation of instability for the higher Sc is becoming as expected at higher reduced wind velocity than for smaller Sc. The ratio between reduced critical wind speeds for these cases with different Sc equal to 1.34. It is a slightly higher than the square root of ratio of corresponding Sc equal to 1.84, which is relation between both critical velocities when applying formula (1). It should be also noted, that the level of vibration for higher Sc was lower than for smaller Sc as expected.

Strong hysteresis behavior was observed during whole testing process. The bottom downwind cylinder in the rectangular array as well as the downwind cylinder in a pair were oscillating with high amplitudes not only above the critical wind velocity, but also when the wind velocity was decreased below the critical one, see the dashed lines in Fig. 3. However, with further decrease in wind velocity at some moment a sudden significant reduction in the response occurred. This holds for all of the analyzed configurations.
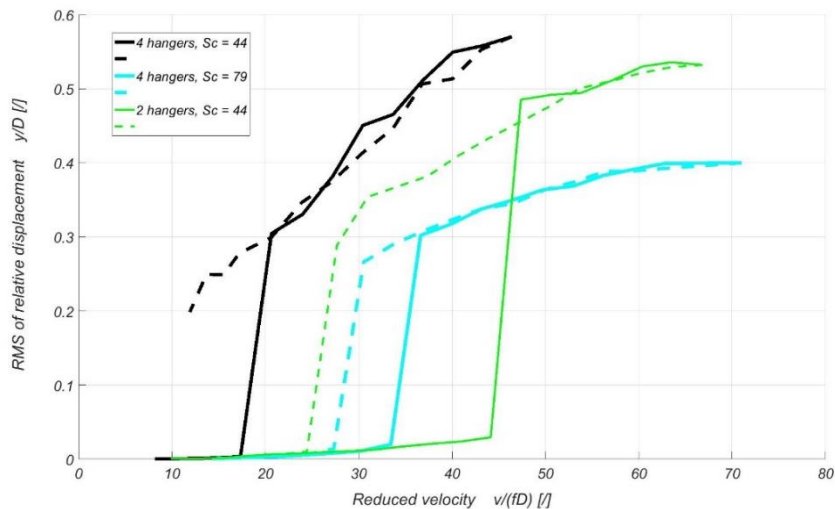
Fig. 3. Root Mean Square (RMS) value of relative displacement of the oscillating cylinder as a function of reduced velocity (solid line – increasing velocity branch, dashed line – decreasing velocity branch)

The estimations of critical wind speed for interference galloping of real bottom downwind hanger on site based on combination of experimental results and formula (1) was done. In the case of the rectangular array of the hangers, the critical wind speeds determined for both values of Sc are not too much apart from the value determined according the code [2] corresponding to the pair of hangers. In particular, the critical wind speed equal to 10.9 ms^{-1} and 15.1 ms^{-1} were determined for smaller Sc and higher Sc, respectively. The wind speeds in this range can occur on-site and can cause serious vibrations and damages as already observed at the real structure. In case of a pair of the hangers, the critical wind velocity equal to 26.4 ms^{-1} obtained from the wind tunnel results is significantly higher than its counterpart calculated according formula (1). It is because we consider the code value is representing very conservative estimate that secures the highest level of the safety comprising large amount of cases of the geometrical arrangement. It must be also noted, that the estimated critical values can be affected by prerequisites and limitations of the experiment, e.g., only cross-wind vibration of the bottom downwind hanger was allowed, the rest of hangers were assumed as static, etc.

The aforementioned conclusions can be of interest of specialist dealing with similar problems in engineering practice and also be a motivation for further investigation of the influence, e.g., the spacing among the hangers in the rectangular array on the instability and the whole character of flow around such bundle of individual structural elements.

Acknowledgements

References

[1] de Sá Caetano, E., Cable vibrations in cable-stayed bridges, IABSE, 2007
[2] Eurocode 1: Actions on structures - Part 1-4: General actions - wind actions, 2005.
[3] Sumner, D., Two circular cylinders in cross-flow: A review, Journal of Fluids and Structures 26 (6) (2010) 849-899.
[4] Yoshimura, T., Savage, M.G., Tanaka, H., Urano, D., Wind-induced oscillations of groups of bridge stay-cables, Journal of Wind Engineering and Industrial Aerodynamics 54-55 (1995) 251-262.
[5] Zdravkovich, M.M., The effects of interference between circular cylinders in cross flow, Journal of Fluids and Structures 1 (2) (1987) 239–261.