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Preliminary evaluation of two new cable surface innovations

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ABSTRACT: In this paper, the aerodynamic performance of two innovative bridge cable surfaces with concave fillets are examined and compared with traditional helical fillets. To this end, an extensive wind-tunnel test campaign was undertaken to measure the aerodynamic static force coefficients up to a Reynolds number of 3.2 x 10^5. The tests confirmed the results obtained from the preliminary tests performed by Kleissl and Georgakis (2013) on the prototype cable surfaces with the concave fillets. Despite a more than 100% increase of the fillet height compared to a traditional helical fillet profile, the static force coefficients are the same as that of a traditional helical fillet model at high Reynolds numbers. It is hypothesized that this is due to the ability of the concave shape of the fillet to enhance vorticity. Furthermore, both innovations are able to suppress vortex shedding formation at low Reynolds numbers, leading to a smooth and prolonged transition from the subcritical to the postcritical Reynolds number range.

KEY WORDS: Cable Aerodynamics, Helical Fillets, Concave Fillets, Static Tests, Force Coefficients.

1 INTRODUCTION

The stabilization of wind-induced bridge cable vibrations, such as rain wind induced vibration (RWIV) and dry-state galloping, has been one of the most significant areas of research in bridge aerodynamics over the last three decades. Several bridge cable manufacturers have introduced surface modifications on the high-density polyethylene (HDPE) tubes of cable stays bridges in order to minimize these vibrations. The modifications are based mainly on research undertaken in Europe and Japan, with two different prevailing emerging systems: one in the form of helical fillets, extensively used in Europe and America, and the second one in the form of dimples, used mainly in Asia.

Helically wrapped wires were initially proposed in the 1950s against Vortex Induced Vibrations (VIV), but it was not installed until 1992, at the CSTB laboratory (Nantes) for the Normandy Bridge (Flamand 1995), and later in 1997 at Danish Maritime Institute (now: FORCE Technology) for the Øresund Bridge (Larose and Smitt 1999), the disruption of the formation of the coherent upper rivulet was correlated with the mitigation of RWIVs. Dimpled cables were used to mitigate the rain-wind induced vibration and reduce the drag force at the Tatara Bridge (Miyata et al, 1994; Fujiwara and Moriyama, 1996).

(a) (b) (c)

Figure 1. Rain rivulet suppression: traditional profile (a), Innovation 1 (b), Innovation 2 (c)

Nevertheless, the introduction of helical fillets and dimples has not completely eliminated RWIVs, often leading bridge owners to the installation of cable vibration dampers or cross-ties (Kleissl and Georgakis, 2013). It has been stated (Yagi, 2011 and Kleissl and Georgakis, 2013) that by modifying the shape, alignment and configuration of the protuberances on the HDPE tube it is possible to eliminate the formation of RWIVs, together with a substantial reduction of drag force, which represents more than 50% of the overall horizontal wind load on long span bridges (Gimsing and Georgakis, 2012). Furthermore, numerous bridges around the world have begun to report snow and ice accretion related operational issues and closures. A particular case was reported in December 2012, where severe cable snow accretion led to the closure of the Port Mann Bridge in Canada (CBC News, British Columbia, 2012). Numerous cars were damaged and several people were injured due to falling snow from bridge cables. It is hypothesized that an increased height of the fillet will be able to retain the snow and ice longer and then subsequently allow the melted accretions to fall from cables in smaller, less hazardous pieces, while maintaining the same low level of drag coefficient experienced in previous applications. Snow and ice accretions on bridge cables have become increasingly problematic for the safe operation of the bridge and the lifetime of the cables.

In particular two innovative solutions with concave fillets, studied by Kleissl and Georgakis (2013), were found to outperform the current cables with a traditional helical fillet, in terms of drag reduction and rivulet suppression (Figure 1).

The two innovative surfaces with helical and staggered concave fillets have been patented and are currently supplied by VSL International. The objective of the present study is to examine the performance of the two innovations in their manufactured configuration compared with a traditional helical fillets through a wind-tunnel testing campaign.

2 MODELS

The models tested were full-scale samples of a high density polyethylene (HDPE) tube, provided by VSL, with an outer diameter of 160mm (excluding fillets). Three different surfaces were tested. The first one was a cable fitted with a traditional helical fillet. The ribs consist of a pair of parallel continuous rounded spiral, which are welded to the pipe with continuous welds. Furthermore, they have a 3.14 x tube diameter pitch length, which results in a 45^{o} pitch angle and a spiral distance of 251mm (Figure 2). The other two models are non-optimized innovative profiles that involve the application of concave protruding fillets. The fillet cross section has a trapezoidal shape with concave sides, a height of approximately 5mm, (corresponding to 3% of the cable diameter) and a top width of approximately 2mm. This new profile, with concave sides, was firstly proposed by Kleissl and Georgakis (2013) and has two major mechanical functions. Firstly, they work as a ramp for rain rivulets, forcing water to leave the surface of the cable. Secondly, the concave sides and the sharp tip lead to stronger directional guidance of the remaining water along the fillet (Kleissl and Georgakis, 2013). In the first model, Innovation 1, the fillets replicate the typical arrangement of current stay cables with helical fillets, which consists in a 45^{o} pitch angle and a spiral distance of 251mm. (Figure 3). In the second model, Innovation 2, the fillets are arranged laterally in a staggered helical pattern with a pitch angle of 30^{o} and spacing between the fillets of 20mm (Figure 4).

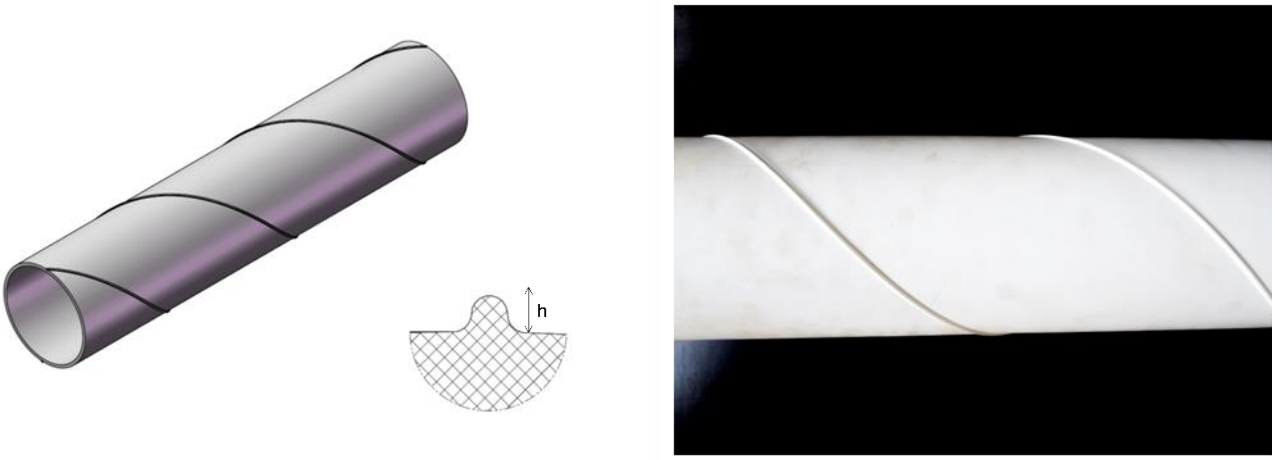
It is of interest herewith to examine the differences between the prototypes designed and tested by Kleissl and Georgakis (2013) and the actual profiles supplied by VSL International. The fillets designed and tested by Kleissl and Georgakis (2013) vary in height and top width compared to the one supplied by VSL International. In the first case, the height and top width are respectively 6mm and 0.9mm and in the second case it is 5mm and 2mm respectively. It can be stated that these differences might further increase the amount of streamwise turbulence generated by the innovative surfaces. Furthermore, the fillets in the two cases are made of two different materials. In the first case the fillets were made of rubber, which has the ability of bending at high wind velocities and in wet conditions. In the second case the fillet was made of HDPE plastic, which is the same rigid material as the rest of the tube.

3 EXPERIMENTAL WORK

3.1 Wind-tunnel Facilities

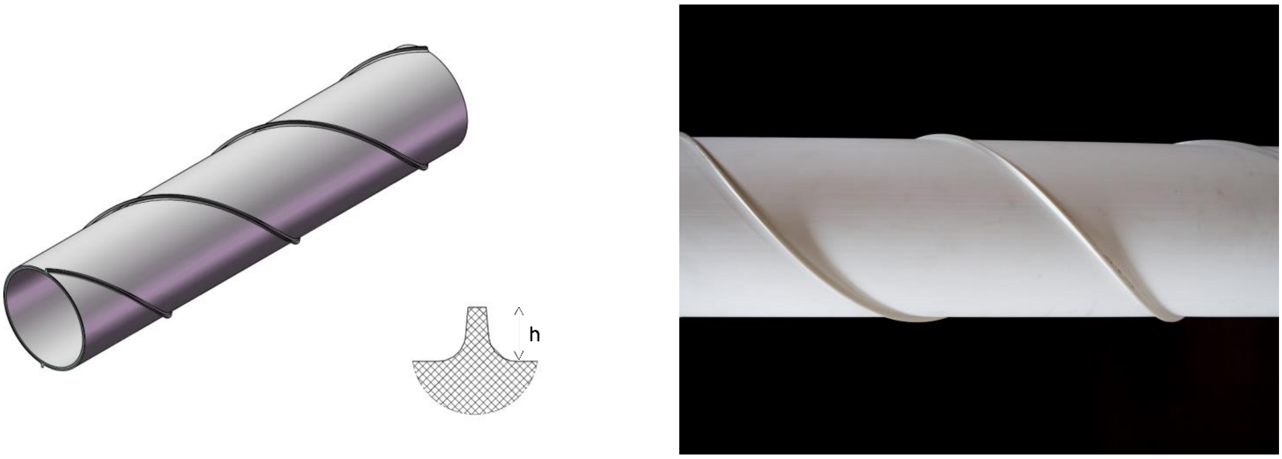
Experimental investigations were carried out in the DTU/FORCE Technology Climatic Wind Tunnel (CWT) in Lyngby, Denmark. The wind tunnel is a closed circuit (Georgakis et al., 2009), which is predominantly used for the testing of structural cables. The test chamber has a cross-section of 2m x 2m and is 5m long, which allows testing of full-scale cable section models up to approximately 200mm in diameter in cross-flow with an area blockage ratio of 10. The maximum achievable wind velocity in the test section is approximately 30m/s and the minimum temperature is ÷10^{o}C. The wind velocity was measured with a pitot-tube, which was located in the middle of the test chamber´s cross section and placed 1.5m upstream of the tested model.

Tests were performed in smooth flow. The characterization of the flow, in the wind-tunnel cross section, was carried out with a TFI Cobra probe. The turbulence intensity measurements were performed along the cable axis revealing uniform along-wind turbulence intensity. In smooth flow, a turbulence intensity of approximately I_u=0.9% was found with variations in a range between I_u=0.7% and I_u=1.1% for varying wind velocities.



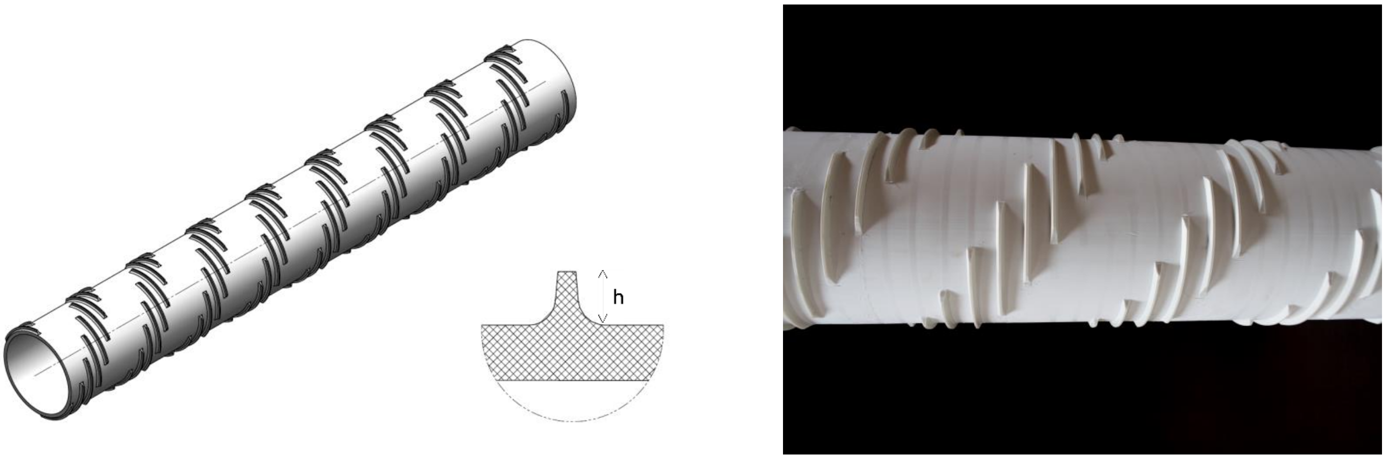
(a) (b)

Figure 2. Traditional helical fillet cable section model: model and fillet section drawing (a), model photo (b)



(a) (b)

Figure 3. Innovation 1 cable section model: model and strake section: drawing (a), model photo (b)



(a) (b)

Figure 4. Innovation 2 cable section model: model and strake section: drawing (a), model photo (b)

Corrections between the pitot-tube readings and mean flow velocities at the cylinder centerline position were obtained from measurements made using a cobra-probe installed upstream of the cable section model.

During the tests the wind velocity was increased by regular increments of approximately 1m/s within a range of 5 to 30m/s, allowing for supercritical Reynolds numbers to be reached for all tested repetitions.

3.2 Normal Flow Test Set up

The cables section prototypes were placed horizontally in the wind-tunnel cross section, resulting in a near two-dimensional flow normal to the cable section. The set up was made as rigid as possible for the execution of the static tests (Figure 5). The drag and lift forces were measured using six DOF force transducers (AMTI MC3A-500) at either end. The two force transducers were installed between the cable model and the supporting cardan joints. The cardan joints were installed in order to reduce the bending moments on the force transducers and to align the cable to the floor and the ceiling. The transducers and the joints were covered with dummy pieces of the same cable material and diameter. A gap of approximately 2mm was allowed between the cable model and the dummy pieces. The cables prototypes were full-scale sample of a high density polyethylene (HDPE) tube, with an outer diameter of 160mm, placed on an inner aluminum tube to increase the stiffness (Figure 4). The HDPE tube and the inner aluminum tube were fixed by means of screws in order to avoid any relative movement.

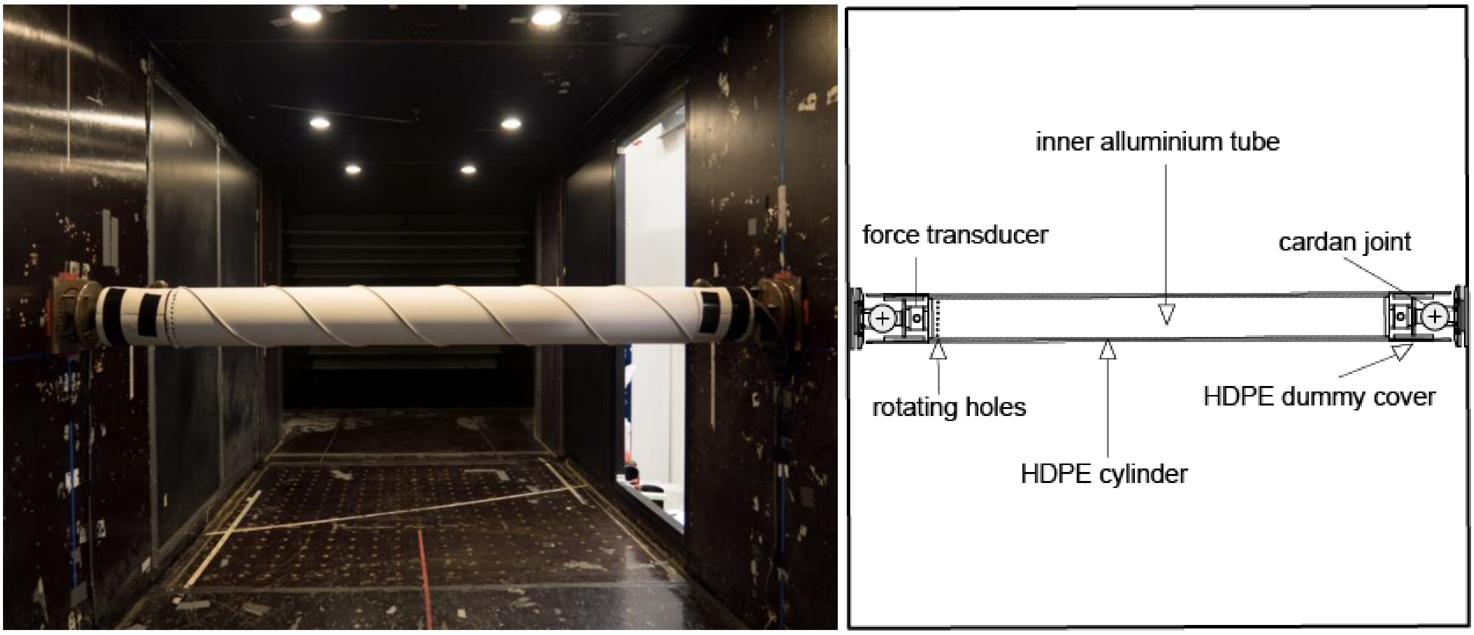
The length of the models was 1.42m, resulting in an aspect ratio of 8.9:1. The blockage ratio for the cable model was 8% and thus the drag coefficients have been corrected using the Maskell III method, according to Cooper et al. (1999).

For each tested configuration, the drag C_D and the lift C_L coefficients were calculated, based on the averaged along-wind and across-wind forces respectively, normalized by the along-wind flow velocity:

$$C_D = \frac{F_D}{\frac{1}{2}\rho U^2 LD} \quad (1)$$

$$C_L = \frac{F_L}{\frac{1}{2}\rho U^2 LD} \quad (2)$$

where F_D is the along-wind force and F_L is the across-wind component, U is the mean wind, L is the effective length of the cable, D the outer diameter and ρ the air density, taken here as 1.25kg/m^3.



(a) (b)

Figure 5. Test set-up in cross flow: photo (a), drawing (b).

4 SELECTED RESULTS AND DISCUSSIONS

4.1 Force Coefficients

The corresponding mean force coefficients for the three different cable section models tested in the Climatic Wind Tunnel are analyzed below. The cable section fitted with a helical fillet exhibits a constant behavior in the subcritical Reynolds number region, with an accentuated transition in the critical region, corresponding to a Reynolds number range between 2.0 to 2.6 x 10^5. On the other hand, both Innovation 1 and Innovation 2, fitted with the concave fillets, exhibit a more smooth and prolonged transition in the critical region which starts at a lower Reynolds number of 0.8 – 1.2 x 10^5 and enters the post critical state at a lower Reynolds number of 2.2 x 10^5. As a result, the two innovations are able to avoid an accentuated transition from the subcritical to the postcritical state, which can lead to different forms of vibrations, such as dry galloping (Macdonald and Larose 2006).

These results are in agreement with the ones reported in previous studies where, despite the profile differences, the higher fillet does not affect the performances of both innovations. For Innovation 1, the prototype supplied by Kleissl and Georgakis (2013) shows a higher drag in sub-critical state and the same value in post-critical compared to the model supplied by VSL International. The difference in the sub-critical state can be attributed to the higher profile of the fillet directly facing the flow of the first prototype. On the other hand, Innovation 2 shows the same performance for both models along the whole range of Reynolds number tested, from the sub-critical state to the post-critical state. This behavior is particularly accentuated and clear in Innovation 2.

From Figure 6 we can see that for a traditional helical fillet, the drag coefficient drops in the critical region from 0.85 to 0.65, and this last value corresponds also to the value reached at maximum wind velocities in the postcritical state. On the contrary, for Innovation 2 the transition in the critical flow state is very prolonged, reaching a drag coefficient of approximately 0.67 at maximum wind velocity. It is hypothesized that this is a result of the fact that the circumferential orientation of the fillets reduces the drag penalty, whilst introducing a pair of counter-rotating streamwise vortices. Furthermore, the beginning of the postcritical state is shifted at lower Reynolds numbers for Innovation 2 compared to a traditional helical fillet (Figure 6).

As a result, despite more than 100% increased height of the concave fillet, both innovations experience similar extreme drag forces with the advantage of avoiding an acute drag transition, as experienced with a traditional profile.

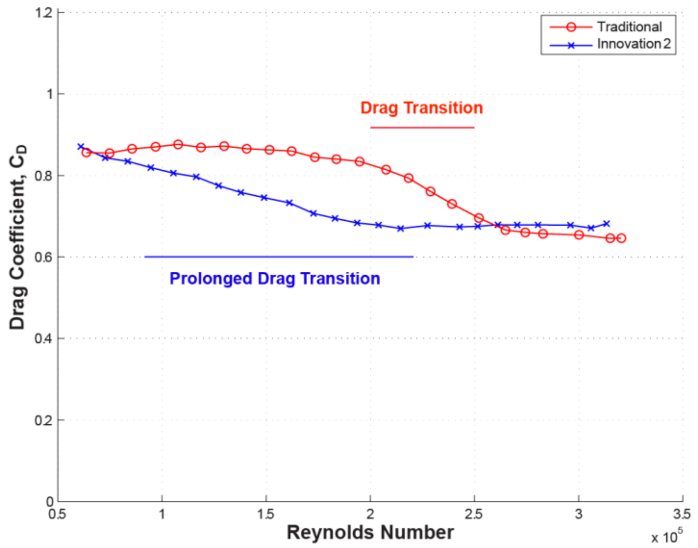


Figure 6. Drag coefficients comparison between a traditional profile and Innovation 2.

Concerning the lift force, a traditional helical fillet exhibits an almost zero lift along the whole range of wind velocities tested (Figure 7). This is most likely due to the fillet´s ability to generate variations in the flow and separations lines along the length of the cable, as largely reported in previous studies (Kleissl and Georgakis, 2011; Flamand and Boujard 2008; Flamand 1995).

Both Innovation 1 and 2 shows small positive and negative variations in relation to the mean lift value for increasing Reynolds number, but on the other hand they do not readily show a peak that identifies the transition to the critical Reynolds range. As a result, both innovations are able to generate a gradual flow transitions, leading to near zero lift coefficients in relation to the mean value (Kleissl and Georgakis 2013).

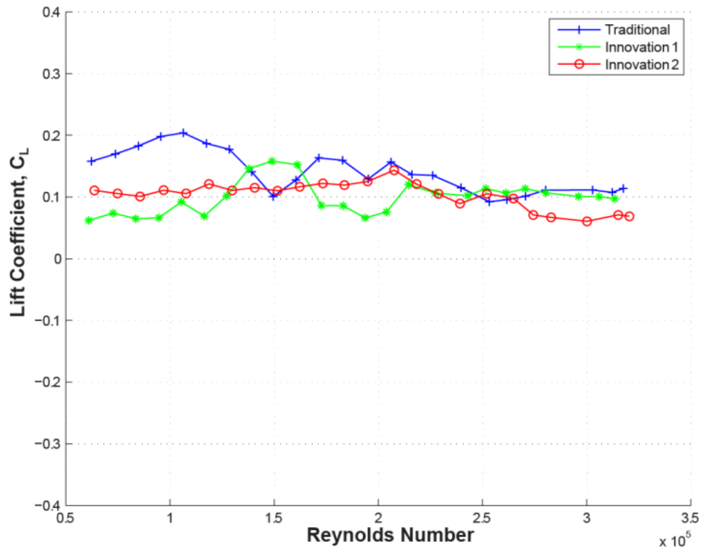
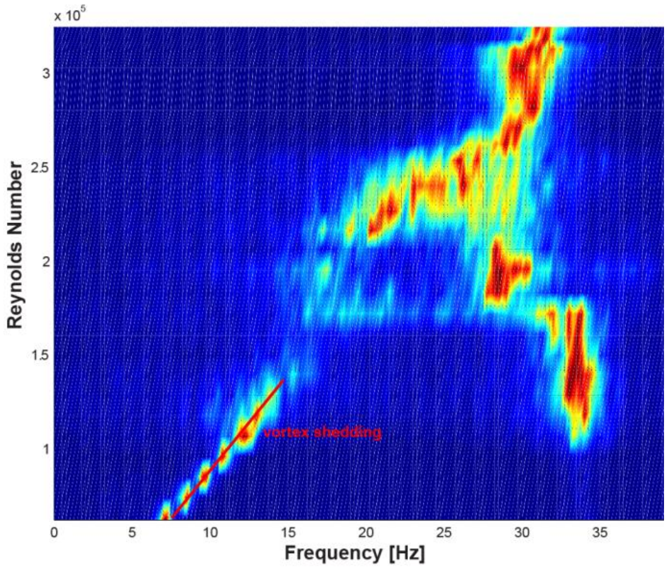


Figure 7. Lift force coefficients comparison between traditional profile, Innovation 1 and Innovation 2.

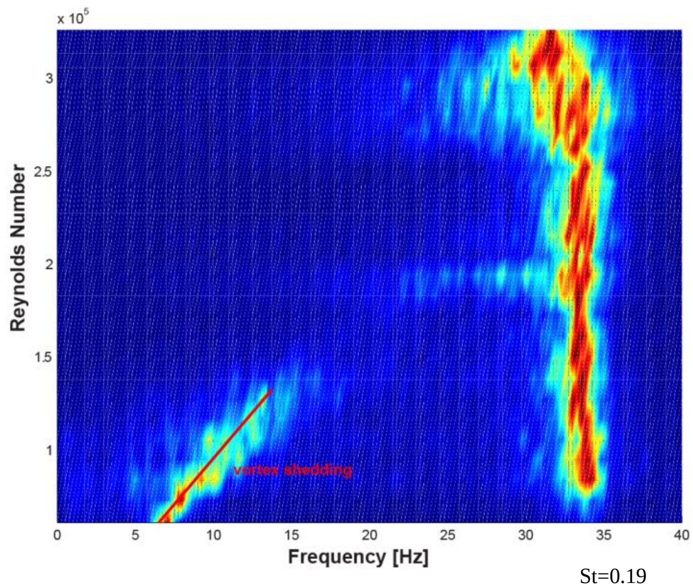
4.2 Fluctuating Lift Forces

A frequency analysis of the unsteady cross-stream force (fluctuating lift) was undertaken. With the particular cross flow test set up employed, the fluctuations of the total lift force on the model can be estimated. The frequency distributions of the lift force are determined using a Fast Fourier Transformation (FFT) to compute the power spectral density (PSD) of the lift coefficient. The PSD is computed for each of the flow velocities tested. The discrete number of flow velocity-specific spectra is then expanded into a two-dimensional contour plot, as seen in Figure 8c, for each of the three cable models. All the three cable model present the same Strouhal number ($St = f_S D/U$, where f_S is the frequency of the vortex shedding) of 0.19. The linear trend identifying vortex shedding disappears around a Reynolds number of 2.2 x 10^5 for the cable with traditional helical fillets. This value corresponds to the accentuated flow transition from subcritical to postcritical state highlighted in Figure 6. The same linear behavior disappears at much lower Reynolds numbers for Innovation 1 and 2 (Figure 8a and 8b). Here this occurs at Reynolds number of 1.2 x 10^5 and 1.0 x 10^5 respectively, which correspond to the respective value of start of the smooth and prolonged drag transition. The increased PSDs around 30 and 35Hz can be explained as the incidences of model resonance. As a result, both innovations are able to suppress vortex shedding formation at much lower wind velocities than a traditional profile.



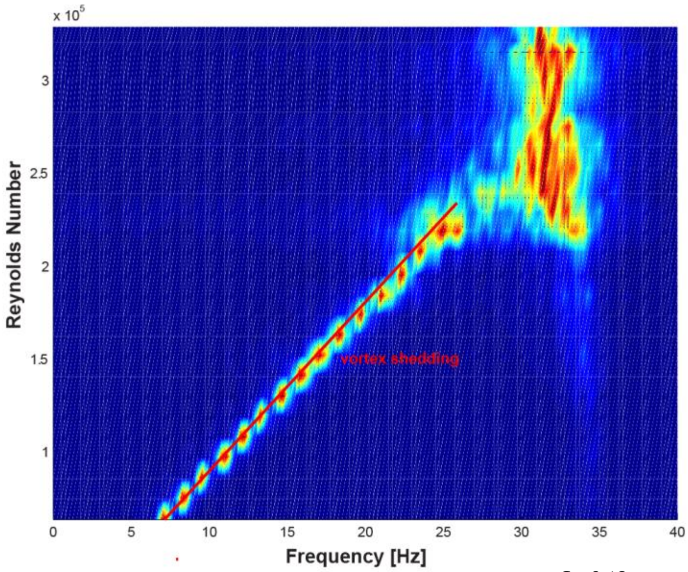
St=0.19

(a)



St=0.19

(b)



St=0.19

(c)

Figure 8. Normal flow lift coefficient PSD: Innovation 1 (a), Innovation 2 (b), traditional profile (c).

5 CONCLUSIONS

Two preliminary cable surface innovations supplied by VSL International have been wind-tunnel tested for the determination of the aerodynamic force coefficients. In order to understand their performance, the drag and lift coefficients were compared with a traditional helical fillet supplied by the same company. The concluding remarks are as follows.

- The aerodynamic coefficients of both Innovation 1 and Innovation 2 are similar at high Reynolds numbers, when compared to a traditional helical fillet, despite a higher profile of the fillet. It is hypothesized that this is due to the ability of the concave shape and sharp-edge of the fillet to enhance the vorticity.
- Both Innovations 1 and 2 are able to suppress vortex shedding at low Reynolds numbers, in the range of 1.0 – 1.6 x 10^5. It is believed that this behavior is related to the smooth and prolonged drag transition.

Further studies are currently being undertaken on the prototypes of Innovation 1 and 2 supplied by VSL International in order to optimize the aerodynamic performance and to further understand the behavior of the cables subjected to snow and ice accretions. It is thought that the higher fillet, compared with the lower traditional helical fillet will lead to longer ice retention allowing for the melted accretions to fall from the cables in smaller, less hazardous pieces.

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