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Flutter stability of twin-box bridge decks

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SUMMARY:
The present paper reports on wind tunnel tests and analyses carried out to investigate the effect of the static angle of attack on the aerodynamic stability of a twin-box bridge deck section. It is found that the critical wind speed for onset of flutter increases with increasing positive static angles (nose-up) and that this effect relates mainly to a decrease in the loss of aerodynamic stiffness. It is concluded that it is desirable to design twin-box bridge deck sections to have a positive moment coefficient at zero angle of attack and decreasing moment slope for increasing nose-up angles.

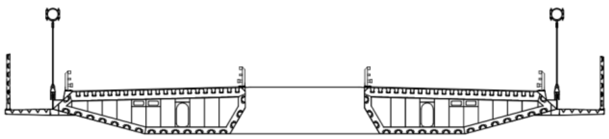
Keywords: Aerodynamic stability, flutter stability, twin-box bridge deck, aerodynamic derivatives.

1. INTRODUCTION

The twin-box bridge deck composed of two individual hull girders separated by a central air gap allows higher critical wind speeds for flutter to be reached as compared to a mono-box girder having identical overall width of the carriage ways and is thus the logical choice for suspension bridges having super long spans. During wind tunnel tests for the design of the twin-box girder for the 1915 Çanakkale Bridge (main span of 2023 m) it was discovered that the critical wind speed for onset of flutter increased significantly when the elastically sprung deck section was allowed to rotate to positive angles of attack relative to the horizontal wind. A behaviour referred to as the "nose-up" effect. A theoretical investigation (Rønne, Larsen, Walther 2021) supported the "nose-up" effect and liked it to the progression of the section moment coefficient. The present paper reports on an experimental investigation carried out to support and quantify the "nose-up" effect for a twin-box bridge deck section similar to that of the 1915 Çanakkale Bridge.

2. WIND TUNNEL TESTS

Wind tunnel tests were carried out for a twin-box section having hull girders of similar geometry, cantilevered inspection walkways and 9 m wide central gap as the 1915 Çanakkale Bridge (Fig. 1). Minor details such as the layout of wind screens and the railings were different. Also, the gantry rails running along the bottom plate of the 1915 Çanakkale Bridge omitted in the present model. The tests were carried out in the FORCE 2.6 m x 1.8 m boundary layer wind tunnel, Lyngby, Denmark. The tests included measurement of the static wind load coefficients for an angle of attack range of -10 to +10 deg. Vertical and torsion aerodynamic derivatives were measured by the forced motion method for angles of attack of -2, 0, +2 and +4 deg relative to horizontal. The data were analysed assuming dynamic data identical to the 1915 Çanakkale Bridge, Table 1.



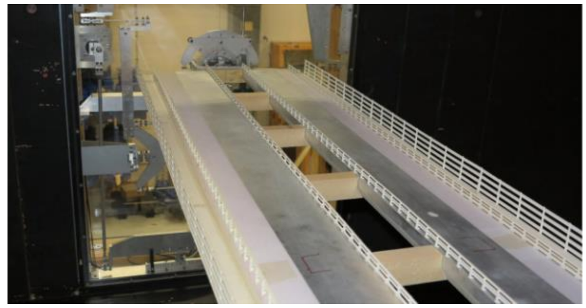


Figure 1. Geometry of twin-box section tested and definition of static wind load coefficients. (left). View of model test set-up in the wind tunnel (right).

Table 1. Basic section inertia and frequency data for the 1915 Çanakkale Bridge

Mass m	Mass mom of inertia I	Vertical frequency f_z	Torsion frequency f_α	Struct. Damping ζ
$28.85\cdot10^3$ kg/m	$6.215\cdot10^6$ kg·m²/m	0.072 Hz	0.146 Hz	0.003

2.1. Static wind loads and section rotation to mean wind speed

The static wind load coefficients are shown in Fig. 2 (left). It is noted that the moment coefficient C_M is positive C_{M0} = 0.013 at 0 deg angle of attack and that the moment is continuously decreasing for positive angles. A second order polynomial was fitted to the positive part of the C_M curve to facilitate theoretical analysis (magenta curve).

The development of the angle of attack as function of mean wind speed U can be evaluated by assuming that the aerodynamic moment is balanced by the moment capacity of the elastically suspended section. Taking the first symmetric torsion mode of the 1915 Çanakkale Bridge (Table 1) yields a development of the angle of attack shown in Fig. 2 (right). It is noted that the development of the C_M curve makes the angle of attack increase as function of mean wind speed. At first slowly but at steeper rates for wind speeds above 60 m/s. For a mean wind speed U = 45 m/s which is typical for design of large suspension bridge in Europe, the angle of attack of the deck will be about 0.5 deg which is about 1/3 of the typical cross fall of the roadway. At a mean wind speed of 90 m/s an angle of attack of about 5 deg is estimated.

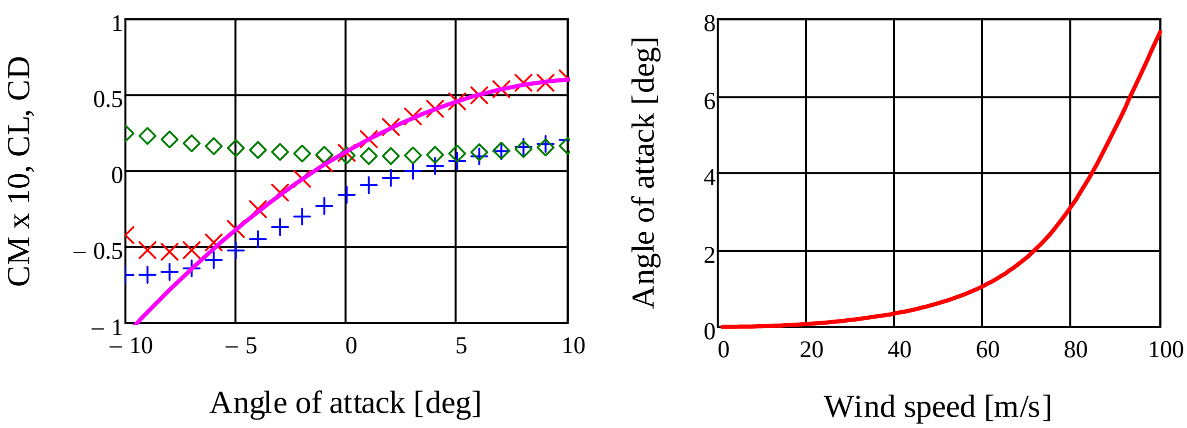


Figure 2. Measured static wind load coefficients C_M (x), C_L (+), C_D (◇) and polynomial fit to C_M (left). Development of section angle of attack as function of mean wind speed (right)

2.2. Measured aerodynamic derivatives.
The measured aerodynamic derivatives obtained for angles of attack Rs = -2, 0, +2 and +4 deg were fitted by second order polynomials. Examples for the A_3^* and H_3^* derivatives measuring the aerodynamic stiffness of the section are shown in Fig. 3. The sign convention and normalization adopted for the aerodynamic derivatives is that originally proposed by (Simiu, Scanlan 1985).

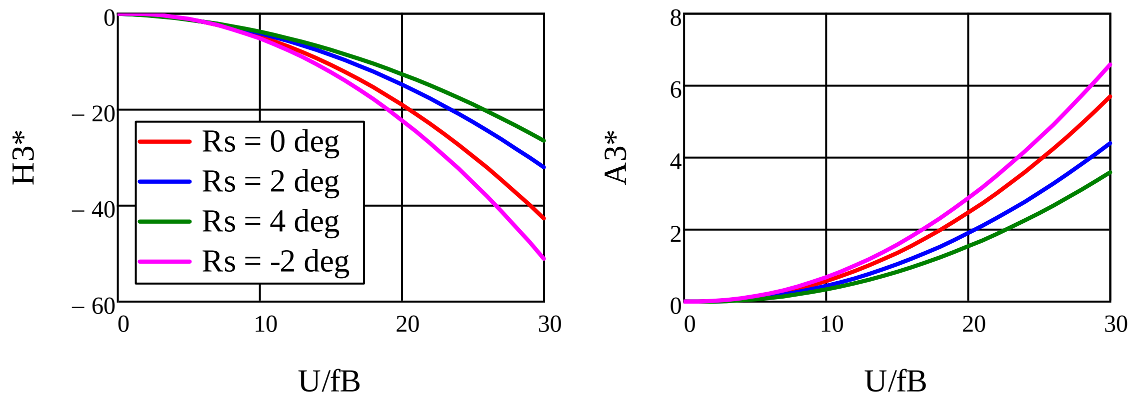


Figure 3. Aerodynamic derivatives at angles of attack of -2, 0, +2, +4 deg by forced motion method.

From Fig. 3 it is indicated that the aerodynamic derivatives change in a systematic way as function of angle of attack. The A_3^* and H_3^* aerodynamic derivatives shown here as examples are observed to decrease with increasing angle of attack indicating an expected increase of the critical wind speed. The remaining 6 aerodynamic derivatives not shown are displaying a similar trend.

3. BI-MODAL FLUTTR ANALYSIS
The aerodynamic derivatives obtained from the wind tunnel tests are applied in a flutter analysis for the twin-box deck section applying the structural data listed in Table. 1 The result of the bi-modal analysis (Rønne, Larsen, Walther 2021) yielding predicted critical wind speeds of flutter and corresponding flutter frequencies are shown in Figure 4 and summarized in Table 2.

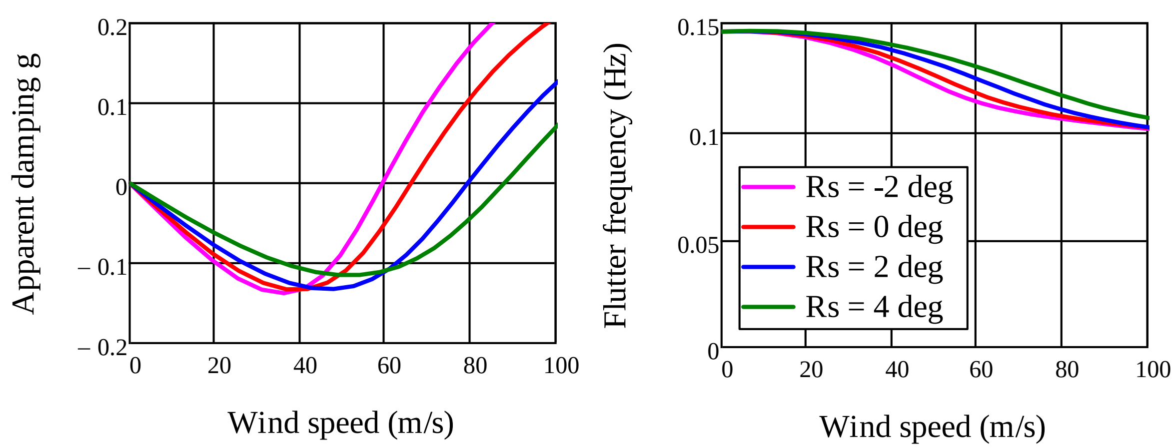


Figure 4. Bi-modal flutter analysis for the twin-box deck section. Aerodynamic damping (left). Flutter frequencies (right).

Table 2. Critical wind speed for onset of flutter based on aerodynamic derivatives and simple theory

Angle of attack Rs (deg)	U_{cr} (m/s). Bi-modal analysis	U_{cr} (m/s) Simple formula (1)	U Static load
-2	60	62	-
0	67	67	0
+2	80	74	72
+4	89	83	85

3. SIMPLIFIED FLUTTER ANALYSIS

Simple formulae for estimation of the critical wind speed for onset of flutter are convenient as for initial estimates during early stages of a long span bridge project. One such equation borrowing from quasi-steady theory relates the critical wind speed to the slope of the moment coefficient dC_M/dRs to the critical wind speed for onset of flutter U_{cr}:

$$U_{cr} = 2\pi f_\alpha B \sqrt{I\left(1-\left(\frac{f_\alpha}{f_z}\right)^2\right)/\rho B^4 \frac{dC_M}{dRs}\mathcal{F}} \tag{1}$$

The empirical factor $\mathcal{F}$ applied to the moment slope serves to model the depreciation of the aerodynamic moment caused by the oscillatory wake of the deck section. Taking $\mathcal{F}$ = 0.73 will make U_{cr} calculated by (1) coincide with the critical wind speed obtained from the bi-modal flutter analysis for Rs = 0 deg. Introducing the second order polynomial fit to dC_M/dRs in (1) allows U_{cr} to be estimated for other angles of attack. The result is listed in Table 2 and compared to the bi-modal flutter analysis applying the measured aerodynamic derivatives. Also, Table 2 lists the wind speeds at which the static wind loading balances the elastic restoring force to produce angles of attack of +2 and +4 deg.

4. CONCLUSION

The analysis of wind tunnel tests of a twin-box bridge deck section confirm that the flutter stability is dependent on the cross sections static angle to the wind yielding higher critical wind speeds for higher positive (nose-up) angles of attack. A simplified expression linking the critical wind speed for onset of flutter to the slope of the moment coefficient yields a similar trend although the effect is less pronounced than obtained by a full bi-modal analysis including 8 aerodynamic derivatives. The present experimental study thus confirms earlier theoretical analyses and findings.

Considering the geometrical layout of twin-box bridge decks for maximum aerodynamic stability the present study confirms that it is desirable to design for positive (nose-up) aerodynamic moment at zero angle of attack and a decreasing moment slope for increasing angles.

5. REFERENCES

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