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Noise characterization of a sub-sea tidal kite

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Abstract: This paper presents the first noise measurements of a quarter-scale subsea tidal kite (anchored to the sea floor by a tether and flying in a figure-of-eight configuration in the water column) operating in field conditions. Challenges in the measurement and post-processing of the data are detailed. Results are presented for three operating conditions of the kite: 1) varying turbine rotations per minute (RPM), 2) varying kite speed and 3) a twisted tether. Turbine RPM was identified as the main parameter influencing noise emissions.

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1. Introduction

Some concern has been raised about the potential environmental impacts of tidal energy installations (Donovan et al.; Hastie et al., 2018; Hawkins et al., 2017; Sparling et al., 2018; Wilson et al., 2013), including the emission of underwater sound arising from operating turbines (Hafla et al., 2018; Lossent et al., 2018). In-situ noise measurements are rare (Lossent et al., 2018; Polagye and Murphy, 2015; Schmitt et al., 2015), therefore, if we are to better understand the potential effect of such noise emissions on marine fauna, including mammals and fish, more work in this field is needed. It has been established that turbine noise needs to be assessed in the context of the ambient noise, particularly in high flow environments. For instance, a significant component of the turbine noise presented by (Schmitt et al., 2015) was not solely caused by the interaction of the flow with the turbine blade, but was also due to gearboxes and other parts of the device which are not in direct contact with the fluid. This is an important aspect to consider since fluid simulations (Lloyd et al., 2014) only focus on the noise associated with the turbine blades. Therefore, further field measurements in realistic operating conditions are required.

Here, we present field measurements of the noise emissions of a quarter-scale prototype of a unique tidal energy concept, a subsea tidal kite, located in Strangford Lough, Northern Ireland, Fig 1. The varying modes of operation for this type of technology pose some challenges in the measurement of noise emissions, which are explained in detail. This paper aims to present the first general characterization of the noise emissions of the subsea kite system.
2. The sub-sea kite

The subsea kite investigated in this paper is a quarter-scale prototype tidal energy device, developed by the company Minesto AB (Schmitt et al., 2017; Zambrano, 2016). The kite consists of a fixed wing with a wingspan of 3 m, which during the tests described here carried a nine bladed ducted turbine directly coupled to a generator in a nacelle at the center of the wing. The turbine is located at the front of the nacelle, facing the undisturbed inflow. Rudders and elevators at the end of the nacelle allow control of the kite’s flight path. A 27 m long tether is connected via a two point link to the left and right side of the wing and an adjustable strut connects to the rear of the nacelle. The kite follows a figure-of-eight shaped path as indicated in Fig. 2(a), accelerating to velocities of up to 10 times the ambient flow. By adjusting the length of the rear-strut, the angle of attack of the wing can be controlled. Kite speed is thus not directly dependent on current speed, settings during the tests resulted in two ranges: 2.5 m s$^{-1}$ to 4 m s$^{-1}$ and 4.0 m s$^{-1}$ to 5.5 m s$^{-1}$. A typical figure-of-eight takes about 6 s to 8 s to complete. The flight path extends approximately 20 m across the flow direction, its mid-point is typically 7 m below the surface with the height of the figure-of-eight approximately 3 m (Lieber et al., 2017). Beside the kite speed, the control system also allows to vary the turbine revolutions within physically feasible bounds and the kite can be flown manually. By flying full circles it was thus possible to twist the tether, changing its shape and stiffness.

3. Field measurements
Acoustic measurements were collected on 28th July 2016 during fair weather conditions (World Meteorological Organization sea-state 0-1) using a ST300HF autonomous underwater acoustic recorder (Ocean Instruments Ltd, New Zealand). The ST300HF recorder consists of a calibrated omnidirectional hydrophone (sensitivity $-203 \text{ dB re } V/\mu \text{Pa}$, range $0.02 \text{ kHz to } 150 \text{ kHz}$), pre-amplifier and digital recorder (set at high gain, 16-bit, $288 \text{ kHz}$ sampling rate). The recorder was set to record continuously and was manually operated using the remote control. Electronic calibration checks were undertaken at the start of each recording through the recorder’s self-calibration function. The recorder was secured $2 \text{ m}$ below the sea surface using a free-floating buoy. A maximum depth of $2 \text{ m}$ was allowed to ensure a safe clearance above the kite as it passed through the shallowest apex of its flight path. An underwater camera (GoPro Hero3™) was also attached to later verify that the unit drifted over the top of the kite (Fig 2). The ST300HF was deployed off the research vessel, after which the vessel moved $50 \text{ m}$ transverse to the flow direction away from the deployment location before the engine was switched off. A GPS waypoint was taken at both, the deployment and retrieval locations, using a Garmin®GPSMAP62, Fig 1. The ST300HF was deployed $300 \text{ m}$ upstream of the operating kite and retrieved after drifting $300 \text{ m}$ past the test site. Current speed was measured using a Teledyne RDI WH600 acoustic Doppler current profiler (ADCP) $50 \text{ m}$ east of the foundation. Typical speeds during the testing were $1 \text{ m s}^{-1}$. Additional current data from a vessel-mounted ADCP survey across the test site was obtained from Minesto. All measurements were performed during a single ebb tidal cycle, with the flow in south easterly direction. After retrieving, the ST300HF was returned to the start of the transect.
line and the process was repeated until 24 runs were completed. Operational data from the kite, including turbine revolutions (RPM) and relative kite speed (ms\(^{-1}\)), were continuously recorded through the kite’s control system and provided by Minesto AB.

4. Analysis

First, data from the ST300HF recorder’s built-in accelerometer were assessed to confirm that vertical movement had been minimal. Power spectral densities, waveforms and sound pressure levels were also analyzed to ensure the absence of any extraneous noise contamination. Kite speed and orientation to the incoming flow varies at each point during a figure-of-eight and each figure-of-eight will be influenced by variations in the ambient flow field. We thus use data averaged over an entire figure-of-eight as a representative example and since we are mostly interested in the main drivers and characteristics of the noise signature do not to correct for range. However, considering the large swept area and depth variation over one figure-of-eight, the horizontal displacement of the hydrophone is expected to have little effect for a distance of about 15 m up or downstream of the kite. Video from the GoPro camera was used to find the point in time when the hydrophone was just above the kite Fig 2b and about 15 s, or not more than 15 m considering the flow speed from the ADCP, before and after passage were used. Fig 1 shows tracks from all runs as straight lines bounded by the start/end positions. All runs considered in the analysis passed within 10 m lateral distance of the kite midpoint and are shown in red in Fig 2.

Spectrograms over a time span of 15 s before and 15 s after the crossing were then generated using Raven Pro 1.5. with a 1 s Hann window, 50% overlap, 0.68 s hop size
Fig. 1. Overview of the test area in the Strangford Narrows, Northern Ireland. Lines indicate the straight-line assumed tracks of the floating hydrophone (to scale), where dots indicate the hydrophone’s start/end positions. Tracks used in analysis are shown in bold. Shaded black arrows indicate flow direction as obtained from a vessel-mounted ADCP survey. The insert in a), shaded in the overview, provides a magnified view of the tracks in the vicinity of the kite. The area swept by the tether during operation is marked by two black lines, connected by a dashed line indicating the flight path of the kite.
and 1.4 Hz 3 dB filter bandwidth. Each run yielded up to 4 samples of complete figures of
eight. To compare significant changes in operating conditions, defined as a range of kite
velocity (2.5 m s\(^{-1}\) to 4 m s\(^{-1}\) and 4.0 m s\(^{-1}\) to 5.0 m s\(^{-1}\)), turbine RPM (300-500 rpm and
500-700rpm) and tether twist (0 and 5), samples were then grouped in sets of 5. For each set
of comparable samples mean 1/3 octave bands and standard deviations were calculated using
custom MATLAB code. Center and peak frequencies, the 90 % bandwidth and the overall
bandwidth were also evaluated. A T-test was performed on those values using SigmaPlot 12
and changes were deemed significant if the P value was below 0.05.

5. Results

Fig 3 a, b and c present spectrograms for three different cases. The first example (Fig 3 a)
shows the sound levels for the kite operating between 500 and 700 rpm. High broad band
sound levels are observed in the range from 0.2 kHz to 0.7 kHz. Only between 11 s to 14 s,
17 Hz to 19 Hz and again for 22 s to 25 s high energy tones can be observed at 0.5 Hz. Also,
a repetitive variation of sound levels and range of affected frequencies can be observed every
seven seconds. As a comparison, the 2nd spectrogram (Fig 3 b) presents a case where the
kite operates at the same kite speed but turbine revolutions are reduced to a range from 300
to 500 RPM. The spectrogram displays a reduction in overall sound levels. Neither clear
tones nor a regular variation of about 7 s, as was seen in the previous case, was observed.
The third spectrogram (Fig 3 c) presents a case where the kite is operating again at a turbine
RPM between 500 and 700, but the kite speed has now increased and ranges from 4 m s\(^{-1}\)
to 5.5 m s\(^{-1}\). Here, the emitted noise levels occurred over a wider range, 0.05 kHz to 0.9 kHz,
Fig. 2. Schematic illustration of the tidal kite (elliptic shape), tether (continuous straight line) and flightpath (dashed line). The two characteristic regions, the midpoint (MP) and apex, are shaded (a). The current acts in x direction while z is pointing upwards. Images captured from the video of the kite as the GoPro camera passed over the kite during a transect (b).
Fig. 3. Spectrograms for three different configuration changes. Turbine RPM (a), kite speed (b) and tether twist (c).

as compared to the first case. For all three cases, no overall trend over time or major change at 15 s, when the hydrophone drifted just above the kite, is visible.

To provide a more quantitative evaluation of the sound levels, Fig 4 presents 1/3 octave band plots and standard deviation over frequency for different control settings of the turbine. Fig 4(a) shows results for a reduction of turbine revolutions from a range of 500 to 700 RPM, shown in blue, to 300 to 500 RPM shown in red. The overall shape of the spectrum remains similar, but the reduction in turbine RPM reduces the noise levels. The highest levels around 300 Hz reduce from 105 dB re $\mu$Pa to approximately 95 dB re $\mu$Pa.

In the higher frequency range above 100 Hz the levels remain about 10 dB below the higher RPM case. Interestingly the standard deviation for the high RPM case is considerably higher Fig. 4d, reaching 7 dB. Changes are also observed for the peak frequency which shifts from 392 Hz to 537 Hz and the 90 % bandwidth, which drops from 13 463 Hz to 2791 Hz.
Fig. 4. Mean 1/3 octave band (a-c) and standard deviation (d-f) over frequency for three different configuration changes. Turbine RPM (a,d), kite speed (b,e) and tether twist (c,f). SD = standard deviation.

Fig 4 (b) shows 1/3 octave bands for different kite speeds. The blue line represents the kite at 4 m s\(^{-1}\) to 5.5 m s\(^{-1}\) relative velocity compared to a kite experiencing 2.5 m s\(^{-1}\) to 4 m s\(^{-1}\) (red). For both kite speeds, the sound levels increase rapidly from approximately 70 dB at the lowest frequencies up to a peak of around 105 dB at 500 Hz. They then drop again to approximately 85 dB around 5000 Hz and stay almost constant before trailing off towards the higher frequency range. The highest standard deviation is observed around a frequency of 100 Hz for the case of 2.5 m s\(^{-1}\) to 4 m s\(^{-1}\) flow Fig. 4(e). Overall the standard deviation is within the range of the differences observed for the two cases. Changes in kite
speed increased the center frequency of the spectrum from 422 Hz to 568 Hz and the peak frequency shifted from 395 Hz to 537 Hz.

Fig 4(c,f) presents data for the standard configuration, that is no tether twist, compared to a case with five tether twists. The tether was twisted by manually flying the kite in full circles. Under normal operation, the tether is twisted and untwisted in each figure-of-eight. Twisting the tether is a simple way to investigate the effect of design changes on this part of the kite structure. Very little difference can be seen between the two 1/3 octave band representations. The main change is a sharp rise in noise levels for the zero twist case around 120Hz, resulting in levels 11 dB above the 5 twist configuration. The highest octave level was also reduced from 110 dB to 108 dB. The standard deviation, Fig. 4(f), shows a sharp increase up to 8 dB one 1/3 octave band below the steep rise in sound level for both configurations. Statistical analysis reveals that significant changes in center as well as peak frequencies and 90 % BW occur. Center and peak frequency both reduce with increasing tether twist, 467 Hz to 452 Hz, and from 530 Hz to 460 Hz, respectively. The 90 % BW increases from 1203 Hz to 5253 Hz.

6. Discussion

Measuring the sound emissions of a tidal kite is challenging, particularly due to the large volume of water across which the kite moves during operation and because the exact kite position is unknown at each time step. Usable data is limited to short traces obtained in close proximity to the kite from the runs that drifted directly over the kite as validated by the camera footage. For the chosen range of data, no clear trend of increasing or decreasing sound
levels while approaching or leaving the kite could be observed, validating the assumption that the samples used are comparable.

Earlier work on noise emissions from other turbines such as the horizontal axis tidal turbine described in (Schmitt et al., 2015) and (Lossent et al., 2018) clearly showed distinctive tones over several rotations, related to certain components like the gear box. Sound emissions from the kite did not exhibit clear tones at constant frequencies over significant times, noise emissions were instead much more broad band and variable in time.

By far the biggest variation in sound emissions of the kite was the observed changes in turbine revolution. There was more than a 12 dB variation between the highest energy octave band, with much higher levels across almost the entire frequency range. These results suggest that the turbine is clearly the main source of noise from the device. Changes in kite speed also result in clearly distinguishable changes in the 1/3 octave band plots but with only a 3 dB decrease of the peak SPL, the effect is minor compared to the RPM. Changes in kite speed or tether twists only changed the peak noise levels by less than 4 dB. The peak and center frequency showed significant changes. The drop in sound levels around 100 Hz when twisting the tether is somewhat counter-intuitive. It could have been expected that a better streamlined shape yields less noise. A possible explanation is that the ideal tether creates noise in a well defined narrow frequency band, shedding vortices at its edge similar to a hydrofoil. The twisted tether is a relatively blunt body and likely to have a more broadband signature which is difficult to detect against the background noise.

7. Conclusion
This paper presents the first measurement of the sound emissions of a sub-sea tidal kite. Some challenges in the measurements exist due to the variability and spatial extent of the kite position and the logistics involved in performing drifting measurements. Nevertheless, the limited number of runs and suitable data sets were sufficient to characterize the tidal kite’s noise signature and to identify the turbine as the main source. Kite speed and variation of the tether twist have less influence on overall sound levels than does turbine RPM, however significant changes to the noise emissions have been identified. The untwisted tether shows a peak in SPL around 100Hz which is missing in the twisted configuration.

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References and links


