Acoustic Characterization of a Hydrokinetic Turbine

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***Abstract*— This study describes the sound produced by a hydrokinetic turbine operating in a riverine environment near Iguigig, AK (USA). Drifting spar buoys equipped with hydrophones and GPS loggers were used to characterize temporal and spatial variability in turbine sound over a range of turbine operating conditions. Because of the quasi-stationary nature of river flows, multiple replicates could be obtained under steady-state operation. The sound from this turbine consists primarily of tones (ascribed to the generator) and broadband emissions (ascribed to blade vibration). The frequency of the tones varies in proportion to the turbine rotation rate. At the closest point of approach, for an optimally operating turbine, one-third octave levels are elevated by up to 40 dB relative to braked conditions. Broadband spatial patterns suggest relatively limited sound directivity. This study highlights the benefits of using Lagrangian drifters to characterize turbine sound (e.g., flow noise mitigation, spatially-resolved acoustic fields) and challenges (e.g., positional accuracy, self-noise contamination). Further analysis is required to interpret spatial variability in the context of acoustic propagation in riverine environments.**

***Keywords*— Acoustics, Underwater Noise, Hydrokinetic Turbine, Hydrophone, Drifter**

I. Introduction

The underwater noise generated by hydrokinetic (river, ocean, and tidal current) turbines has the potential to affect fish and marine mammals [1,2]. While these sounds are not expected to cause auditory injury, they may lead to avoidance, attraction, or undesirable behavioural modification [3]. However, measurements of sound from full-scale turbines are rare [3] and interpretation may be challenging. For example, both turbine sound and ambient noise are likely to have spatial and temporal variability, neither of which is likely to be known *a priori* (i.e., the turbine is an "uncooperative" source of sound) [4].

Acoustic measurements of riverine hydrokinetic turbines afford a number of unique opportunities. Mean river velocities are often statistically stationary over several days, allowing multiple experimental replicates [5], unlike tidal environments where mean currents are only stationary for a few minutes. Further, rivers are generally shallow in comparison to tidal or ocean environments, allowing instrumentation to be deployed in close proximity to a turbine (e.g., sampling both the acoustic near-field and far-field). However, these are balanced against unique challenges. First, unlike ocean soundscapes, ambient noise in rivers has received relatively little attention [6]. Second, no "slack" periods exist to deploy and recover instrumentation. Rather, all instrumentation must be deployed and recovered in areas with strong currents. Third, the characteristic width and length of rivers are such that sound propagation is unlikely to be captured by simple transmission loss models.

This study presents acoustic measurements in the vicinity of a community-scale river current turbine intended to serve a rural village in Alaska (USA). The instrumentation and analysis used characterize sound are described and an assessment presented of the turbine's acoustic characteristics for a selected set of operating conditions. The effectiveness of and challenges to using drifting acoustic measurements for sound characterization from hydrokinetic turbines are discussed.

II. Methods

A. Turbine Description

The Ocean Renewable Power Company (ORPC) RivGen turbine is a cross-flow helical turbine designed to provide community-scale power (10^4 W). The RivGen turbine consists of two 4.1 m long rotors situated symmetrically about a 2.8 m wide central gap containing a direct-drive generator (Fig. 1). The turbine is supported by a pontoon frame that can be deployed and recovered without specialized vessels. For this deployment, the turbine was connected via an underwater cable to a resistive load bank at a shore station. During acoustic characterization, an operator maintained a specific load setting for a period of several minutes, during which time the voltage and current across the load bank were recorded at 1 Hz. From voltage, turbine angular velocity (ω) was determined via $\omega = V/k$ where k is a known empirical coefficient that is specific to the generator. Turbine data were time-stamped by an internet-synchronized time server.

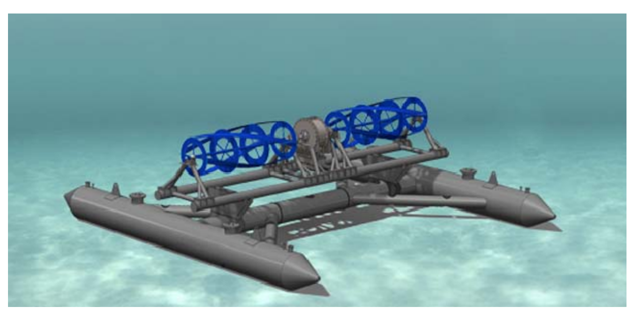

Fig. 1. Ocean Renewable Power Company RivGen turbine (courtesy of Ocean Renewable Power Company)

B. Site Description

The turbine was deployed in August 2014 on the Kvichak River near the village of Iguigig, AK (USA), as shown in Fig. 2. Iguigig currently generates the majority of its power with diesel-fired generators. This results in a high electricity cost, making Iguigig, and villages like it, potentially attractive entry points for commercial hydrokinetic power generation. The Kvichak drains from Iliamna Lake, which acts as a stilling basin and keeps the head of the river generally free of debris and turbidity.

Fig. 2. Satellite photography of Iguigig, AK (USA) showing the turbine deployment site and coordinate system in the turbine reference frame.

At the turbine deployment site, the river is approximately 5 m deep and 150 m wide. The turbine hub-height is approximately 2.5 m below the surface. Water currents exceed 2 m/s at and around the turbine [5]. Visual observations indicate that the river bed is predominantly small cobbles (less than 10 cm diameter), overlying gravel and coarse sand. Based on the shoreline composition, the cobble layer likely overlays fine, unconsolidated sediments.

C. Acoustic Measurements

In fast-moving currents, fixed acoustic recorders are compromised by "flow noise", the non-propagating pressure associated with interaction of turbulent flow with a hydrophone element. Flow noise in currents of 2 m/s can mask propagating sound at frequencies approaching 1000 Hz [7]. Drifting measurements can reduce the relative velocity between the hydrophone and dominant current, limiting flow noise contamination to frequencies less than 100 Hz. However, drifting measurements convolve temporal and spatial patterns and drifting platforms may generate significant "self noise" (e.g., splashing water, cable strum) [8].

For this study, turbine sound was characterized using autonomous drifting spar buoys (SWIFTs) [9]. Each SWIFT was equipped with a recording hydrophone (Loggerhead Instruments DSG) at the base of the spar (hydrophone element submerged to a depth of 1 m). A mast above the waterline housed a recording GPS (QStarz BT-Q1000eX), and meteorological station (Airmar PB200) connected to an Arduino-based data logger. GPS and meteorological station time stamps were provided by satellite. The hydrophones recorded sound files in a .wav format and were synchronized with an internet time server. The hydrophone sampling rate was 50 kHz and GPS/meteorological station update rate varied from 0.5 – 10 Hz due to adjustments made in the field.

For each measurement sequence, the turbine was allowed to reach steady state rotation with a constant resistive load on the shore cable and then up to three SWIFT drifters released from a small boat. Deployment vessel noise was minimized by manoeuvring away from the SWIFTs after deployment and then free-drifting at a separation distance of at least 100 m. From August 15th – August 24th, 178 drifts were conducted. The majority of these occurred with the turbine in one of three operating states: braked (i.e., no rotation, short-circuit load on the generator of ~0 Ω), free-wheel (i.e., maximum rotation rate, open-circuit load on the generator of ~∞ Ω), and at a resistive load that maximized turbine power generation (i.e., an optimal operating condition ~5.4 Ω). Additional measurements were carried out at ten other load settings that spanned the turbine's characteristic performance space. One of these (~9.4 Ω) is presented here to contrast sound produced with the turbine at maximum efficiency with sound produced at non-optimal efficiency (i.e., operating at a higher rotation rate to "shed power" above rated conditions).

Hydrophones were calibrated following deployment using two methods. A single, low-frequency (250 Hz) calibration was performed with a pistonphone (G.R.A.S. 42AA) with each hydrophone attached to the same analog-digital converter as during deployment in the field. Hydrophone sensitivities were within 1 dB of manufacturer supplied calibration information. Each hydrophone was also calibrated over a range of higher frequencies (3-20 kHz) using Navy reference transducers (F41 and F42) at the University of Washington Applied Physics Laboratory's Acoustic Test Facility. For these calibrations, the hydrophones were installed within the lower hull of a SWIFT spar and equipped with a perforated PVC shield, mirroring their deployment configuration in the field. At the low end of the calibration frequencies, sensitivities were similar to pistonphone calibration results. However, above 5 kHz, the PVC shields significantly affected received sound, with up to 10 dB variation depending on shield orientation relative to the reference transducer. Consequently, all analysis presented here is restricted to frequencies below 1 kHz.

D. Acoustic Data Processing

Acoustic data were separated into sequences of 2^{16} points (1.3 s intervals), each with 90% overlap, then detrended (linear mean), windowed to 2^{13} points with 50% overlap, weighted by a Hamming filter, and analysed using a fast Fourier transform. Recorded voltage was converted to pressure using a frequency-independent hydrophone sensitivity (from pistonphone calibration) and a frequency-dependent analog-digital converter gain (provided by the hydrophone manufacturer). The resulting, merged narrowband spectra had fifteen degrees of freedom and a bandwidth of ~6 Hz. Narrowband spectra were subsequently integrated into one-third octave band levels [10]. Acoustic data were georeferenced by comparing acoustic time stamps to GPS time stamps and position. Geo-referenced data were then rotated into a coordinate frame centred on the turbine in which the +x direction was perpendicular to and downstream of the turbine, while the +y direction was parallel to the turbine and oriented towards the eastern shore (Fig. 2). All analysis and data manipulation were performed in Matlab (R2014b).

E. Acoustic Data Quality Assurance

Not all acoustic data collected over the course of the study was suitable for characterizing turbine sound for one of three reasons.

First, the Kvichak River in the vicinity of Iguigig is a sport-fishing destination and, at times during data collection, small boats would motor past the turbine, masking its sound. Portions of acoustic spectra containing vessel noise were manually identified and quarantined from further analysis.

Second, drifter self-noise could also mask turbine sound. Self-noise originated primarily from vertical bobbing across the small hydraulic drop created by the turbine (leading to self-noise from splashing at frequencies around 1 kHz and flow noise at frequencies < 100 Hz). Significant self-noise associated with flapping of a pennant flag was also present in a few drifts during windy conditions. In a relatively few cases, flow noise from relative horizontal motion between the hydrophone and water currents contaminated the spectra at frequencies up to 200 Hz. These artefacts were manually identified and quarantined from further analysis.

Third, GPS position information for the drifters was, in a number of cases, found to be substantially worse than 5 m. Through post-hoc analysis, these inaccuracies (i.e., "dilution of precision") were determined to result from relatively low satellite coverage at this latitude and the reduction in view factor associated the relatively steep bank on the west side of the river. For those drifts in which both the GPS logger and met station were operating, the relative difference in reported location was calculated and drifts with an average variation > 6 m were quarantined from further analysis. Second, for drifts passing directly over the turbine, maximum sound levels were found to correspond to the closest point of approach. Drifts were quarantined in cases where the variation between the position at which peak sound levels were observed and the actual turbine position was > 6 m (predominantly in cases where only a single GPS was logging on a drifter).

Drift data for the four primary operating conditions are summarized in Table I. The turbine power and rotation rate ranges are for the average value across all drifts, not the range of variation observed within a particular drift, which is higher due to turbulence.

F. Characteristics of Turbine Sound

Drifts that passed directly over the turbine within the margin of GPS accuracy (i.e., at $x = 0$ m, -10 m $\leq y \leq$10 m) were aggregated for each operating case to evaluate the variation in acoustic spectra between operating conditions. This was done at two along-channel positions: the closest point of approach ($x = 0$ m) and a position downstream of the turbine ($x = +50$ m). Given the frequencies of interest (10's of Hz to 1000 Hz), the closest point of approach places the hydrophone well within the acoustic near-field and these measurements cannot be interpreted as a "source level".

TABLE I
ACOUSTIC DRIFT SUMMARY

Operating Condition	Drifts (Viable/Total)	Turbine Power (kW)	Turbine Rotation (rad/s)
Braked (0 Ω)	21/38 (55%)	~0 kW	~0
Optimal (5.4 Ω)	22/39 (56%)	12.1±0.3	4.88±0.12
Power Shedding (9.4 Ω)	4/6 (67%)	10.0±0.1	5.79±0.03
Free-wheel (∞ Ω)	12/16 (75%)	~0 kW	8.32±0.32

To evaluate spatial variations in sound a "broadband" (50 Hz – 1000 Hz) sound pressure level (SPL) was adopted. The range of frequencies correspond to those high enough to be unaffected by flow noise and low enough to be unaffected by flow shield attenuation. As discussed in Section III.B, during turbine operation, elevated sound is observed over this entire range of frequencies relative to the braked (non-rotating) case. Geo-referenced SPL were gridded at 5 m resolution for the braked, optimal, and free-wheel operating states. These were then averaged in linear pressure space [11] to obtain a representative value for each grid cell. An insufficient number of drifts were conducted to evaluate spatial patterns for the power-shedding case.

III. RESULTS

A. Variation in Turbine Sound with Operating State

Representative acoustic information from drifts associated with four operating conditions are shown in Fig. . Narrowband spectra are shown as a function of along-channel distance relative to the turbine (i.e., $x < 0$ m upstream, $x > 0$ m downstream). Because river currents are non-uniform [5], the spatial extent varies for 1.3 s interval used for acoustic analysis. Several features are notable. When the turbine is rotating, an energetic tone and higher harmonics are present. At optimal operation, the fundamental tone oscillates about 100 Hz with the second and fourth harmonic also clearer apparent. When rotation rate increases, as for power shedding or free-wheel conditions, the fundamental frequency and harmonics also increase. In addition to these tones, at < 10 m distance from the turbine, generally elevated sound is observed at all frequencies of interest. Sound intensity is notably lower at all locations when the turbine is braked, but there is still a generalized increase in intensity around the turbine relative to locations upstream and downstream. Regions quarantined due to self –noise are indicated in Fig. 3 by dashed red boxes. The distinction between self-noise and turbine sound is not always obvious, particularly in close proximity to the turbine, and the quarantining approach imperfect. Nonetheless, it is effective at removing the majority of self-noise from the acoustic spectra.

Figures 4-5 show the details of the spectra for each of the four operating conditions at the closet point of approach and a location 50 m downstream, respectively. The solid lines denote the average sound level at a specific operating state (linear average in pressure space), while the shaded region denotes the minimum and maximum intensity of sound observed for each frequency band over all drifts.

At the closest point of approach, all operating states elevate sound levels relative to the quasi-ambient condition represented by the braked turbine. The "quasi" caveat is appropriate because, even while braked, the marker floats moored to the turbine and blade vibration produce propagating sound that would otherwise not be present in the ambient soundscape (as evidenced by the general elevation in sound level for the braked turbine in Fig. 3). Considering the narrowband spectra from the point of closest approach, a fundamental tone is most apparent in the optimal and power-shedding cases at 100 and 120 Hz, respectively. The second and fourth harmonics of this tone are also visible for the optimal case, albeit over a broader range of frequencies. This would be expected since the frequency of this tone is closely correlated with variations in turbine rotation rate due to turbulence over time scales of 1 s [12]. There is also some indication from the narrowband spectra that the level of the tone is correlated with turbine power output (i.e., the level of the tone increases with turbine power output). However, a more in-depth analysis is required to investigate this hypothesis.

For the optimally operated turbine, in the 1/3 octave band centred at 100 Hz, the increase is particularly notable, exceeding braked levels by 40 dB. At higher frequencies, the difference drops to approximately 10 dB, though is still outside of the range of uncertainty in the measurements. At a downstream distance of 50 m, the difference between operating and braked conditions narrows, but is still pronounced, particularly for the tonal contributions.

B. *Spatial Extent of Turbine Sound*

Figure 6 shows the spatial extent of broadband sound pressure level (50 – 1000 Hz) around the turbine for optimal, braked, and free-wheel operating states. Overall, the spatial patterns are in close agreement with the trends observed for narrowband and one-third octave spectra, with the highest intensity sound associated with the optimal operating condition and lower intensity sound with the braked condition. As expected, sound levels are most intense at the turbine and decrease with distance. The spatial patterns in broadband levels show limited directivity despite variations in river bathymetry (east of the thalweg where the turbine operated, river depth shallowed from 5 m to < 2 m).

IV. Discussion

As discussed by [12], there are several potential sources of turbine sound that could contribute to the observed acoustic signature. The tonal contribution could be related to either blade "singing" [13] or the direct-drive generator [14]. However, "singing" is unlikely for blades with this design (relatively high thickness to chord ratio, supported at four points along the span) and discussions with turbine company staff suggest that the tonal frequency is consistent with the generator construction and rotation rate. The interaction of turbulent flow with the leading and trailing edges of the blades may also produce broader-band noise with dipole characteristics by locally exciting the blades, which would be consistent with the generally elevated spectra at non-tonal frequencies. While it is possible for turbines to cavitate at sufficiently high rotation rate (an efficient, monopole sound source), cavitation was not visually observed in the field. Turbulence shed by the blades is also a potential sound source, but has quadrapole characteristics and would be an inefficient sound source.

Finally, as with any assessment of an environmental stressor, it is important to remember that turbine deployment locations are rarely acoustically pristine. Iguigig is no exception to this. Small boat traffic, which has a similar mix of tonal and broadband noise characteristics to turbine sound, is persistent on the river during guided fishing season. Consequently, any evaluation of the effect turbine sound may have on marine animals in this location would need to be evaluated against that baseline to develop a probabilistic estimate for exposure and response.

V. Conclusions

Drifting hydrophones are used to characterize the sound produced by a river hydrokinetic turbine. The method is effective at characterizing variations in turbine sound as a function of operating state and spatial position on the river. Results suggest that this turbine locally elevates sound, particularly at rotation-rate dependent tonal frequencies associated with its generator. Further work is required to evaluate narrowband spatial patterns, the effectiveness of propagation models to estimate a source level that can be extrapolated to other locations of interest, and any environmental implications of this sound on the ecology of the river.

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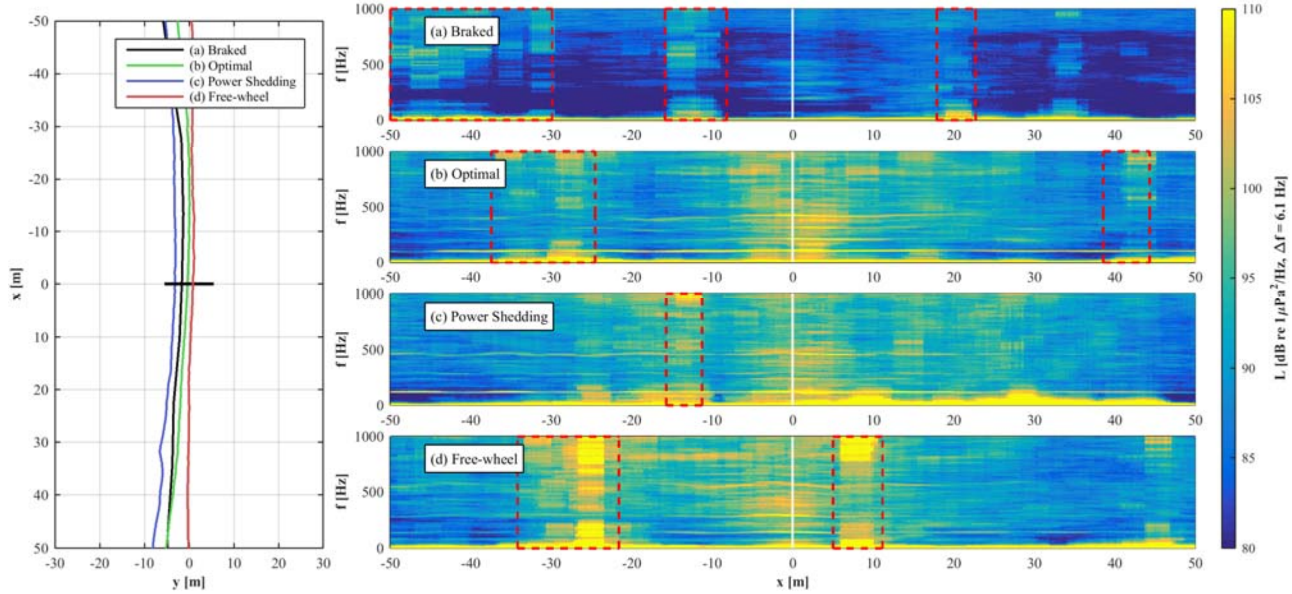

Fig. 3. Representative spectrograms for four different turbine operating states. (left) Drifter trajectories for each operating state. (right) Pressure spectra density for each operating state. Dashed red boxes denote data quarantined due to non-turbine noise contamination. White line centred on turbine (x = 0 m). Colour scale saturates at 80 and 120 dB re 1μPa^2/Hz.

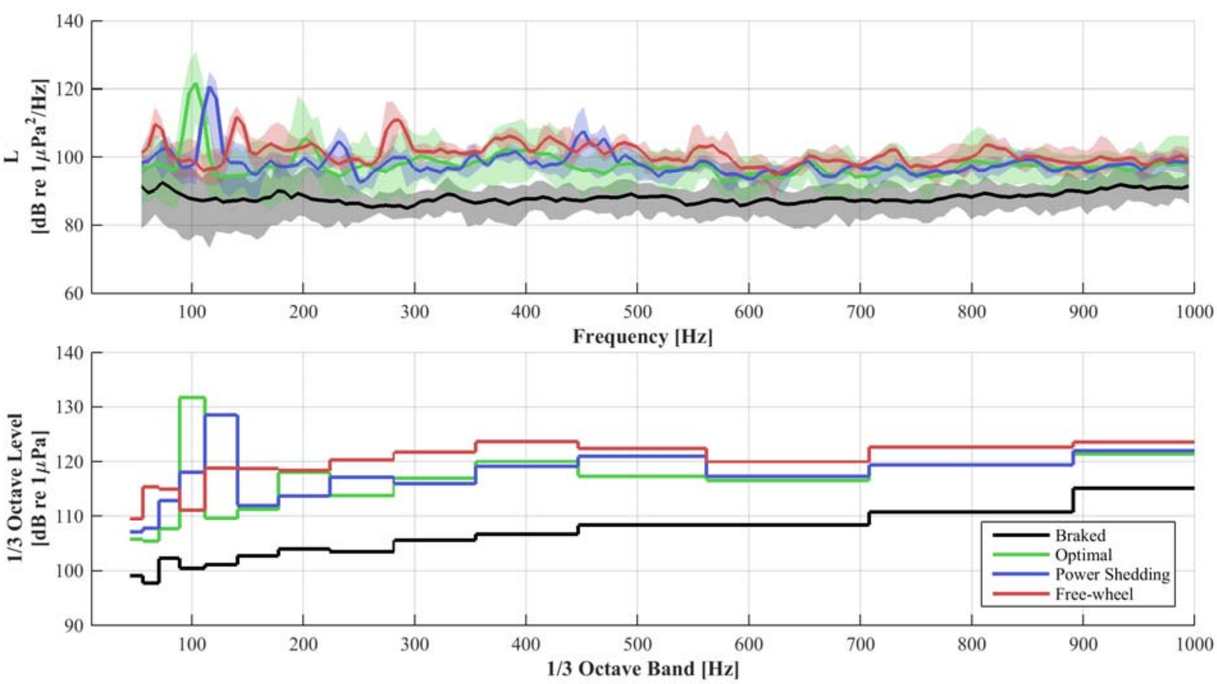

Fig. 4. Acoustic spectra at closest point of approach to turbine for four different operating states. (top) Narrowband spectra. Thick lines denote averages, shading denotes maximum and minimum observations. (bottom) Average one-third octave levels.

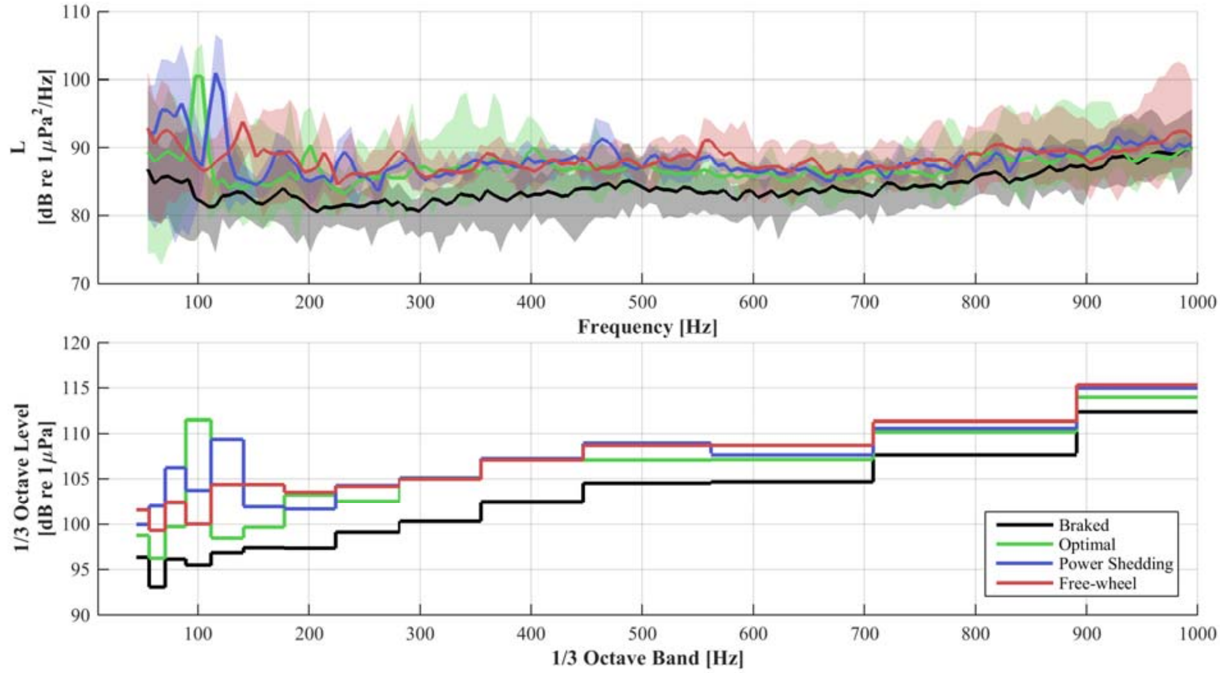

Fig. 5. Acoustic spectra 50 m downstream of turbine for four different operating states. (top) Narrowband spectra. Thick lines denote averages, shading denotes maximum and minimum observations. (bottom) Average one-third octave levels.

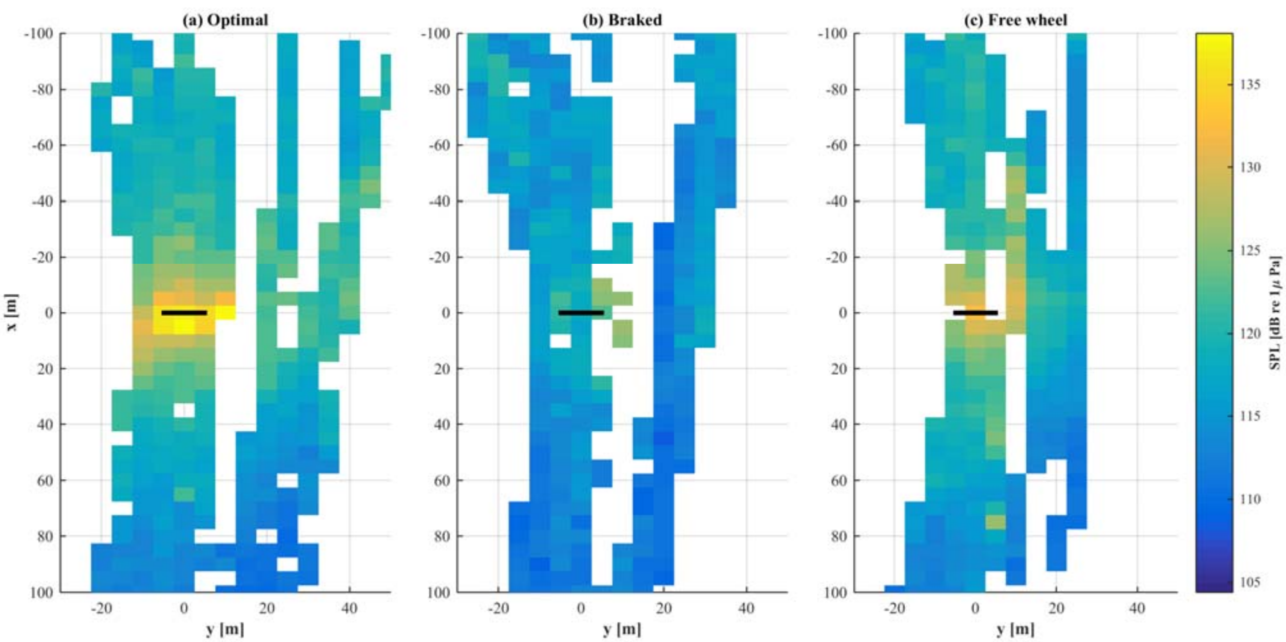

Fig. 6. Spatially-resolved broadband sound pressure levels (50-1000 Hz) for (a) optimal, (b), braked, and (c) free-wheel operating states. Solid black line denotes location and extent of the turbine.

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