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Acampora, Antonio; Georgakis, Christos T.

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Aerodynamic coefficients of plain and helically filleted twin circular cylinders for varying wind angles-of-attack

A. Acampora[1,2], C.T. Georgakis[1]

[1]Department of Civil Engineering, Technical University of Denmark, Building 118, Brovej, 2800 Kgs. Lyngby, Denmark, antac@dtu.byg.dk, [2]IPU, Building 404, 2800 Kgs. Lyngby, Denmark

Abstract

Moderate vibrations continue to be recorded on the Øresund Bridge twin-stay cables. System identification techniques have been applied to investigate the aerodynamic characteristics of the cables based on ambient vibration measurements. As might be expected, the measured aerodynamic damping ratios vary from those estimated through use of aerodynamic coefficients of single circular cylinders, as reported in literature. To address this issue, wind tunnel tests were performed on a 1:2.3 scale section model of the Øresund Bridge cables with and without the presence of helical fillets. The twin cables are circular cylinders with an outer diameter D of 250mm and a centre-to-centre distance of 2.68D. In this paper, the results of those tests are presented for varying wind angles-of-attack.

1 Introduction

Large amplitude cable vibrations have previously been reported on the Øresund Bridge for varying meteorological conditions (Svensson *et al.*, 2004). In 2010, the Technical University of Denmark installed a new monitoring system on the bridge and moderate vibrations under rain-wind conditions have since been reported (Acampora & Georgakis 2011). In 2011, Acampora et al. investigated the aerodynamic damping of the bridge's twin stay cables using system identification techniques applied to the acquired cable vibration data (Acampora et al, 2011). The results showed some deviations of aerodynamic damping of the actual twin stay cables compared to aerodynamic damping based on quasi-steady theory and determined using values from the aerodynamic coefficients of single circular cylinders obtained from previous wind tunnel tests. In an attempt to understand this discrepancy, a new set of wind tunnel tests were performed on a 1:2.3 scale section model of the Øresund Bridge twin stay cable arrangement. The drag, lift and moment coefficients about the longitudinal axis of the twin cable, with and without double helical fillets, are presented herewith for varying wind angles of attacks. The aerodynamic damping of the cable pair is finally re-evaluated based on the resulting coefficients.

2 Model and wind tunnel tests

The Øresund Bridge twin stay cables comprise parallel monostrands covered by a black 250 mm diameter HDPE tube with double helical fillets (2.1 x 3 mm, helix angle 55 °, pitch 550 mm). A 1:2.3 scale twin cylinder section model of the cables was manufactured from PVC piping for the scaled tests. The grey PVC surface was sanded to approximately match the scaled target surface roughness of the full-scale cables. The measured value of the average surface roughness, Ra, of the tubes was in the range of 0.5-1 μm. The distance, d, between stays, from centre to centre, is 670 mm (Larose & Smitt, 1999). Two versions of the scaled section model were tested; one with plain cylinders and the second with double helical fillets attached. The total length, L, of the cylinder pairs was 1615 mm. Static wind tunnel tests were performed at the 2×2 m^2 cross-section closed-circuit DTU/Force Technology

Climatic Wind Tunnel in Kgs. Lyngby, Denmark. The wind tunnel has a maximum wind speed of 31 m/s and a maximum measured turbulence intensity of approximately 0.62% (Kleissl & Georgakis 2011). The other technical specifications of the wind tunnel are reported by Georgakis et al. (2009). 6 degree-of-freedom (DOF) force transducers (AMTI MC3A-500), placed on either end of the hinged arrangement, measured forces in all directions. The test programme consisted of 3 repetitions of wind velocity sweeps between 4 and 31 m/s, corresponding to Reynolds numbers of 3×10^4 – 2.3×10^5, for varying wind angles-of-attack, α = 0°, 30°, 60°, 70°, 80°, 90°, 100°, 110°, 150° and 180° (Figure 2). Mean values of the aerodynamic coefficient over the repetitions are reported.

Figure 1: Wind tunnel test setup of twin cylinders without (left) and with (right) double helical fillets for wind angle-of-attack α = 0°.

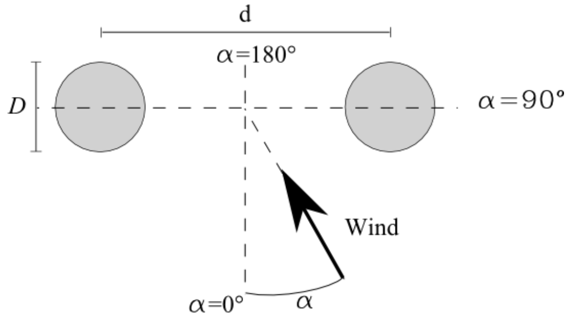

Figure 2: Setup of the twin cables for the different angles-of-attack.

3 Results and discussion

Reynolds number for the section of the twin cylinders is defined as $\mathrm{Re}=\rho VD/\mu$, where ρ is the air density, V is the wind velocity, D is the single diameter of the twin cylinder configurations and μ is the air viscosity. Drag, lift and moment coefficients, about longitudinal axis of the twin cable, were measured during the tests. The aerodynamic force coefficients C_F are defined as the total measured force F over the frontal surface projection ($2DL$) at α = 0° for all varying angles-of-attack α, so that:

$$C_F = \frac{F}{DL\ V^2}$$

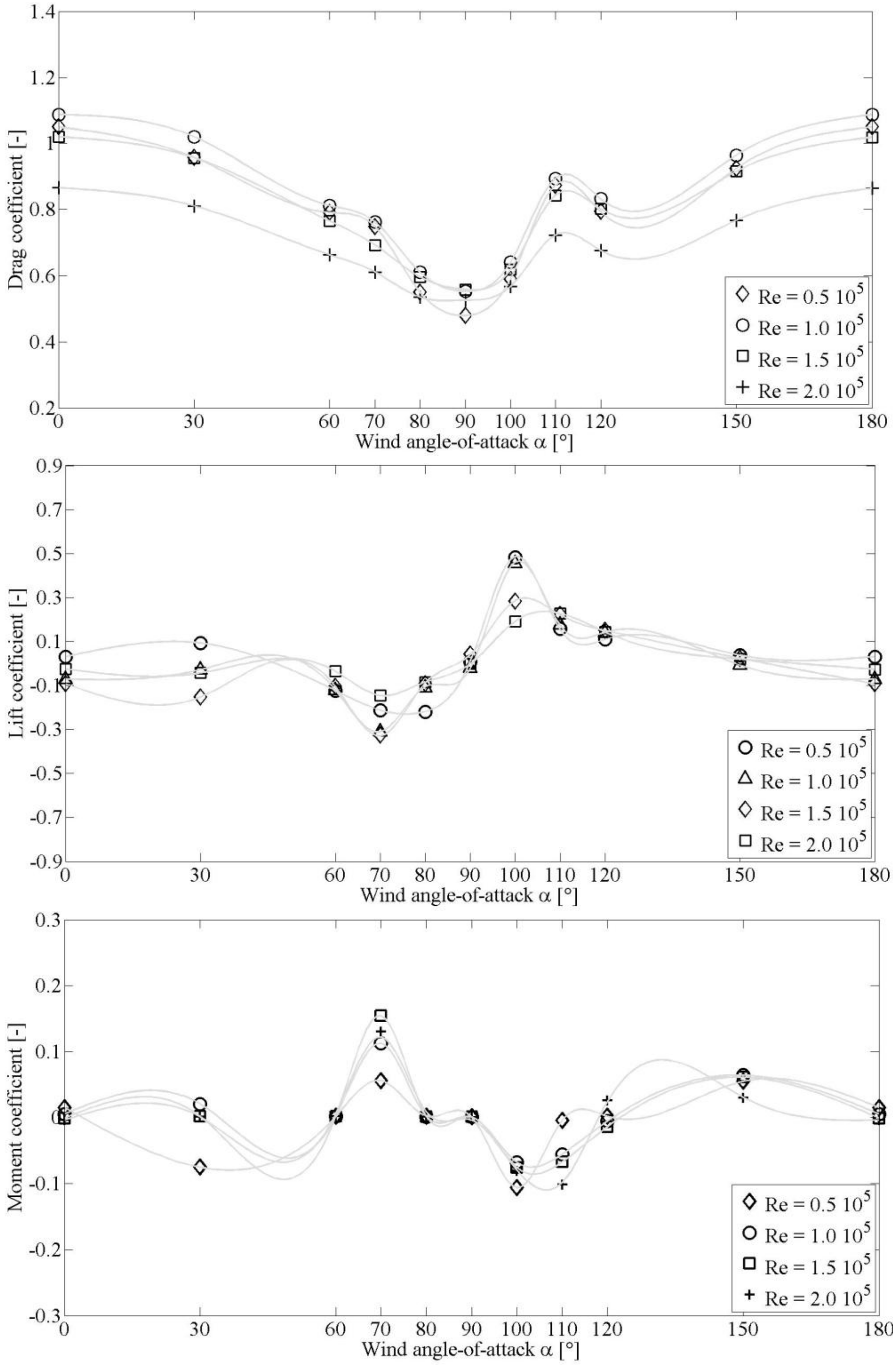

Figure 3. Drag (top), lift (center) and moment coefficients (bottom) for twin cable with double helical fillet vs wind angle-of-attack.

In Figure 3, the drag, lift and moment coefficients for the twin cable with double helical fillet are plotted versus wind angle-of-attack for Re = 0.5, 1.0, 1.5, 2.0×10^5. With respect to symmetry, the drag coefficent at $\alpha = 70°$ differs from that at $\alpha = 110°$. This is most likely due to the variation in interaction of the cylinders, due to the orientation of the fillets. Lift and moment coefficients about $\alpha = 90°$ are generally antisymmetric in sign, but not in magnitude.

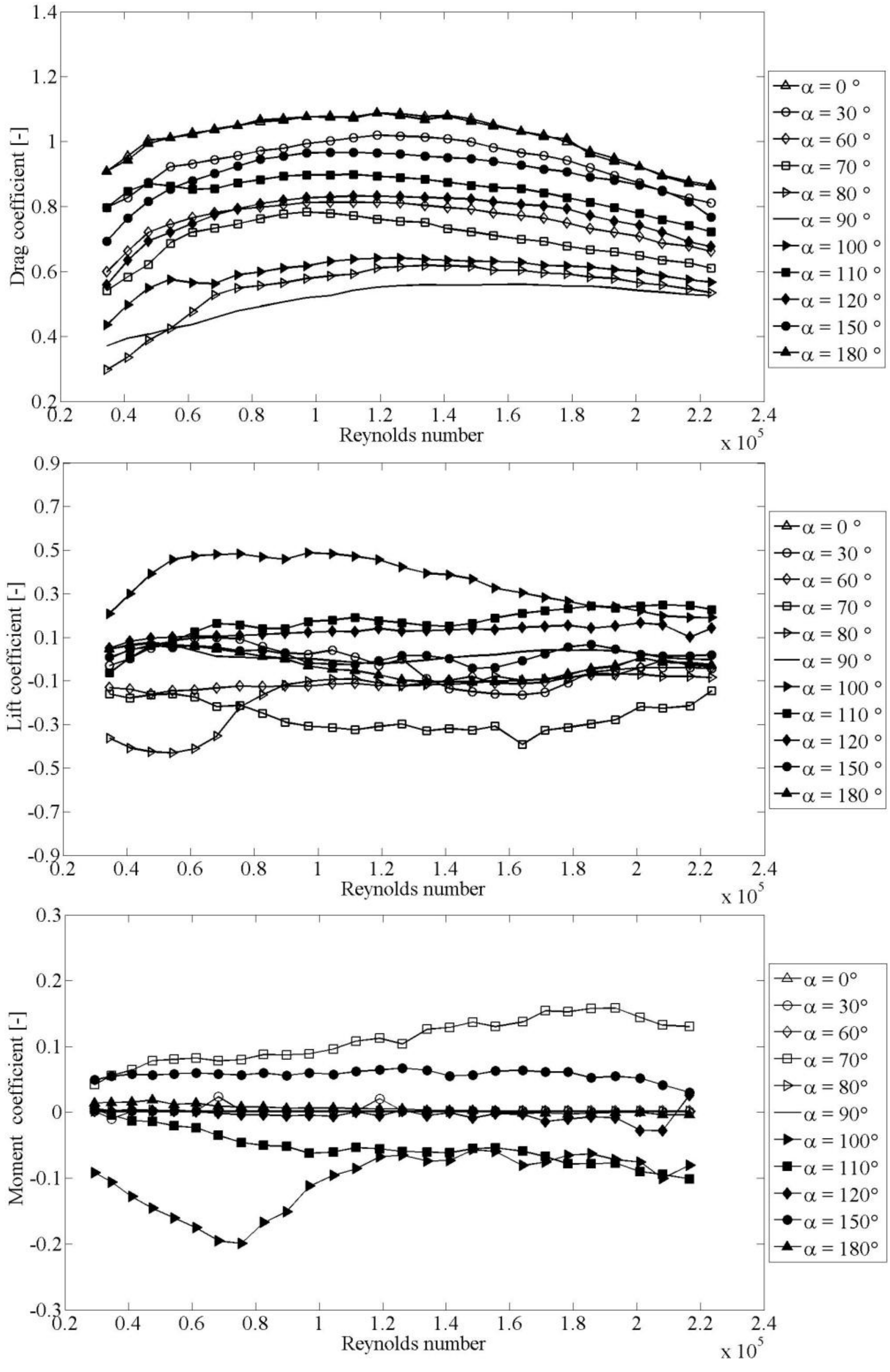

Figure 4 Drag (top), lift (center) and moment coefficients (bottom) for vs Reynolds number for different wind angles-of-attack for the double cylinders with double helical fillets.

In Figure 4, the drag, lift and moment coefficients for the twin cable with the double helical fillet are plotted versus Reynolds number for α = 0°, 30°, 60°, 70°, 80°, 90°, 100°, 110°, 150° and 180°. A gradual reduction in drag coefficient with Reynolds number can be observed, due to the presence of the double helical fillets. The beginning of this drop can be identified between Re = 1-1.4×10^5. As might be expected, the drag coefficients reduce with wind angle-of-attack, due to the change of the cross-section seen by the oncoming wind.

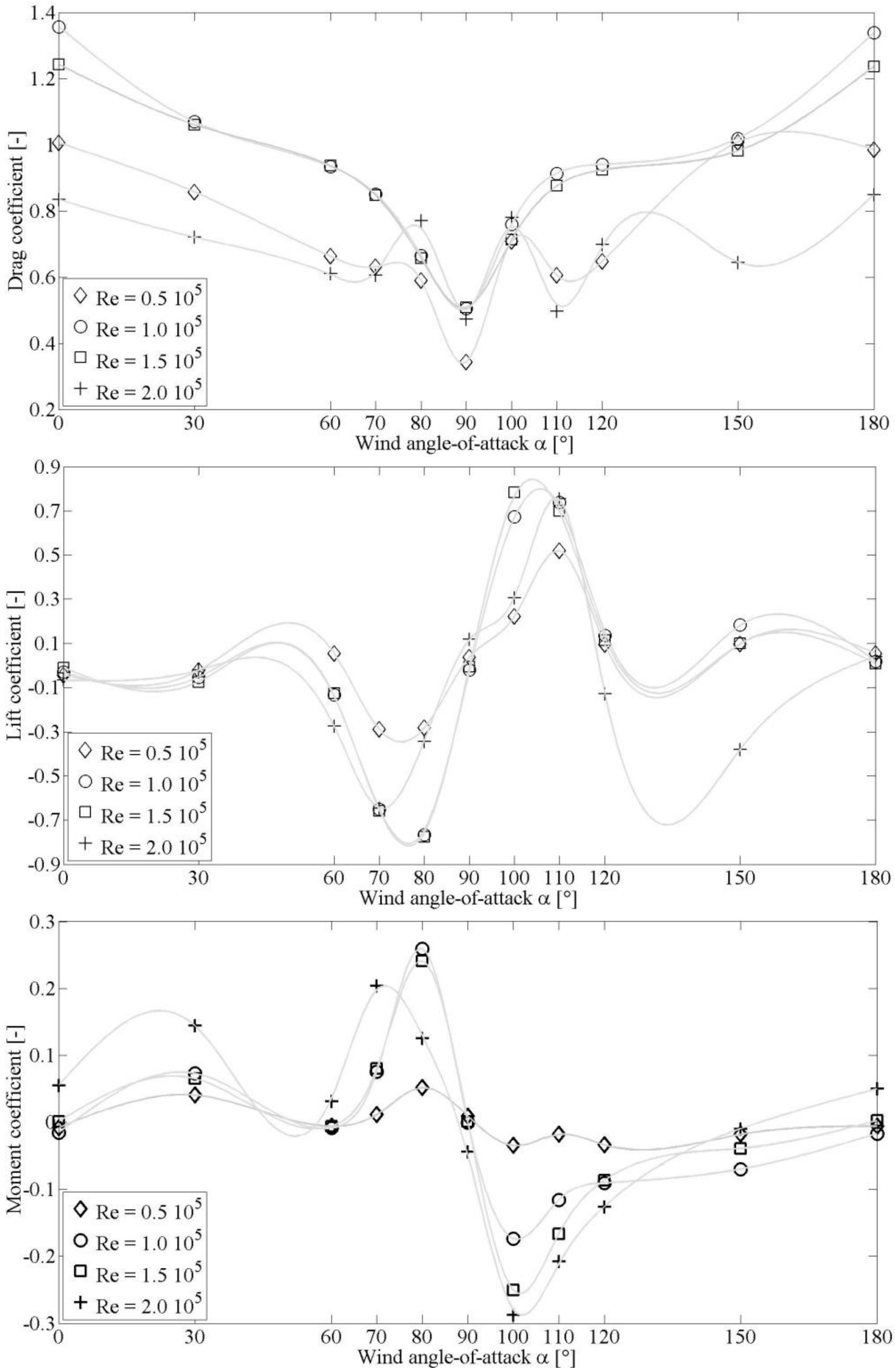

Figure 5. Drag (top), lift (center) and moment (bottom) coefficients for twin cable without double helical fillet vs wind angle-of-attack.

In Figure 5, the drag, lift and moment coefficients for the twin cable without double helical fillet are plotted versus wind angle-of-attack for Re = 0.5, 1.0, 1.5, 2.0×10^5. Drag coefficients about $\alpha = 90°$ are generally symmetric in sign and magnitude. Lift and moment coefficients about $\alpha = 90°$ are generally antisymmetric.

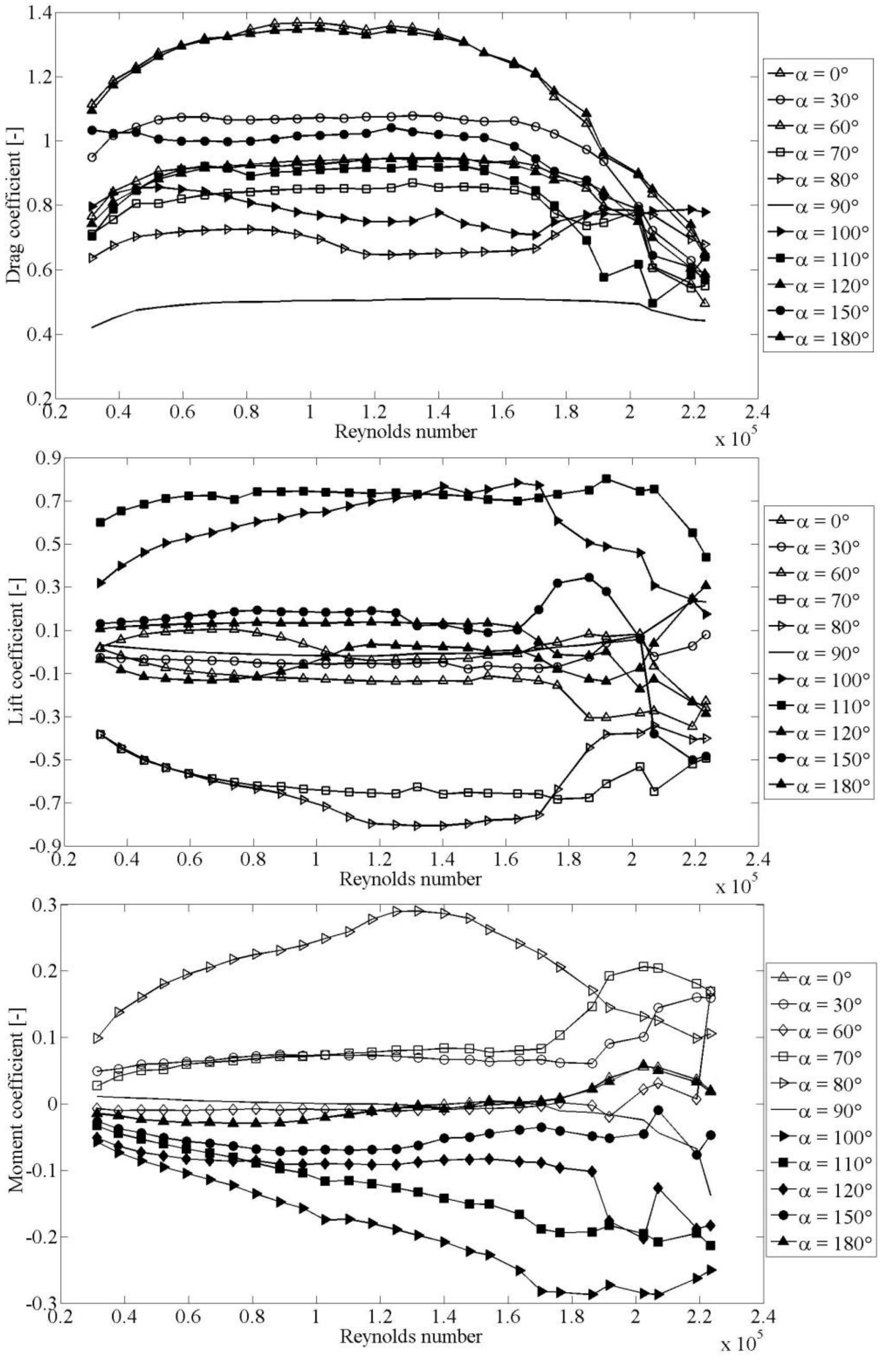

Figure 6 Drag (top), lift (center) and moment (bottom) coefficients vs Reynolds number for different wind angles-of-attack for the twin cylinders without double helical fillets.

In Figure 6, the drag, lift and moment coefficients for the twin cable without the double helical fillet are plotted versus Reynolds number for α = 0°, 30°, 60°, 70°, 80°, 90°, 100°, 110°, 150° and 180°. The beginning of the drop in drag coefficients can be identified between Re = 1-1.6×10^5. Again, as might be expected, the drag coefficients reduce with wind angle-of-attack, due to the change of the cross-section seen by the oncoming wind. Comparing aerodynamic coefficients from the two setups, it can be observed that the presence of helical fillets reduces the magnitude of aerodynamic coefficients with respect to the results obtained without helical fillets. The double helical fillets produce a transition to the critical Reynolds number region that is not clearly localized (Figure 4) but prolungated over the entire investigated Reynolds number range. Similar results were obtained by Kleissl and Georgakis (2011), when comparing the results from a plain HDPE cylinder and a HDPE cylinder fitted with helical fillets.

Lift and moment coefficients are reduced in magnitude when helical fillets are fitted on the twin cylinders. From the results it can be observed that lift coefficients are less angle-of-attack dependent in presence of helical fillets compared to the results of twin cylinders without helical fillets. In Figure 3 the lift coefficient for α = 70° (and 110°) is about 8 times higher than α = 0° while, in absence of helical fillets, the lift coefficients for α = 70° (and 110°) is about 20 times higher than α = 0° (Figure 5). Moment coefficients exhibit similar patterns with wind angle-of-attack.

4 Aerodynamic damping

Theoretical values of the aerodynamic damping based on quasi-steady theory using aerodynamic coefficients of the twin cylinders for wind angle-of-attack $\alpha = 0°$ are shown in Figure 7. The results are compared with the aerodynamic damping identified from full-scale data from Øresund Bridge for the first five cable vibrations modes (markers) and the theoretical aerodynamic damping based on data from wind tunnel tests on a single cable with single helical fillet, similar to the cables on the Øresund Bridge (Kleissl & Georgakis 2011). Furthermore, the aerodynamic damping based on tests on a single cable with a single helical fillet for a previous study for the bridge carried out by Freyssinet (Øresundsbron 2003) is also presented. Quasi-steady theory assumes that the aerodynamic forces on a moving cable are given by the forces on a stationary cable experiencing the same relative wind velocity; the generalised 2DOF aerodynamic damping matrix is given by Macdonald & Larose (2008a). For a uniform cable in a uniform wind normal to the cable axis, the theoretical quasi-steady in-plane and out-of-plane aerodynamic damping can be expressed as:

$$\frac{C_{a,IP}}{M} = \frac{\rho D U}{2m}\left(2C_D + \frac{\partial C_D}{\partial \mathrm{Re}}\mathrm{Re}\right) \qquad \frac{C_{a,OP}}{M} = \frac{\rho D U}{2m}\left(C_D + \left.\frac{\partial C_L}{\partial \alpha}\right|_{\alpha=0}\right)$$

where $C_{a,IP}$ is the in-plane aerodynamic damping, $C_{a,OP}$ is the out-of-plane aerodynamic damping, ρ is the density of air, D is the reference dimension (cable diameter), U the wind speed, m the mass per unit length, C_D and C_L respectively the drag and lift coefficients, α the angle-of-attack about the cable axis and Re the Reynolds number.

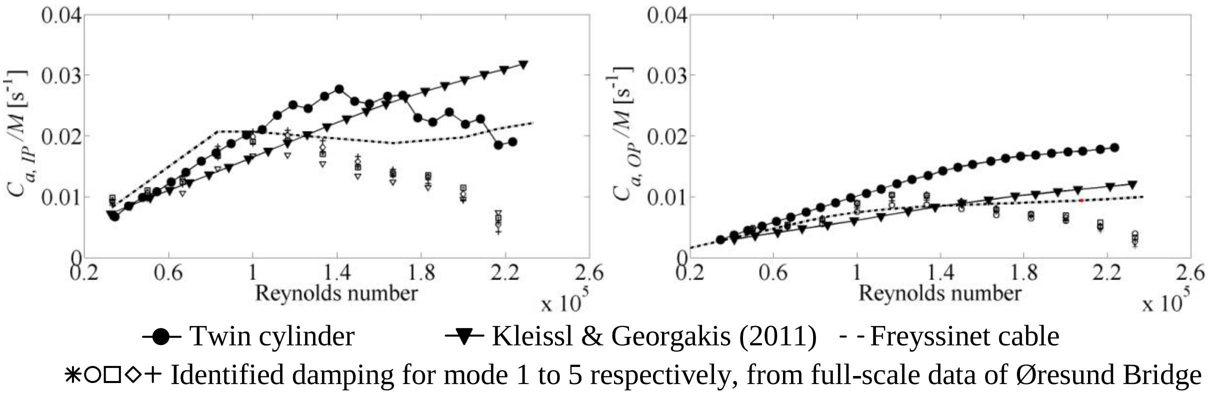

Figure 7. Comparison of theoretically evaluated in-plane (left) and out-of-plane aerodynamic damping (right) for twin cylinders test, for single cylinder tests with identified damping from full-scale data of Øresund Bridge, for angle-of-attack $\alpha = 0$.

The aerodynamic damping evaluated with aerodynamic coefficients from twin cylinders test shows a better match with the aerodynamic damping identified from full-scale cable of Øresund Bridge. The differences between the theoretically evaluated aerodynamic damping based on the wind tunnel tests and the aerodynamic damping identified from Øresund Bridge could be explained by possible differences in surface roughness of the cable on the bridge and the tested cylinders.

5 Conclusions

Static wind tunnel tests on a vertical twin circular cylinder configuration – with and without helical fillets - have been carried out. From these, drag, lift and moment coefficients, for Reynolds numbers ranging between 3×10^4 – 2.3×10^5 and for varying wind angles-of-attack, have been determined and are presented herewith. The results show the importance of the double helical fillets in the change of aerodynamic coefficients, both when comparing the two different configurations and when examining the variation of drag, lift and moment coefficients for varying wind angles-of-attack. The presence of the double helical fillets reduces the magnitude of all aerodynamic coefficients. The aerodynamic damping based on helically filleted twin circular tests using quasi-steady theory gives a reasonable description of the actual behaviour of the cable of Øresund Bridge.

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