Field Testing a Full-Scale Tidal Turbine Part 3: Acoustic Characteristics

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***Abstract*—Like any new technology, tidal power converters are being assessed for potential environmental impacts. Similar to wind power, where noise emissions have led to some regulations and limitations on consented installation sites, noise emissions of these new tidal devices attract considerable attention, especially due to the possible interaction with the marine fauna. However, the effect of turbine noise cannot be assessed as a stand-alone issue, but must be investigated in the context of the natural background noise in high flow environments. Noise measurements are also believed to be a useful tool for monitoring the operating conditions and health of equipment. While underwater noise measurements are not trivial to perform, this non-intrusive monitoring method could prove to be very cost effective. This paper presents sound measurements performed on the SCHOTTEL Instream Turbine as part of the MaRINET testing campaign at the QUB tidal test site in Portaferry during the summer of 2014. This paper demonstrates a comparison of the turbine noise emissions with the normal background noise at the test site and presents possible applications as a monitoring system.**

***Index Terms*—noise, tidal turbines, full scale, environmental impact**

I. Introduction

The tidal industry, while still in its infancy, promises to contribute to clean, carbon neutral electricity production in the coming decades. As with any other new technology, potential impacts on the environment during installation and operation must be assessed carefully. One issue under consideration is the noise emission of such machines [1, 2], although quantifying the impact of underwater noise is a complex task.

Kastelein et al. (2008) [3] investigated the impact of noise on different fish species while Ellison et al. 2012 [4] researched the effect of acute and chronic noise on marine mammals and recommended a new approach for ecosystem-level management and spatial planning of off-shore work. Generalisations about the effects of sound on marine fauna should be made with care since the reactions depend on various factors like location, temperature, physiological state, age, body size, and school size. Other researchers already indicate that the noise emitted by tidal turbines might interfere with local fauna, although, due to the lack of existing turbine noise data, previous studies are mainly based on noise sources created from relatively vague assumptions [5].

A review by the Crown Estate [6] on the current knowledge on sound emissions of wave and tidal power devices also highlighted significant knowledge gaps, especially the lack of fully publicly disclosed data from noise measurements in full scale operating conditions.

Other areas of research on underwater noise pollution and the effects on local fauna have been ongoing for decades. Investigations range from ship traffic [7] to engineering works like pile driving [8], to name just a few.

Typical installation sites for tidal turbines seem to be subject to high levels of ambient noise. Strong currents can mobilize sediments resulting in significant ambient noise at frequencies (typically > 1 kHz) related to the size distribution of sediment present at the site [9, 10]. Turbulence advected over hydrophones can result in flow noise, which, although not a true ambient noise source, can dominate low frequency noise measurements [11, 12]. The acoustic effects of new anthropogenic noise sources must be considered in the context of preexisting background noise levels.

This document presents both fixed and drifting acoustic

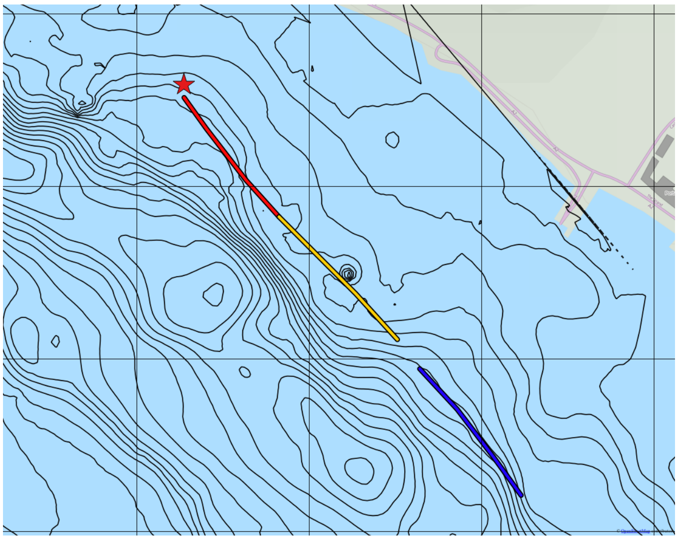

Fig. 1. Bathymetry of the test area. The red star shows the turbine position. The coloured tracks indicate the sections used for averaging. Gridlines are 300m apart. Depth contours represent 2m.

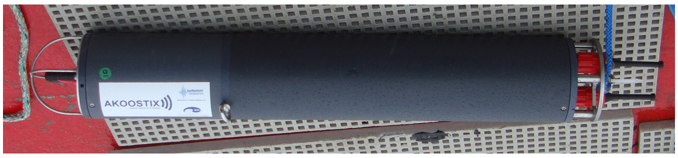

Fig. 2. Hydrophone and data acquisition system.

measurements of a full-scale operating tidal turbine in Strangford Lough, Northern Ireland. The turbine was installed on a barge, moored in about 10 m water depth and located in a tidal channel. A bathymetry of the test area can be seen in Figure 1.

The turbine hub was fixed at a depth of 3.4 m below the water surface. The seabed is characterized by small boulders on bedrock base layer. The sea state was 1-0, and no precipitation was falling. More details on the turbine setup can be found in Jeffcoate et al. [13]. Measurements were performed in flood tides when the mean flow direction in the channel is northwest. During the measurements the tidal current velocities at the turbine were 1-2 m/s, in the middle of the channel they increase to up to 4 m/s.

The measurements obtained at the site are used to describe the influence of changes in operating mode on the sound signature. In a second section sources levels of the operating turbine are estimated.

II. Equipment

Underwater noise measurement equipment was provided and operated by Akoostix Inc. Figure 2 shows the data acquisitions system (DAQ), an Akoostix GuardBuoy. The GuardBuoy uses a GeoSpectrum Technologies Inc. (GTI) omni-directional M24 hydrophone, which can be seen on the left hand side of the buoy in Figure 2 protruding from the watertight casing. A metal cage protects the sensitive hydrophone head from damage. The Guardbuoy samples at 96 kHz, providing measurements from approximately 20 Hz to 40 kHz, and uses a 24-bit analogue-to-digital converter (ADC).

While GTI provided a sensitivity (calibration) curve for the M24 hydrophone, technicians calibrated the assembled Guardbuoy to account for other system gains such as analogue-to-digital gain. This produced a calibration to convert the data from from bits, as the data are recorded in .wav format, to μPa. During calibration, the GuardBuoy was immersed in a tank with an acoustic source and a calibrated reference hydrophone. The acoustic source was positioned 0.74 m from the GuardBuoy and the reference hydrophone. The source transmitted a series of sinusoidal tones from 40 kHz down to 3 kHz in steps of 0.5 kHz. Each pulse transmission was 0.98 ms in duration, and the pulse repetition interval was 5 s. During the test, the reference hydrophone voltage was recorded which, in conjunction with a corresponding sensitivity curve, provided a measure of the sound pressure level in the tank for each tone. Once the test was complete, analysts downloaded the GuardBuoy data, and measured the root mean square (RMS) level of each tone, taking precaution to exclude signals reflected from the sides of the tank. The onset of reflected signals corresponds to visible fluctuations in the amplitude of the raw signal. Also, the measured signals were fit to a sinusoidal curve to avoid underestimation of the RMS levels due to under-sampling (with a sample rate of 96 kHz and test frequencies up to 40 kHz, it's unlikely that peak signal levels were sampled, so curve fitting is required). The measured RMS levels, which are in units of least significant bits (LSB), were converted to dB re LSB/μPa as follows:

$$\frac{\mathrm{dB}\, re\, \mathrm{LSB}}{\mu Pa} = 20\log\left(\frac{\mathrm{RMS_{measured}}}{\mathrm{V_{ref}}}\right) + \mathrm{V_{refsens}} \quad (1)$$

where $\mathrm{V_{ref}}$ is the voltage measured on the reference hydrophone, and $\mathrm{V_{refsens}}$ is the reference hydrophone sensitivity in dB re V/μPa. This calculation was repeated for each frequency, resulting in a frequency dependent calibration curve. For signals between 10 and 200 Hz, the test was repeated using a carefully designed in-air calibration method, as the tank was too small relative to the wavelength of the acoustic waves.

III. Methods

Measurements were performed at the QUB tidal test site in Portaferry, Northern Ireland, during the Marine Renewables Infrastructure Network (MaRINET) testing campaign of the SCHOTTEL STG turbine. Details of the turbine setup can be found in Jeffcoate et al. [13].

Datasets used in this paper were recorded at the times as shown in the following table:

Name	Date	Time
fixed 9m:	Aug 25th	10:20:00 - 10:21:00
background 20min	26th Aug	08:29:00 - 08:49:00
background 60s	26th Aug	09:42:00 - 09:43:00
100m	Aug 28th	10:00:41 - 10:01:41
250m	Aug 28th	09:59:33 - 10:00:33
450m	Aug 28th	09:58:05 - 09:59:05

Background noise was measured with the turbine turned off. Two sets of recordings are discussed in this paper. In the first set of recordings, the DAQ was fixed to the barge at a depth of 1.7 m. The range to the turbine remained constant at 9 m during these measurements. As a result, these recordings contain low-frequency flow noise from the motion of the water relative to the hydrophone. This presents a considerable experimental challenge, since low-frequency signals from the turbine will be masked by flow noise, making characterization of these signals impossible [12, 11].

A second set of measurements was collected with the DAQ drifting past the turbine. For these tests the DAQ was attached to a floating buoy so that the hydrophone was placed 4 m below the water surface. The system was released upstream of the turbine and recovered downstream. A Global Positioning System (GPS) was placed in a watertight box, tethered to the buoy, providing GPS position of the buoy throughout the drift. Spikes in data were confirmed to be from tapping on or near the buoy. The resulting acoustic data are less affected by flow noise. However, this configuration may not be feasible for longer-term monitoring since it requires personnel to deploy and recover the buoy on a regular basis, and the risk of damage to the buoy is markedly increased due to potential collisions with other objects. Also, measurements are limited to shorter durations and if source levels (SL) are desired, the resulting data have to be corrected for changing position and propagation conditions.

A hydrophone produces a voltage fluctuation that is proportional to fluctuations in the ambient pressure. Sound is often measured as the logarithm of the ratio of the root mean square (RMS) pressure p to a reference value p_0 [14] as follows

$$SPL = 20 \log_{10} \left(\frac{p}{p_0} \right) \quad (2)$$

The reference pressure for hydrophone measurements is 1 μPa, while 20 μPa is used in air [15]. dB levels in water are thus not comparable to dB levels in air due to different reference pressures.

To assess the overall noise emissions of the turbine, $1/3$ octave spectra from 10 Hz to 20 kHz were computed as follows:

- the 96 kHz raw time-series data were processed using 16384 point FFT processing, resulting in 5.86 Hz spectral resolution. Hann windowing with a 75 % overlap was used, any frequencies less than 20 Hz and greater than 30 kHz were discarded later.
- Sensor and processing calibrations were applied to convert to power spectral density (PSD)
- the PSD were averaged over 60 s seconds, except for the 20-minute noise sample.
- $1/3$ octave spectra were obtained by averaging over the frequency bins that define the $1/3$ octave scale [14]

Using the range from the buoy to the turbine, computed from GPS positions, noise data can be adjusted for transmission loss (TL) due to spreading. To obtain SL from the recorded levels RL the following equation was used:

$$SL = RL + TL \quad (3)$$

This provides an estimated broadband source level at 1 m from the source (turbine), which is a standard measure for noise sources. TL can be estimated as a combination of spherical spreading to the water depth D, and cylindrical spreading beyond that distance as expressed in equation 4.

$$TL = 20 \log_{10}(D) + 10 \log_{10}(range) - 10 \log_{10}(D) \quad (4)$$

It should be noted that equation 4 does not take into account attenuation and losses due to interactions with the surface or seabed and is thus a conservative estimate, yielding higher SL than expected in reality.

Since the buoy is continuously drifting towards the turbine during the measurement, the signal levels continuously increase within the 60-second windows over which the averaged spectra are computed. This increase will be more significant for measurements closest the turbine where spherical spreading likely contributes more to propagation loss, and the change in source-to-receiver distance is comparable to the mean distance over the averaging period. Therefore, the averages will be biased higher by spectra in the latter portions of the 60-second window. A more robust average would include range-correction of the individual spectra prior to averaging, or use shorter time periods where changes in range are not as significant. These improvements are being considered for future work.

IV. Results

A. Operating Modes

This section presents data taken during varying turbine operation modes.

Figure 3 shows a spectrogram computed from a fixed measurement, taken at the 25th Aug, around 10:30am. The x-axis shows the frequency and the y-axis the time, while the greyscale represents sound pressure levels, with brighter shades indicating higher levels.

Figure 3 shows the three distinct operating modes of the turbine. The top half shows the noise emissions of the turbine in normal operating conditions, generating electricity. Several discreet, narrowband sound sources can be observed as vertical lines, varying only little in frequency and amplitude.

The centre part of Figure 3 shows the turbine in free-wheeling mode, where the turbine blades are allowed to rotate faster under the force of the current, after being disengaged from the load of the internal generator. The narrowband sound sources observed when the turbine is generating are absent in free-wheeling mode. Instead, there are some narrowband signals that have a more natural variable frequency instead of controlled steps.

In the third operating mode the brake is applied. New sound sources at higher frequencies appear for a short duration, and several narrowband signals become prominent These narrowband signals decrease in frequency, maintaining their mechanical relationship (gear ratios) until the turbine stops rotating completely (not shown in Figure 3).

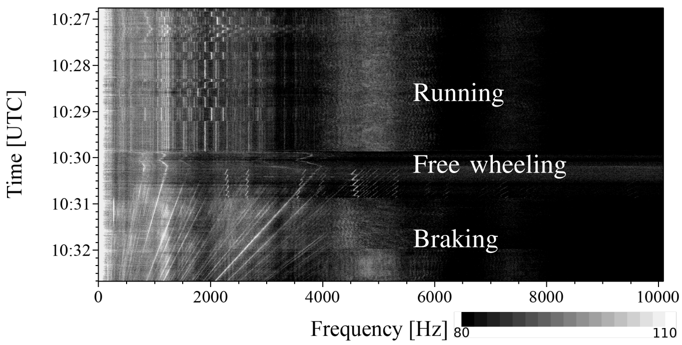

Fig. 3. Spectrogram of the noise measured at a fixed position beside the turbine. Grey values are given in dB re $\mu Pa^2/Hz$.

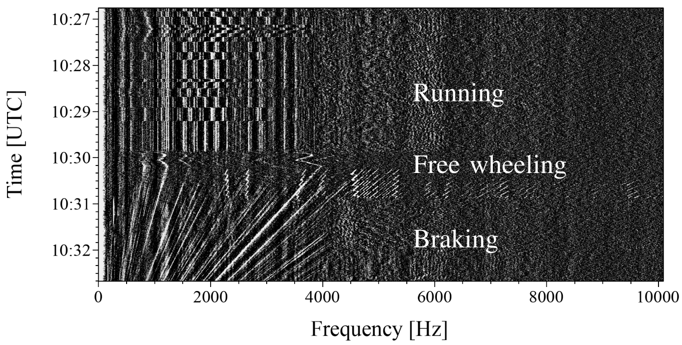

Fig. 4. Normalised spectrogram of the noise measured at a fixed position beside the turbine.

The observed noise from 20-300 Hz is attributed to flow noise.

Normalization of a spectrogram is performed to enhance signals of interest, in this case narrowband signals. Normalization is achieved by estimating a background noise level and dividing the data by that level, though the method of noise estimation varies with the type of signals to be enhanced. As shown in Figure 4 this enables the identification of weaker narrowband signals, particularly in the low frequency range. Though this normalization mode optimizes narrowband signals, it also suppresses broadband noise and transient signals that may otherwise show up as spikes or horizontal stripes on the spectrogram. In this case, there is a broadband signal between 4 and 6 kHz, which is visible in the unnormalized image, but absent from the normalized image. In Figure 3 weak signals are not visible at higher frequencies, but they can be detected in the normalized image, Figure 4.

B. Noise Levels

With the exception of one of the noise samples, spectra were averaged over 60 s. For the drifting measurements this equates to approximately 100 m displacement with the current. One noise sample is 60 s in duration and represents the minimum noise levels recorded over the entire experiment. The second noise sample is averaged over 20 min and is a representative measure of the typical background noise in the strait. In this twenty-minute period, noise from a ferry and possible sounds

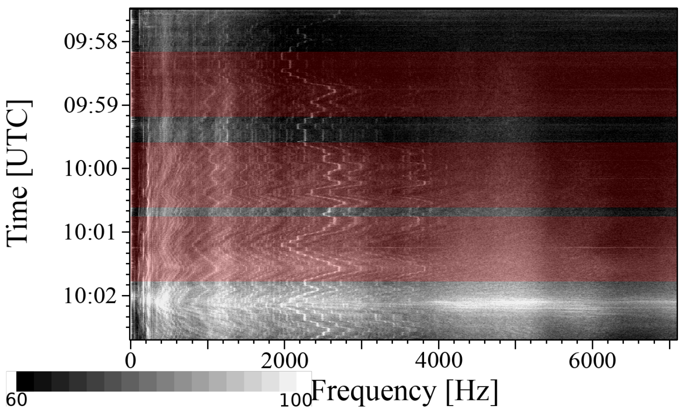

Fig. 5. Ranges used for distance correction. The red bands show data which was averaged and then corrected for distance. Grey values are given in dB re $\mu Pa^2/Hz$

of rocks moving on the sea floor due to the current could be identified.

Figure 5 shows a spectrogram with 60 s samples highlighted in red.

Figure 6 displays spectral density level over frequency for both ambient noise measurements and three reference ambient noise curves showing typical noise levels for sea state 1 and 6 along with the typical quietest ocean noise level as reported by [16]. The noise levels related to sea states seem a useful reference since they are widely accepted and many future installation sites will be exposed to waves.

The noise measurement over 20 min is very similar to the noise reported for sea state 6 for the frequency range from 200-2000 Hz with noise levels decreasing with increasing frequency from 72 dB re $\mu Pa^2/Hz$ to 62 dB re $\mu Pa^2/Hz$. Above 2000 Hz the data for sea state 6 continues to drop while the measured noise data remains almost constant. The 60 s noise measurement includes a noise spike in the 200-300 Hz range. The structure of the signals around 200 Hz do not exhibit the discreet, 'stair-step' appearance visible in the other turbine signals, indicating that these signals do not respond to changes in turbine speed, suggesting that they are not related to the turbine.

The noise levels for sea state 1 are about 20 dB less than for sea state 6 over the entire frequency range. Between 500 Hz and 20000 Hz they are lower than for sea state 1. In the following plots only the noise data averaged over 20 min and the theoretical minimum is plotted for comparison with noise samples taken with the turbine running.

Data below 100 Hz is probably affected by shallow water effects, [15] estimates the cut-off frequency for a water depth of about 10 m as 70 Hz.

Figure 7 shows ambient noise with data recorded while the turbine was running. Turbine noise was measured both with the hydrophone fixed 9 m from the turbine and with the hydrophone drifting by the barge at varying distances.

As might be expected, the highest levels of around 100 dB re $\mu Pa^2/Hz$ are measured when the hydrophone is only 9 m

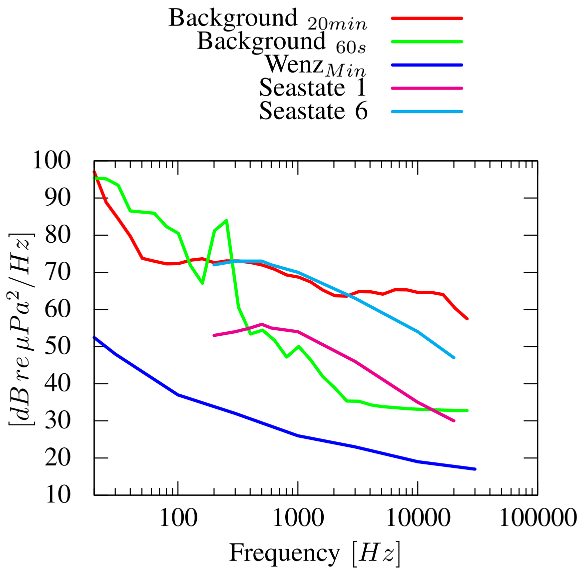

Fig. 6. Power spectral density over frequency for ambient noise as measured below the barge and typical spectra for different seastates according to Wenz (1962) [16].

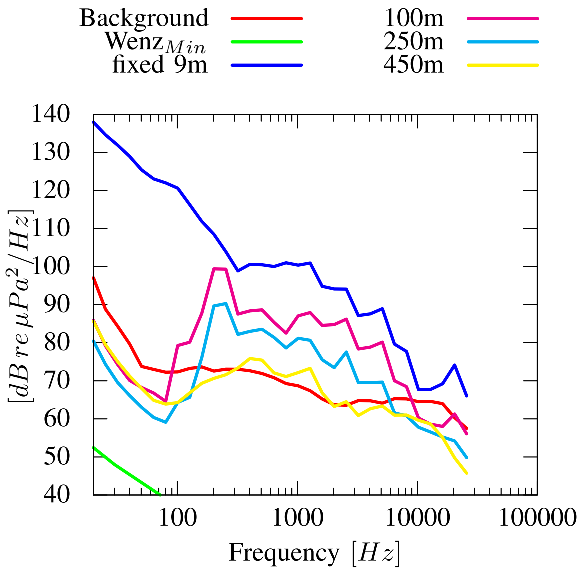

Fig. 7. Power spectral density over frequency for ambient and turbine noise measured at a fixed location $9m$ from the turbine and floating tests at various distances.

from the turbine and fixed to the barge. The data from the test runs performed at 100 m, 250 m and 450 m distance from the turbine are all similar in shape but lower in level, as observed sound levels typically reduce with distance from the source.

Floating measurements in 100 m and 250 m distance and the fixed measurement all show elevated noise levels between 300 kHz and almost 10 kHz compared to the ambient noise. The measurement taken at a distance of 450 m is overall at levels close to the 20 min background noise, but, similar to all other measurements performed when the turbine was running, shows characteristic peaks at the same frequencies, while background data results in a smooth line. These peaks are consistent with the tones observed in the spectrograms shown earlier.

The highest turbine noise levels occur below 1 kHz in all tests. In that range the fixed test reveals sound levels of about 100 dB re μPa^2/Hz, which is about 30 dB more than the 20-minute ambient noise sample. The one-third octave spectral levels drop about 10 dB per 150 m in the range between 300 Hz to 10 kHz.

Sediment generated noise has been shown in other studies of tidal currents to be relevant in frequencies above 1 kHz for gravel beds [10]. Evidence from divers suggests that the sea floor at the test site and large areas of the Strangford Narrows consists of small boulder on bedrock.

All floating measurements, except the one at 450 m range, show a spike around 200 Hz , similar to the one observed in the 60 s ambient noise measurement shown in Figure 6. This spike may not be caused by turbine sound and since the spectra below 100 Hz are comparable to background noise levels, projection of these frequencies to source level estimates is not appropriate. Therefore, these frequencies are also excluded from the following plots.

Figure 5 shows a spectrogram highlighting the data that are averaged to form the noise curves for the 450, 250, and 150 metre ranges shown in Figures 7 and 8. The track followed by the buoy in each range are also shown in the map in Figure 1.

Figure 8 shows the previous data projected back to a standardized distance of 1 m from the turbine, resulting in broadband source level SL estimates. After the correction, all drifting measurements align fairly well, indicating broadband source levels of 120 dB re 1 μPa^2/Hz @ 1m around 300 Hz, decreasing slightly to 100 dB re μPa^2/Hz @ 1m at 10 kHz.

It should be reiterated that the values shown in Figure 8 are projected levels at 1 metre from the turbine, and the actual signal level depends on range from the source, as shown in Figure 7.

V. Conclusions

This paper presented results from an underwater noise measurement campaign of a full scale tidal turbine. It was shown that fixing the hydrophone relative to the flow introduces low frequency noises. Allowing the hydrophone to drift with the current significantly reduces the flow noise, but requires considerable effort.

Noise characteristics of a turbine vary due to mode of operation. Constant running, free spinning and braking can readily be identified for the SCHOTTEL SIT turbine.

Considering the environmental background noise, third-octave spectral levels indicate that turbine sound is relevant from 100 Hz.

Floating measurements require correction for signal loss due to varying range. A simple TL model appeared sufficient in

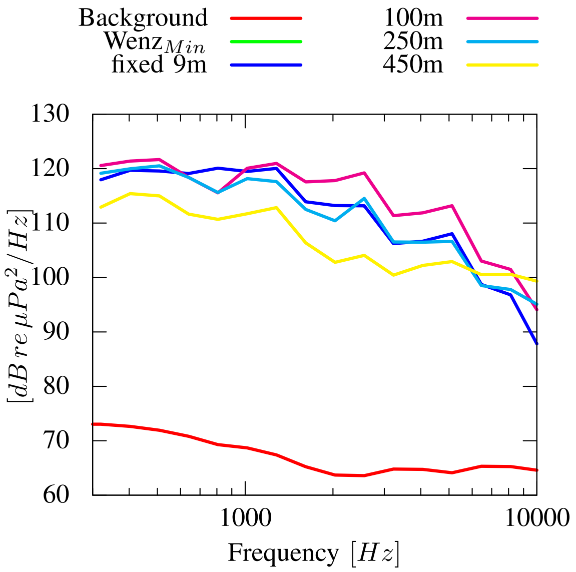

Fig. 8. Third-octave spectral levels for turbine noise adjusted to a standardized distance of $1m$ from the source, compared to the 20-minute ambient noise sample.

this case because corrected results for different ranges agree well.

Overall sound levels of the SCHOTTEL SIT turbine are on the same order as natural and other anthropogenic background noise measured at the test site. However, further analysis is required to determine the range of ambient noise conditions experienced at the test site.

During these tests, the current speed was estimated at approximately 1-2 m/s. However, higher current speeds occur at the test site, and the turbine is expected to operate in higher flow conditions. Therefore acoustic measurements in higher flow conditions are required to understand the full range of acoustic signal levels emitted by the turbine.

References

[1] G. Cada, J. Ahlgrimm, M. Bahleda, T. Bigford, S. D. Stavrakas, D. Hall, R. Moursund, and M. Sale, "Potential impacts of hydrokinetic and wave energy conversion technologies on aquatic environments," *Fisheries*, vol. 32, no. 4, pp. 174–181, 2007. [Online]. Available: http://dx.doi.org/10.1577/1548-8446(2007)32[174:PIOHAW]2.0.CO;2

[2] B. Polagye, B. V. Cleve, A. Copping, and K. Kirkendall, Eds., *Environmental Effects of Tidal Energy Development*. U.S. Dept. Commerce, NOAA Tech. Memo. NMFS F/SPO-116, March 2010.

[3] R. A. Kastelein, S. van der Heul, W. C. Verboom, N. Jennings, J. van der Veen, and D. de Haan, "Startle response of captive north sea fish species to underwater tones between 0.1 and 64khz," *Marine Environmental Research*, vol. 65, no. 5, pp. 369 – 377, 2008.

[4] W. T. Ellison, B. L. Southall, C. W. Clark, and A. S. Frankel, "A new context-based approach to assess marine mammal behavioral responses to anthropogenic sounds," *Conservation Biology*, vol. 26, no. 1, pp. 21–28, 2012. [Online]. Available: http://dx.doi.org/10.1111/j.1523-1739.2011.01803.x

[5] M. K. Pine, A. G. Jeffs, and C. A. Radford, "Turbine sound may influence the metamorphosis behaviour of estuarine crab megalopae," *PLoS ONE*, vol. 7, no. 12, p. e51790, 12 2012. [Online]. Available: http://dx.doi.org/10.1371%2Fjournal.pone.0051790

[6] The Crown Estate, "Review of current knowledge of underwater noise emissions from wave and tidal stream energy devices," August 2013.

[7] N. D. Merchant, E. Pirotta, T. R. Barton, and P. M. Thompson, "Monitoring ship noise to assess the impact of coastal developments on marine mammals," *Marine Pollution Bulletin*, vol. 78, no. 12, pp. 85 – 95, 2014. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S0025326X13006802

[8] H. Bailey, B. Senior, D. Simmons, J. Rusin, G. Picken, and P. M. Thompson, "Assessing underwater noise levels during pile-driving at an offshore windfarm and its potential effects on marine mammals," *Marine Pollution Bulletin*, vol. 60, no. 6, pp. 888 – 897, 2010. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S0025326X10000044

[9] P. Thorne, "Laboratory and marine measurements on the acoustic detection of sediment transport." *Journal of the Acoustical Society of America*, vol. 80, no. 3 , Sep. 1986, p.899-910., 1986, cited By 15. [Online]. Available: http://www.scopus.com/inward/record.url?eid=2-s2.0-0022547156&partnerID=40&md5=eb14e7a6b63a0520140b95adf74516ec

[10] C. Bassett, J. Thomson, and B. Polagye, "Sediment-generated noise and bed stress in a tidal channel," *Journal of Geophysical Research: Oceans*, vol. 118, no. 4, pp. 2249–2265, 2013, cited By 4. [Online]. Available: http://www.scopus.com/inward/record.url?eid=2-s2.0-84878028623&partnerID=40&md5=875d7f5f966e8402fece098bbbb5d342

[11] M. Strasberg, "Nonacoustic noise interference in measurements of infrasonic ambient noise," *The Journal of the Acoustical Society of America*, vol. 66, no. 5, pp. 1487–1493, 1979. [Online]. Available: http://scitation.aip.org/content/asa/journal/jasa/66/5/10.1121/1.383543

[12] C. Bassett, J. Thomson, P. H. Dahl, and B. Polagye, "Flow-noise and turbulence in two tidal channels," *The Journal of the Acoustical Society of America*, vol. 135, no. 4, pp. 1764–1774, 2014. [Online]. Available: http://scitation.aip.org/content/asa/journal/jasa/135/4/10.1121/1.4867360

[13] P. Jeffcoate, R. Starzmann, B. Elsaesser, S. Scholl, and S. Bischoff, "Field measurements of a full scale tidal turbine," *International Journal of Marine Energy*, no. 0, pp. –, 2015. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S221416691500017X

[14] W. Richardson, J. Charles Greene, C. Malme, and D. Thomson, *Marine Mammals and Noise*, 1st ed. Academic Press, 1995.
[15] *Underwater Noise Measurement Good Practice Guide No. 133*, National Physical Laboratory, 2014, crown Copyright.
[16] G. M. Wenz, "Acoustic ambient noise in the ocean: Spectra and sources," *The Journal of the Acoustical Society of America*, vol. 34, no. 12, pp. 1936–1956, 1962. [Online]. Available: http://scitation.aip.org/content/asa/journal/jasa/34/12/10.1121/1.1909155