Vehicle wind loading and overturning at bridge towers

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SUMMARY:
The wind loading on vehicle models close to the towers of a suspension bridge has been investigated with a view to clarify the physics underlying the increase in wind related overturning accidents at these locations. It is found that the vehicle wind loading is governed by vortex shedding from the tower legs. Erection of local wind screens at the towers eliminates the vortex shedding loads and increases the driving wind speed for overturning beyond the value estimated at a distance from the towers.

Keywords: Vehicle wind loads, vortex shedding from bridge towers, wind induced vehicle overturning.

1. INTRODUCTION

Driving comfort and the risk of accidents in high winds are of concern for safe operation of most high-level bridges. Driving conditions in the wake of the towers are known to be particularly challenging, likely due to the sharp variations of the mean wind speed and turbulence levels at these positions. Since the opening of the Storebælt Link in 1998 the owner has logged wind-induced traffic accidents on the bridges recording information on the position, the wind speed and the type of vehicle. A review of the accident log revealed that 56 wind induced accidents was logged for the suspension bridge of which 33 happened adjacent to the towers and anchor blocks supporting that the wind conditions at these locations are particularly severe. Most of the accidents involved overturning of light highsided vehicles such as auto-trailers. One proposal for improvement of the driving conditions at the towers is to erect local wind screens in these locations, (Smith and Barker, 1998). Intuitively the effect of a local wind screen is to smoothen the local gradients of the wind field to yield smoother driving conditions when entering or exiting the wake zone of the tower. This paper discusses wind tunnel tests carried out to clarify vehicle wind loading at the towers of the Storebælt suspension bridge and the effect of local wind screens to improve the traffic wind climate in these locations.

2. WIND TUNNEL TESTS

Wind tunnel tests of a section of the tower-deck assembly of the Storebælt bridge at scale 1:30 were carried out in FORCE Technology’s 7.5 m wide boundary layer wind tunnel, Kgs. Lyngby, Denmark, Fig 1. The tests involved measurement of time histories of the overturning moment $M(t)$ acting on a generic model of a small light auto-trailer mounted on a force balance inserted in the deck structure.

Figure 1. 1:30 scale model of the Storebælt tower deck assembly carrying local wind screens and model of auto-trailer.

The measured moments are normalized by the trailer length L and height squared H^2 and the dynamic head of the wind $½\rho U^2$, $C_M = M/½\rho U^2 L H^2$. Time histories of the overturning moment acting on the trailer model were measured for the situations with and without local wind screens. The wind screens extended 20 m from the walls of the tower into the main and side spans of the bridge and were composed of vertical posts to yield an open area ratio of 50%. The stationary vehicle model was located at four positions along the deck in the outer (slow) lane and at distances s = 7 m, 14 m, 21 m and 50 m full scale from the centreline of the 9 m wide tower leg. The measured time series were low pass filtered to exclude mechanical resonances of the force balance to yield amplitude spectra and peak values of the moment coefficients.

Fig. 2 displays examples of the amplitude spectra for the situation without and including the wind screens at a position s = 7 m and s = 21 m from the centreline of the tower. The frequency axes are normalised by the mean wind speed in the wind tunnel U = 8 m/s and the crosswind dimension of the tower leg D = 0.3 m (model scale) to yield a Strouhal Number. The amplitude axis of the spectra is normalized by the peak amplitude of the spectrum obtained at position s = 7 m.

For the situation without the wind screens (red curve) it is observed that the C_M spectrum is composed of a sharp high amplitude peak at St = 0.12 set in a lower amplitude broad band signal associated with random turbulence. The peak at St = 0.12 is identified with rhythmic vortex shedding action along the square section legs of the tower. For the situation including the wind screens (blue curve) the load contribution at the vortex shedding frequency is eliminated and the broad band contribution reduced to a significantly lower level. At the position s = 21 m the general appearance of the spectrum repeats but the vortex shedding peak as well as the broadband level has decreased as the location of the model trailer is moved away from the tower.

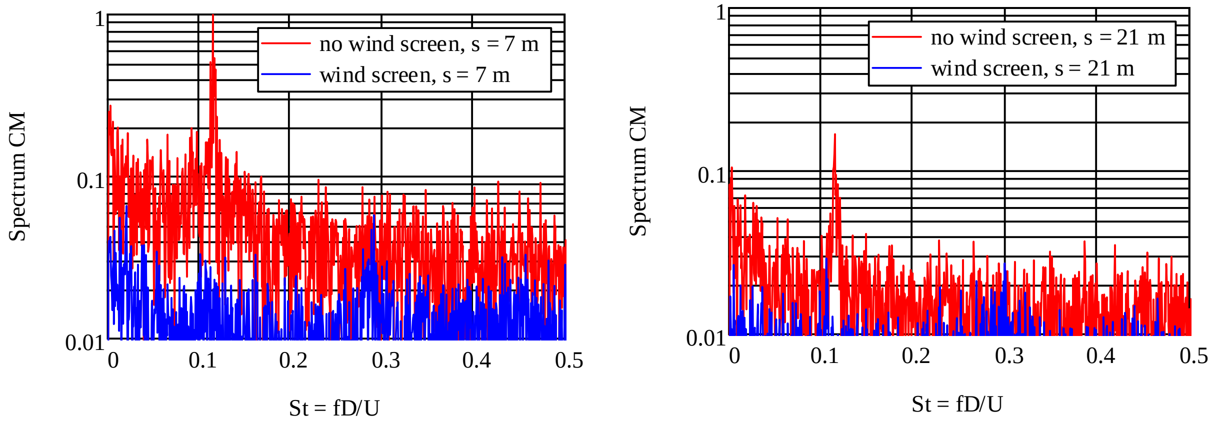

Figure 2. Normalized amplitude spectrum of measured overturning moment at position $s = 7$ m (left) and $s = 21$ m (right).

3. WIND INDUCED OVERTURNING OF LIGHT VEHICLES

Wind induced overturning of light high-sided vehicles is governed by the mass of and the wind load acting on the vehicle. A simple physical model for overturning involves balancing of the overturning moment from the wind by the stabilizing moment from gravity. Introduction of a few simplifications to the balance model, the vehicle speed V_{OT} (km/h) at which overturning is expected to occur in cross winds can be approximated by the following analytical expression:

$$V_{OT} \approx \frac{3.6}{U}\sqrt{\frac{S^2}{\widehat{C_M}^{\,2}} - U^4} \qquad (1)$$

Where $\widehat{C_M}$ is the peak overturning moment coefficient and $S = mBg/\rho LHz_A$ is the stability parameter combining vehicle mass m, cross wind width B, and gravitational constant g with the air density ρ, the exposed area LH and the height of the aerodynamic centre above the ground level z_A. The peak overturning moment coefficients $\widehat{C_M}$ were obtained from the measured load spectra, Fig. 2 as follows:

$$\widehat{C_M} = \overline{C_M} + 1.4\sqrt{var(SC_{Mvtx})} + k_p\sqrt{var(SC_{Mbb})} \qquad (2)$$

Where $\overline{C_M}$ is the mean value of the moment coefficient, $var(SC_{Mvtx})$ is the variance of the amplitude spectrum at the vortex shedding frequency, $var(SC_{Mbb})$ is the variance of the broad band contribution excluding SC_{Mvtx} and $k_p = 3.5$ is the peak factor.

Fig. 3 (left) displays the development of the calculated peak overturning moment coefficients at positions $s = 7$ m, 14 m, 21 m and 50 m from the centreline of the tower. For the situation without the wind screens, it is noted that $\widehat{C_M} \approx 3$ for the first three positions but falls to $\widehat{C_M} = 1.8$ at a distance $s = 50$ m from the centre line of the tower. In presence of the wind screens $\widehat{C_M} \approx 0.8$ just half the value obtained at a distance from the tower.

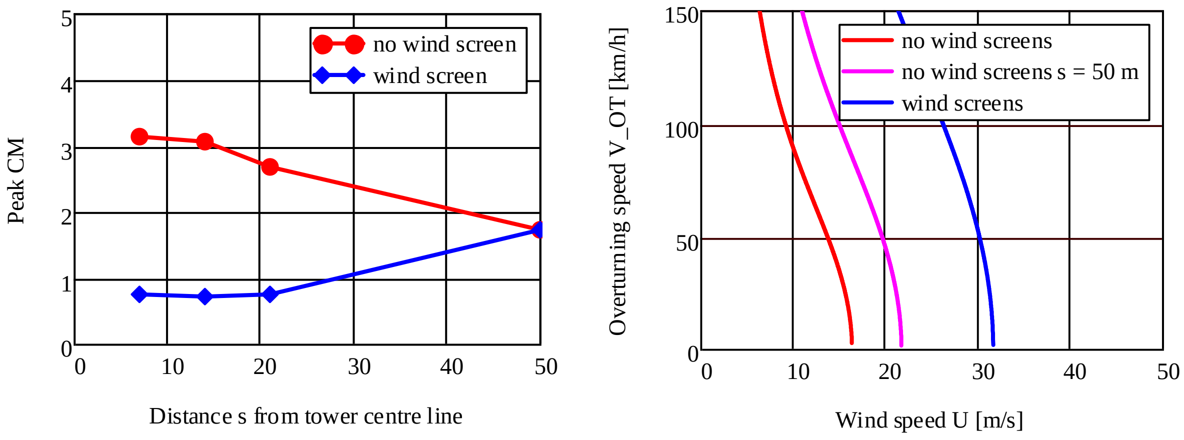

Figure 3. Peak moment coefficients obtained as function of position (left). Driving speeds for overturning as function of wind speed (right).

The impact of the peak moment coefficient on the predicted driving speed for overturning following (1) is shown in Fig. 3 (right). It is assumed that the stability parameter S = 800 which is a fair average for empty small auto-trailers. At a location close to the towers without the wind screens and travelling at 50 km/h overturning is predicted to happen at a mean wind speed of about 14 m/s. Away from the towers (s = 50 m) overturning is predicted for a mean wind speed of 20 m/s. Addition of the local wind screens increases the mean wind speed for overturning to 30 m/s demonstrating a significant improvement of the traffic wind climate at the towers.

4. DISCUSSION

The analysis of the wind tunnel test results above represents a worst-case scenario for which a vehicle enters or exits the tower wake at the instant where the vortex induced loading is at its peak. It is noted that the period of the vortex shedding is relatively slow as compared to the travel time through the tower wake. Taking for instance a mean wind speed of 15 m/s the period of the vortex shedding is estimated to be 5 sec. whereas the tower region will be passed in less than 1 sec. when driving at a constant speed of 50 km/h. Thus, it is expected that only a smaller portion of the traffic will be exposed to the full loading effect from the tower vortex shedding. Nevertheless, overturning accidents may involve damage to persons and the vehicles involved and will impede the traffic flow until they are cleared away. Based on the present study local wind screens have been designed for the towers and anchor blocks of the Storebælt suspension bridge and is presently being erected.

5. REFERENCES

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