Observation and comparison of tower vibration and underwater noise from offshore operational wind turbines in the East China Sea Bridge of Shanghai

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Abstract: Underwater operational turbine noise emitted by China's first offshore wind farm in the East China Sea Bridge of Shanghai was measured and analyzed in this study. Two sensors were used in the measurement: a hydrophone recording the underwater sound and an accelerometer placed in the turbine tower detecting the tower vibrations. Measurements were performed at two different types of wind turbines: a Sinovel 3 MW SL3000 turbine and a Shanghai Electric 3.6 MW W3600 turbine. The two turbines show similar tower vibration characteristics, characterized by a number of tonal components, mainly in the low-frequency domain (30–500 Hz). The peak vibration frequencies changed with the wind speed until the turbine approached its nominal power rating. Spectral analysis of the underwater acoustic data showed that the amplitude spectra had a strong correlation with the spectra of the turbine vibration intensity level, indicating that the measured underwater noise was generated by the tower mechanical vibration.

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1. Introduction

Offshore wind turbines are a new source of underwater noise in the marine environment. During offshore wind-farm operation, turbine and service activities create low-intensity, almost continuous underwater noise. The planned operational period of a wind farm is at least 20 years. It is therefore important to quantify the underwater noise emissions from operational wind turbines.

Several studies of underwater noise from operational wind turbines have been reported in conference proceedings (Betke *et al.*, 2004; Norro *et al.*, 2015; Cheesman, 2016). The sound associated with wind turbine operation has, in general, been described as continuous in nature, and characterized by one or more tonal components, typically at frequencies below 1000 Hz (Degn, 2000; Betke *et al.*, 2004; Madsen, 2005; Wahlberg and Westerberg, 2005; Tougaard *et al.*, 2009; Sigray and Andersson, 2011). For turbines with a staged gearbox system, the noise output was found to vary with the wind speed and wind-driven turbine parameters (including blade revolution rate, and gearbox and generator operation rates) (Betke *et al.*, 2004; Madsen, 2005; Sigray and Andersson, 2011). The correlation between the mechanical vibrations of the turbine tower and the sound pressure and between the vibrations and the particle motion in the water column was demonstrated by Lindell (2003) and Sigray and Andersson (2011), respectively. This confirmed the view that the origin of the turbine noise lay in mechanical vibrations in the nacelle and originated from the rotation of the wind-powered components in the nacelle. This was supported by modeling (Marmo *et al.*, 2013).

Some of the above-mentioned studies investigated the correlation between the mechanical vibration of the turbine tower and the radiated underwater noise; however, they did not provide direct and convincing evidence that the measured underwater noise originated from tower mechanical vibrations. In shallow waters, the turbine noise

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is easily masked by wave and tidal-flow noise. In this paper, the tower mechanical vibrations and underwater sound pressure were measured synchronously to help understand and recognize underwater turbine noise in operational conditions.

2. Measurement location and setup

The East China Sea Bridge offshore wind farm, located in the Pudong New Area of Shanghai, is China's wind-farm demonstration project and the first major offshore wind-farm in Asia. At the end of 2017, it consisted of 34 Sinovel 3.0 MW SL3000 wind turbines, 1 Sinovel 5.0 MW SL5000 wind turbine, and 27 Shanghai Electric 3.6 MW W3600 wind turbines in operation with a total capacity of 204.2 MW. Two wind turbines were examined in this investigation: a Sinovel 3.0 MW SL3000 wind turbine (M1) and a Shanghai Electric 3.6 MW W3600 wind turbine (M2). The wind turbine distribution and the locations of M1 and M2 are shown in Fig. 1. High concrete pile cap foundations were used in the construction of the wind turbines. The average water depth in the wind farm area is 10 m, and the average wind speed is 8.4 m/s at around 90 m above sea level.

The main devices used in the measurements were one self-contained receiver for receiving the underwater sound and one accelerometer placed in the turbine tower for measuring the tower vibrations. The sound recording system consists of a self-contained customized omnidirectional hydrophone with a sensitivity of -194 dB re 1 V/μPa, a RBR duo temperature and depth (T.D) gauge (RBR, Ottawa, Canada), a 60-kg anchor weight, and two round buoys. The T.D gauge was placed 2 m above the sea floor to measure the water depth, and the hydrophone was placed about 0.5 m above the T.D gauge. At the same time, the mechanical vibrations of the tower wall were measured and recorded using a B&K-4371 accelerometer (Brüel&Kjær, Copenhagen, Denmark), a B&K-NEXUS amplifier (Brüel&Kjær, Copenhagen, Denmark), and a LTT multichannel recorder (Labortechnik Tasler, Würzburg, Germany). The accelerometer was fixed on the outer vertical surface of the wind turbine tower.

The sound recording system was deployed about 50 m from the measured turbine to record the underwater sound at a sampling frequency of 24 000 Hz and a 24-bit digital dynamic range. The data were stored in the DAT file format. The tower vibration data were recorded on the LTT recorder with a sampling frequency of 20 830 Hz. Continuous synchronous recording of the radiated underwater noise and the tower vibrations of turbines M1 and M2 was carried out for 2 days. The data for turbine M1 were recorded on August 25–27, 2017 and the data for turbine M2 were recorded during August 27–29, 2017.

3. Results and analyses

3.1 Vibration data and wind speed

After performing spectral analysis of the vibration data from turbines M1 and M2, the total vibration levels in Figs. 2(a) and 2(b) were obtained by summing the power spectral density levels of the vibration data in Figs. 2(c) and 2(d). The power spectral density levels were sampled at an interval of 1-Hz in the frequency domain 0–500 Hz where most of the energy of the wind turbine was concentrated. The total vibration levels, wind speeds, and spectral time series from 0 to 500 Hz of the two wind turbines are shown in Fig. 2 as a function of time over a 2-day period. Figures 2(a) and 2(c) show the data of M1, recorded from 15:00 on August 25, 2017 to 15:00 on August 27, 2017. Figures 2(b) and 2(d) show the data from M2, recorded from 17:00

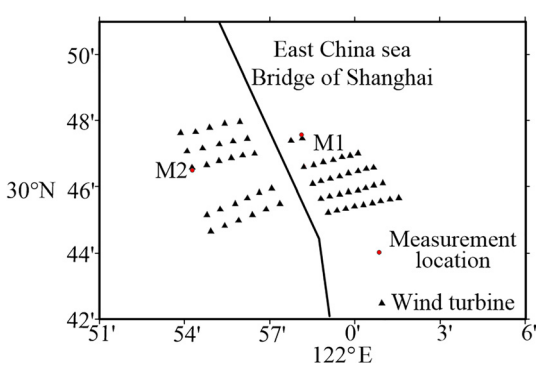

Fig. 1. (Color online) Wind turbine distribution and measurement location in the East China Sea of Shanghai. Measurements were obtained about 50 m from turbines M1 and M2.

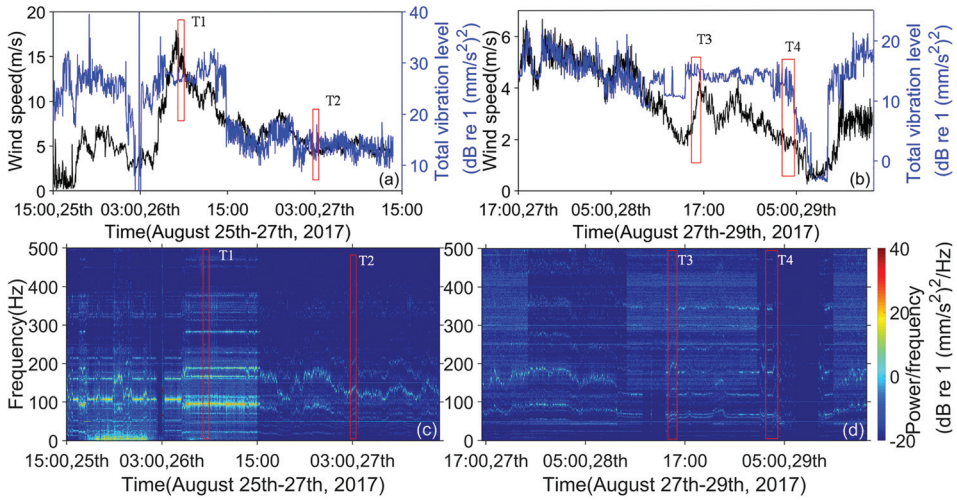

Fig. 2. Total turbine vibration levels (blue solid lines), wind speeds (black solid lines), and spectral time series from 0 to 500 Hz. (a) and (c) near M1—the Sinovel 3.0 MW SL3000 wind turbine; (b) and (d) near M2—the Shanghai Electric 3.6 MW W3600 wind turbine.

on August 27, 2017 to 15:00 on August 29, 2017. The variations in the wind speed (black solid lines) and total vibration levels (blue solid lines) follow similar trends. The turbine vibration intensities varied when the wind speed changed; however, there were also observations of abnormally high vibration levels from around 15:00 on August 25, 2017 to 05:00 on August 26, 2017 when the wind speed was low. The abnormal vibrations may have resulted from other factors in the environment. The vibration level increased with increasing wind speed until the turbine approached its nominal power rating. Between about 06:00 and 10:00 on August 26, 2017 when the wind speed reached up to and even exceeded the rated wind speed 12.5 m/s, the vibration intensity levels almost plateaued, and the peak vibration frequencies stayed the same. After 15:00 on August 26, 2017, the vibration intensity levels showed a gradual decrease as the wind speed decreased. The wind speed of M2 was always smaller than its rated wind speed 12 m/s; hence, the vibrational intensity level was constantly changing with the wind speed. The time intervals T1, T2, T3, and T4 are corresponding to Figs. 3(a1), 3(b1), 3(c1), and 3(d1) in turn.

3.2 Acoustic data

We performed spectral analysis of the underwater acoustic data obtained from turbine M1 during August 25–27, 2017 and turbine M2 during August 27–29, 2017. The total pressure level of the underwater acoustic data (Fig. 4) was obtained by summing the power spectral density levels in the frequency range from 0 to 500 Hz. The power spectral density levels were sampled at an interval of 1-Hz for the two turbines. The total pressure levels and water depths measured at a distance of 50 m from wind turbines M1 and M2 are shown in Figs. 4(a) and 4(b), respectively, as a function of time over a 2-day period. The black solid lines show the water depth variations, i.e., the tidal variations, measured by the T.D recorder, and the blue solid lines show the total pressure levels derived from the underwater acoustic data. The tide had a significant effect on the background noise, with good correlation between the sound intensity peaks and the tidal changes. This shows that the sound fluctuations correspond to the ebb and flood tides motion, interspersed with relatively short periods of reduced sound levels that correlate with the periods of low tidal flow (high and low tide). This is likely the result of the tidal flow's effect on the tower wall and the seafloor, and not a result of changes in the noise radiating from the turbine. All acoustical measurements presented in this paper refer to 1 μPa. The four short periods T1, T2, T3, and T4 of reduced sound levels are corresponding to Figs. 3(a2), 3(b2), 3(c2), and 3(d2) in turn.

3.3 Comparison between vibration and acoustic data

The underwater noise from the wind turbines was completely masked by the tidal noise during ebb and flood tides. However, the tidal noise was low during high and low tides when the speed of the tidal flow was relatively slow. Therefore, we used the four acoustic data segments during the T1, T2, T3, and T4 periods (high or low tides) to study the turbine noise characteristics. Additionally, the tower mechanical vibration data of

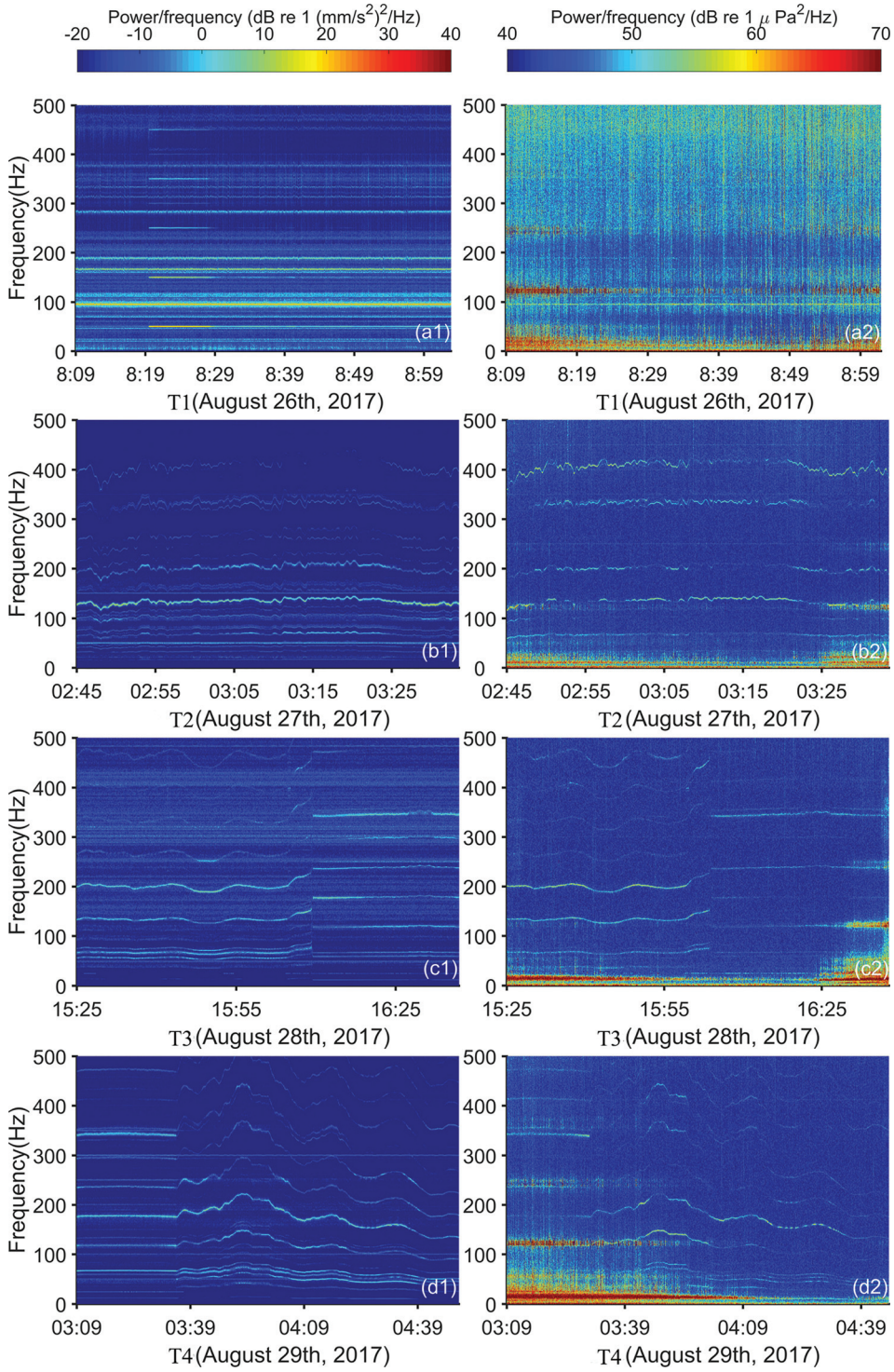

Fig. 3. Spectral time series of the Sinovel 3.0 MW SL3000 turbine tower (four panels on top) and the Shanghai Electric 3.6 MW W3600 turbine tower (four panels on the bottom) from 0 to 500 Hz, recorded during the T1, T2, T3, and T4 periods; mechanical vibrations (left panels) and underwater acoustical data measured about 50 m from the wind turbine (right panels).

turbines M1 and M2 during the same periods were used for comparison with the underwater turbine noise. The spectral time histories of the tower vibration data (left panel) and the underwater acoustic data (right panel) from M1 and M2 are shown in Fig. 3. The acoustic power is concentrated in a narrow range of frequencies, with most of the tonal energy observed at frequencies below 500 Hz. A strong frequency correlation is found between the underwater acoustic spectral data and the turbine vibration spectral data of each wind turbine, and the correlation coefficient of frequencies between the vibration and underwater noise spectra is approximately 1, indicating that most of the measured underwater noise is generated by the tower mechanical vibration,

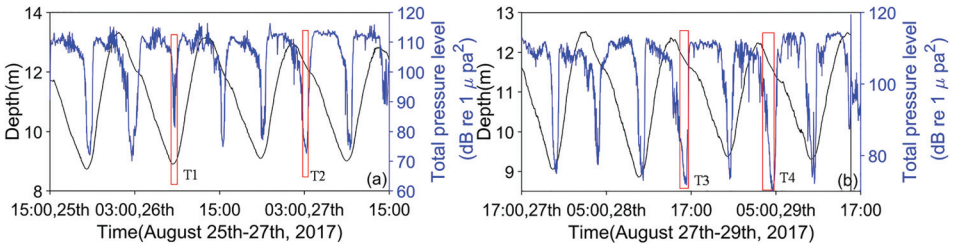

Fig. 4. Total pressure levels derived from the underwater acoustic data for frequencies 0–500 Hz (blue solid lines) and water depths (black solid lines) measured at a distance of 50 m (a) from the Sinovel 3.0 MW SL3000 wind turbine (M1) and (b) from the Shanghai Electric 3.6 MW W3600 wind turbine (M2).

even though the underwater noise from the turbines is very weak. Noise from other sources in the water column was also detected. There is an interesting phenomenon about the turbine vibrational frequencies. When the wind speed exceeded the turbine's rated wind speed 12.5 m/s (T1), the frequencies and amplitudes were stable. When the wind speed is below the rated wind speed (T2, T3, and T4), the peak tonal vibrational frequencies and amplitudes changed. The abrupt change of the vibrational frequencies during the T3 and T4 periods may have a relationship with the change of the turbine blade revolution state.

4. Conclusions

Observations and comparison of the tower mechanical vibrations and underwater noise from the Sinovel 3.0 MW SL3000 wind turbine and the Shanghai Electric 3.6 MW W3600 wind turbine are presented in this paper. The underwater turbine noise is so weak that it is difficult to measure and evaluate. Most of the underwater acoustic data from the wind turbines are completely masked by the tidal noise. However, during high and low tides when the tidal noise is low, the turbine noise is dominant, so the noise data recorded by the hydrophone in these periods can be analyzed as the turbine noise data. The spectral data showed that the tower mechanical vibrations were characterized by a number of tonal components, mainly distributed in the low-frequency domain, and the peak frequencies and sound pressure amplitudes varied with the wind speed until the turbine approached its nominal power rating. The spectral data of the underwater turbine noise from the hydrophone showed strong correlation with the tower mechanical vibration data, indicating that the measured underwater noise resulted from the tower mechanical vibration.

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