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Rubber bearings and vortex shedding of groups of offshore wind turbine towers in high Reynolds number regime

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SUMMARY:
Laminated elastomeric bearings, typically used as seismic isolators, are successfully used to mitigate the across-wind vibrations of towers of offshore wind turbines during installation. A softer foundation interface reduces the first natural frequency of the tower, resulting in across-wind loads smaller in magnitude but triggered at smaller wind speeds. This gives a unique possibility to shed light on the vortex induced vibrations and interference of groups of uncoupled towers in the high Reynolds number regime. This contribution provides an overview of the approach developed to address the non-stationarity of the tower response as well as some preliminary results, which suggest an analysis time-scale of 30 s.

Keywords: vortex induced vibrations, laminated elastomeric bearings, high Reynolds number regime.

1. INTRODUCTION

Siemens Gamesa Renewable Energy (SGRE) patented the use of laminated elastomeric bearing (LEB) as countermeasure against vortex induced vibrations (VIV) for groups of offshore wind turbine towers at the harbour quayside before the loading onto the installation vessel (Fig. 1)

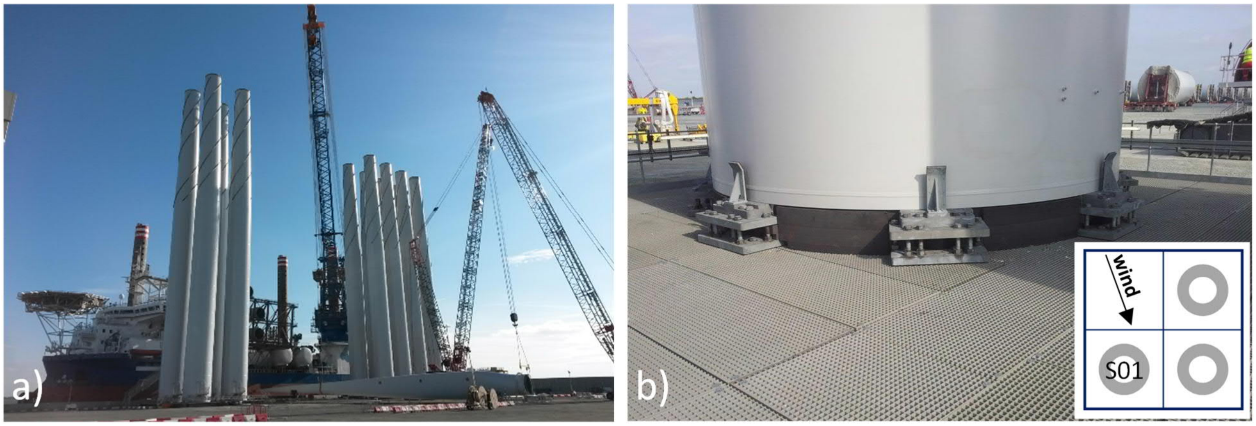

Figure 1. Temporary tower foundations at the port quayside a); tower supported by LEBs b).

Each connection consists of collaborating parts in steel and rubber, where compressive forces are taken by the LEB while tensile forces are taken by a set of bolts tightening two steel plates respectively beneath and above the bearing. An air gap of few millimetres is left between bolts and washers, to allow the LEB decompression in case of small-amplitude vibration and let the tower float on the soft interface. Differently, bolts are engaged in tension in case of severe windstorms or large amplitude VIV. Small horizontal displacements of the LEB are allowed before bolts are engaged in shear. The use of LEBs at the tower-foundation interface has three main advantages against VIV. First, it lowers the first natural frequency of the tower and so the resulting VIV loads in case of vibrations with small-mid amplitude. Second, the engagement of the bolts in case of large-amplitude vibrations causes a change in the frequency of vibration as well as a shift of the neutral axis of the set of vertical forces passing through the 8-point connection; the combination of these two effects makes the vibration chaotic and contributes to disrupt the steady state conditions so as to prevent VIV from further developing. The third advantage is the higher structural damping observed in full-scale measurements. One should stress that lowering the first natural frequency of the tower has the side effect to reduce the critical wind speed for triggering the VIV lock-in but also other aeroelastic instabilities like galloping. Indeed, SGRE is carrying out specific studies about the possibility to experience galloping; however, one should bear in mind the aforementioned chaotic vibrations of towers on LEBs which could give a benefit also against galloping. This belief is empirically supported by zero reported incidents, related to the use of LEBs, over more than 750 wind turbines installed in the past 5 years. SGRE has performed full-scale measurement campaigns to validate the use of LEBs against the VIV of towers supporting the 7.0 MW direct drive offshore wind turbine. The post- and re-processing of the vibrations of towers supported by LEBs measured over the years are not only useful to validate this technology but also give a unique possibility to shed light on the vortex induced vibrations and interference of groups of uncoupled towers in the high Reynolds number regime. Indeed, the large top tower diameters (4-5 meter) leads to Reynolds number frequently higher the 10^6, even for mild frequent wind conditions. On the other hand, the low critical wind velocity makes VIV frequent but harmless for the tower, because the resulting loads and stress levels are typically below or close the cut-off limit for fatigue damage. This contribution provides an overview of some findings and preliminary results considering the non-stationarity of the tower response due primely to the alternation and superposition of VIV and gust buffeting. Among the first goals of this research project, 1) the variability of the Strouhal number of groups of close towers in the high Reynolds number regime; 2) the estimate of the structural damping through the measurements in VIV lock-in events. The remaining part of this document further elaborates these topics, stressing the challenging and presenting potential solutions.

2. TOWER RESPONSE UNDER VIV

SGRE tested the use of LEBs for the first time in June 2017. Two towers were equipped with accelerometers, strain gauges, displacement gauges, and cap anemometers about 2 m above the tower hat. Fig. 2 plots a typical 10-minute acceleration trace recorded by one of the accelerometers placed 36 m below the top of tower S01 (Fig. 1). The wind angle of attack was about 20° offset to the vertical line. A *St* equal to 0.16 has been estimated by following the advice of the Eurocode (EN 1991-1-4:2005) in case of multiple cylinders, also considering the dependency of *St* on the Reynolds number (CNR-DT 207/2008). The resulting critical velocity seems in good agreement with the structural response shown in Fig. 3c. The trace in Fig. 2 bears very close resemble to the across-wind vibrations of the circular cylinders studied by Vickery and Basu (1983) in case of forced-random vibration regime where the response is expected to be nearly Gaussian. This regime is characterized by $K_s/K_a>1$, being K_a and K_s respectively the aerodynamic and structural damping parameters. This finding is seen as a qualitative sign of the health of the tower supported by LEBs against VIV under lock-in; this is also supported by a peak factor about 5 which is associated with the small amplitude vibrations.

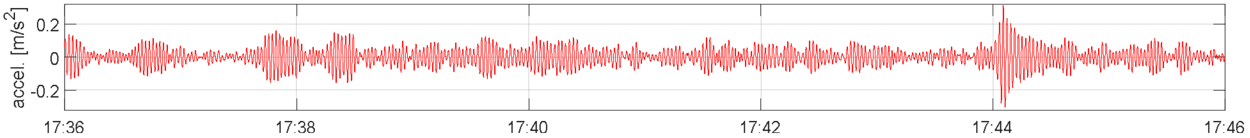

Figure 2. Typical vibrations of a 7.0 MW turbine tower supported by LEB in the lock-in region.

A more robust approach to prove the efficiency of the LEBs against VIV and a deep understanding of this phenomenon passes through the estimate of the K_a and K_s (alternatively the Scruton number). Literature provides charts and empirical formulations for estimating K_a (e.g., Vickery and Basu, 1983; Hansen, 2007), which requires the assessment of the turbulence intensity and the Strouhal number (*St*). If the former does not give any problem since the wind velocity was logged with 25 Hz sampling rate by the top tower anemometer, the complexity of the towers layout (Fig.1b) and the variability of the wind angle of attack, velocity and turbulence intensity make the estimate of *St* challenging. It also noted that the tower layout changed over the measurement campaign evolving from 2 towers side-by-side, to the final configuration of a 2-row and 2-column tower layout. In the specific case in Fig. 2, *St* is assessed through standards, while K_a=0.25 is estimated from literature. Otherwise, *St* may be estimated through full-scale measurements, first by screening traces of tower response effects in order to detect occurrences of VIV in lock-in (see Section 3), and then selecting the corresponding tower frequency of vibration and current wind velocity. The main challenge in such an approach is the non-stationarity of the tower response, pointed out in Section 3. K_s mainly depends on structural damping and eventually the modal shape in case of structure with not-uniform mass per unit length as the towers under discussion. Even though the tower modes can be straight computed by modal analyses, the non-stationary of the tower response to wind loading makes the assessment of the structural damping challenging when environmental excitation is used. The detection of VIV in the lock-in regime in combination with an accurate estimate of the governing parameters may be used to estimate the structural damping as an alternative methodology to more classical techniques like the operational modal analysis, which requires stationary signals and potentially underestimates the structural damping if the analysed traces contain VIV lock-in events, because of the negative aerodynamic damping. A Scruton number equal to 22 and a damping ratio of 6.2% are estimated for the current case. Operational sloshing dampers were installed at the tower top, which are expected to contribute to the estimated damping somehow, even though tuned on the full turbine frequency which is roughly 2 times lower than that of the tower alone.

3. DETECTION OF VIV LOCK-IN

The non-stationarity of the tower response to the wind load is shown in Fig. 3 through the time-frequency analysis of the acceleration trace in Fig. 2. Fig. 3a plots the spectrogram of the acceleration resulting by the short time Fourier transform (STFT) applied to 30-s not overlapped time windows with a uniform spectral window. The 30-s time scale is based on the observations of several traces across different measurement campaigns, as the longest duration of lock-in events.

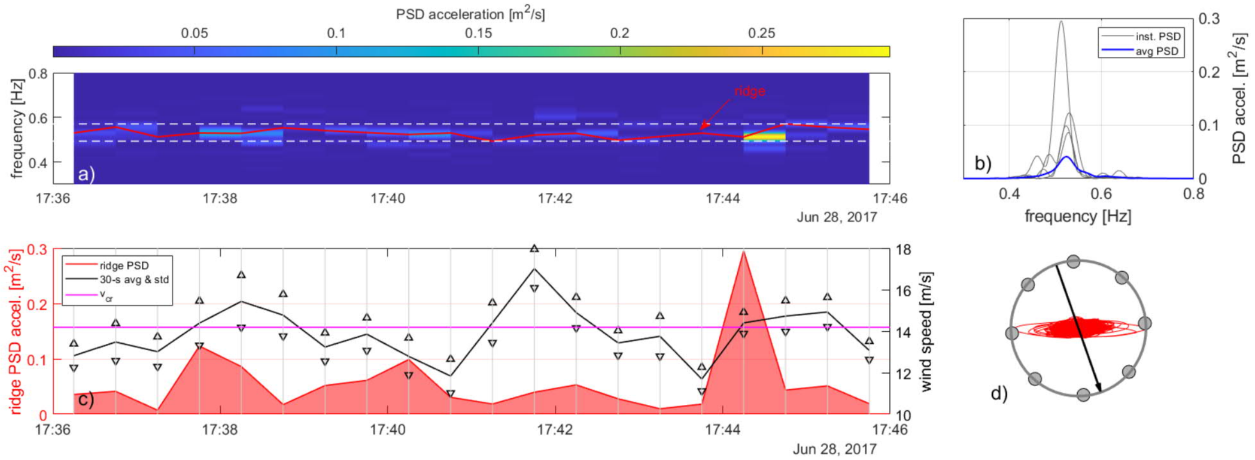

Figure 3. Time frequency analysis of the trace acceleration in Fig. 2.

This application of the STFT is preferred to the more common wavelet transforms, because the former gives full control of the instantaneous probability density function (PSD), does not alter the variance of the raw signal and it finally permits a direct comparison between the mean instantaneous PSDs (blue line in Fig. 3b) and the typical PWelch's PSD estimate. The red line in Fig. 3a plots the time-frequency ridge of the spectrogram, which estimates the instantaneous frequency of vibration variable over the range 0.49-0.57 Hz. The time evolution of the ridge is plotted in Fig. 3c showing a major spike and few narrowband segments whose PSD is plotted in grey colour in Fig. 3b. The approach of mean wind speed to the critical value in the neighbourhood of these systems support the hypothesis to be related to VIV lock-in. Further evidence is given by the trajectory of the tower vibrations (Fig. 3d) nearly perpendicular to the mean wind direction, and the low turbulence intensity at the time of the major PSD spike, which can be assessed by the small standard deviation given by the interval around the mean wind speed.

4. CONCLUSIONS

SGRE has performed full-scale measurement campaigns to validate the use of LEBs against VIV of towers supporting the 7.0 MW direct drive offshore wind turbine. These sets of data provide a unique chance to shed light on the vortex induced vibrations and interference of aeroelastic phenomena of groups of uncoupled towers in the high Reynolds number regime. This contribution provides an overview of the approach used to address the detected non-stationarity of the tower response to the wind load as well as some preliminary results. Studying the tower response on a 30-s time scale seems a promising strategy to detect and investigate VIV lock-in events.

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