

Wind turbines and bat mortality: Doppler shift profiles and ultrasonic bat-like pulse reflection from moving turbine blades

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Bat mortality resulting from actual or near-collision with operational wind turbine rotors is a phenomenon that is widespread but not well understood. Because bats rely on information contained in high-frequency echoes to determine the nature and movement of a target, it is important to consider how ultrasonic pulses similar to those used by bats for echolocation may be interacting with operational turbine rotor blades. By assessing the characteristics of reflected ultrasonic echoes, moving turbine blades operating under low wind speed conditions ($<6 \text{ m s}^{-1}$) were found to produce distinct Doppler shift profiles at different angles to the rotor. Frequency shifts of up to $\pm 700\text{--}800 \text{ Hz}$ were produced, which may not be perceptible by some bat species. Monte Carlo simulation of bat-like sampling by echolocation revealed that over 50 rotor echoes could be required by species such as *Pipistrellus pipistrellus* for accurate interpretation of blade movement, which may not be achieved in the bat's approach time-window. In summary, it was found that echoes returned from moving blades had features which could render them attractive to bats or which might make it difficult for the bat to accurately detect and locate blades in sufficient time to avoid a collision. © 2010 Acoustical Society of America. [DOI: 10.1121/1.3479540]

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I. INTRODUCTION

In recent years concern has been steadily mounting over the impact of wind turbine installations on wildlife, in particular flying wildlife such as birds and bats, which have been found dead (often in large numbers) at several wind plants and turbine installations around the U.S. and Europe (e.g., Howe *et al.*, 2002; Johnson *et al.*, 2002; Kerns and Kerlinger, 2004; Dürr and Bach, 2004). Wind power is a valuable low-carbon renewable energy source, and with many governments legislating for reduction in CO₂ emissions it is critically important to understand and mitigate such issues which could prove a potential obstacle to wind power development. While the phenomenon was initially brought to widespread attention through bird-turbine mortality incidents, studies also revealed that bat carcasses were also being retrieved from turbine bases, often in substantially greater numbers than birds (Howe *et al.*, 2002; Kerns and Kerlinger, 2004; Piorkowski, 2006). Bat-turbine mortality is however not a new issue, the earliest documented incident was recorded at an Australian wind plant in the 1970s (Hall and Richards, 1972). Bats present a unique problem from an acoustic point of view, since they rely heavily on sound and the use of echolocation to navigate their environment. Recent research has shown bats may be not only foraging in the vicinity of wind turbine rotors (Ahlén, 2004; Horn *et al.*, 2008), but also actively investigating turbine blades, during which they can be struck (Horn *et al.*, 2008) [although other

studies have found mortality may also occur through barometric pressure changes in blade wake vortices (Baerwald *et al.*, 2008)]. As insectivorous bats rely on the emission and reflection of high frequency pulses to pursue aerial prey, useful insight may be gained into the bat's perception of operational turbine rotors by assessing how ultrasound interacts with moving blades. In this paper, three approaches to the problem are adopted; Section II details an investigation into the nature of Doppler shift patterns returned from operational rotors, as this is likely to affect the variation in frequency shift of reflected individual bat echolocation pulses. Section III then looks into the short bat-like sampling of these frequency shifts in simulation, and in Section IV bat-like pulses are used to experimentally assess information contained in echoes reflected from an operational turbine rotor. Since bats rely on frequency and amplitude information within each echo to extract the relevant parameters of the object (Neuweiler, 2000), these findings may aid better understanding of the problems faced by bats in the vicinity of turbine rotors and potential mitigation opportunities.

II. CF TONE DOPPLER SHIFT SIGNATURES FROM MOVING BLADES

A. Methodology

A six-blade, tethered microturbine (rotor diameter 0.91 m) placed in a $2.5 \times 2.5 \times 4 \text{ m}^3$ anechoic chamber was used for experimental work. To drive the turbine rotor, a fan was placed opposite and the rotor allowed to rotate freely up to a speed of 10.5 rad s^{-1} , measured by stroboscope, consistent with low wind speeds of 4.1 m s^{-1} (previous research has found bat mortality to be highest on nights of wind speed

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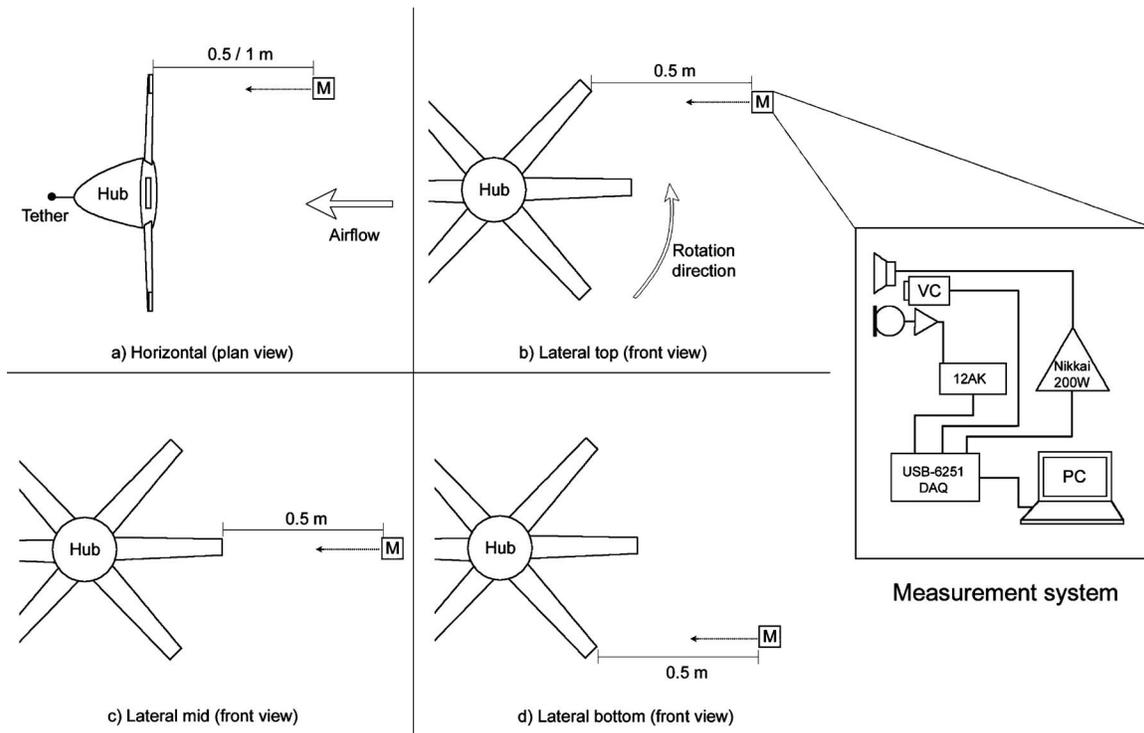


FIG. 1. Schematics for experimental set up indicating the different angles of turbine ensonification: (a) 'horizontal', (b) 'lateral top', (c) 'lateral mid', (d) and 'lateral bottom'. 'M' denotes measurement equipment in all cases (inset) and 'VC' denotes 'Video Camera'.

less than 6 m s^{-1} (Arnett *et al.*, 2008; Horn *et al.*, 2008) measured by anemometer. At this point the fan was turned off (and it was verified that it therefore contributed no appreciable noise to recordings) and measurements taken over a period of 3 s, during which time the rotor could be considered to be rotating with a constant angular velocity. The Doppler shift signatures made by moving blades at a distance of 0.5 m were assessed using a Continuous Wave, Constant Frequency (CW CF) source tone of 40.7 kHz. This was emitted via a MA40B8R (Murata Manufacturing Co., Ltd., Kyoto, Japan) transducer, through a tone generator, situated opposite the turbine. Transducer beam angle was 50° , similar to the beam angle of some bat species [e.g., the FM bat *Eptesicus fuscus* at 40° (Wotton and Jenison, 1997)], giving a beam diameter of approximately 0.4 m at 0.5 m distance. The transducer was placed in horizontal juxtaposition with a calibrated, flat response $\frac{1}{4}$ " 40BF microphone and 26AC preamplifier with 12AK power module (GRAS Sound & Vibration, Holte, Denmark) (frequency range 2 Hz–100 kHz) and a high speed A602fc (Basler AG, Ahrensburg, Germany) video camera set to capture at a rate of 60 frames per second. The camera was positioned to capture roughly the same area of rotor as was ensonified by the transducer. The turbine rotor was then ensonified during operation at one of the following angles to the source: (a) 'horizontal', (b) 'lateral top', (c) 'lateral mid', or (d) 'lateral bottom' (Fig. 1), accurately aligned with the assistance of a low power laser. The reflected echo was recorded and time-synchronized with the motion capture via a USB-6251 (National Instruments Corporation, TX, USA) DAQ card sampling at a rate of 1250 kS s^{-1} at 16-bit resolution, over a 3 s period, which enabled exact blade movements and positions to be corre-

lated with any Doppler shift patterns returned to source. The operational rotor itself was verified not to contribute to the ambient sound in the ultrasonic frequency band.

All recorded data were saved directly to a PC in uncompressed .wav file format and were processed using AUDITION 1.0 (Adobe Systems, Inc., CA, USA) and analyzed using MATLAB 2009b (The MathWorks, Inc., MA, USA).

B. Results

Moving turbine blades were found to produce Doppler shift signatures that varied according to the angle of rotor ensonification and blade position at the point of reflection. Figure 2 describes the Doppler shift signatures for all angles ensonified, indicating the blade positions resulting in shift portions for each blade sweep. In Fig. 2, Doppler shift portions have been segmented (A, B, C, etc.) and the nature of blade movement resulting in these portions detailed beneath the corresponding signature sonogram. For example, segment 'A' of the horizontal shift corresponds to movement of the blade's leading edge from a position above the source to a position parallel with the source; segment 'B' corresponds to the blade becoming parallel with the source; segment 'C' corresponds with movement of the blade's trailing edge from the parallel position to one below the source. The extent of the Doppler shift deviation from the mean shift varied between angles; 'horizontal' shift ranged between $\pm 25 \text{ Hz}$, 'lateral top' shift ranged between $\pm 595 \text{ Hz}$, 'lateral mid' shift ranged between $\pm 785 \text{ Hz}$ and 'lateral bottom' shift ranged between $\pm 730 \text{ Hz}$. Overall, sound reflected from the operational rotor from the horizontal aspect demonstrated slight negative Doppler shift, from the lateral top aspect

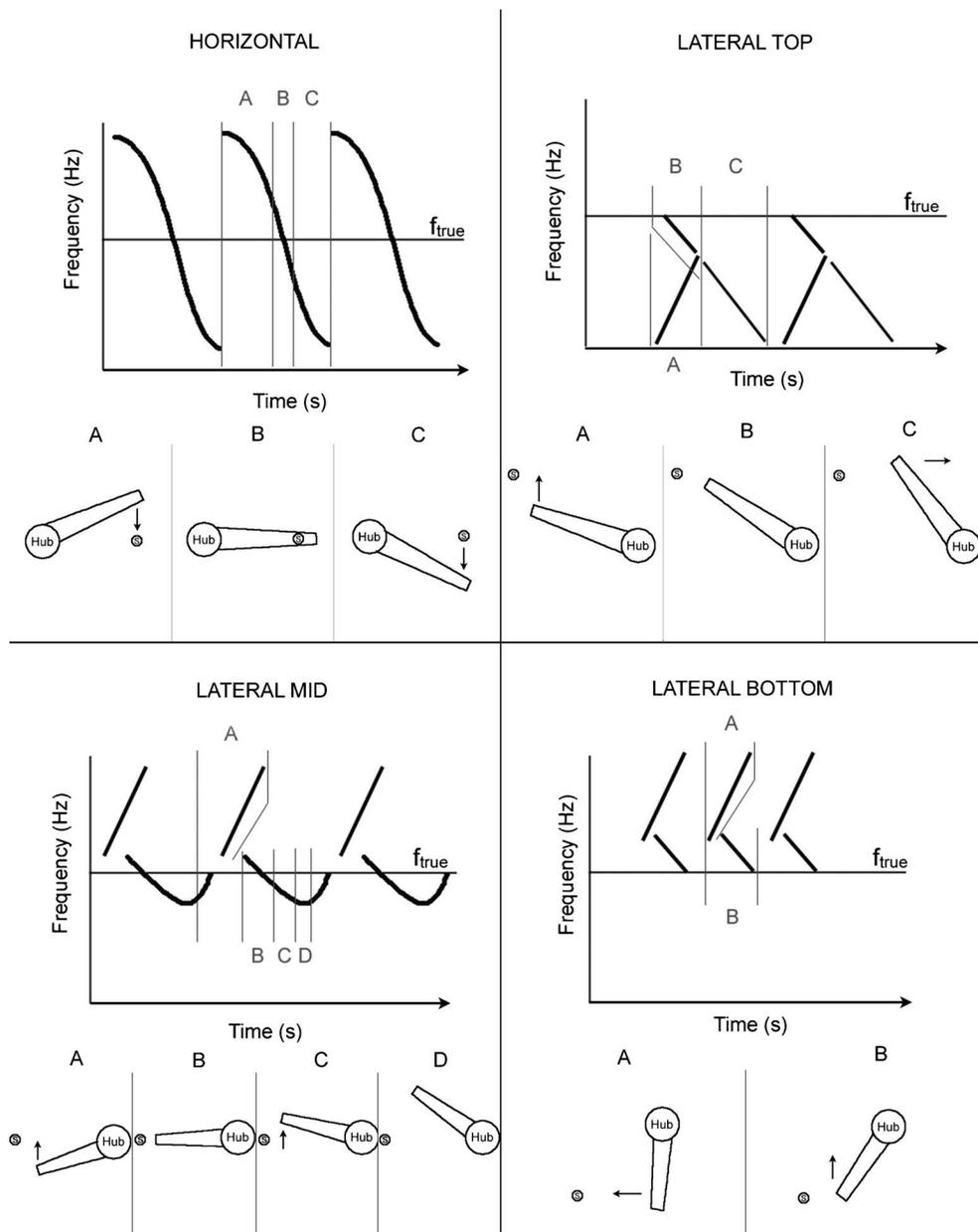


FIG. 2. Representative Doppler shift echo signatures for turbine blade sweeps ensounded from four different angles with an outgoing ultrasonic CF tone (40.7 kHz). Patterns taken from FFT data recorded at 1250 kS s^{-1} (FFT length 16 384 points, Hanning window, 75% overlap, 2% linear energy scaling). F_{true} denotes actual outgoing frequency. Single blade sweep signatures are divided into portions corresponding to the blade positions indicated below each signature, as determined by high speed video footage ('S' denotes source).

demonstrated negative shift, from the lateral mid aspect demonstrated slight positive shift and from the lateral bottom aspect demonstrated positive shift.

III. MONTE CARLO SIMULATION OF BAT-LIKE PULSE ECHO DOPPLER SHIFT

A. Methodology

Since an incoming bat-like echolocation pulse (approximately 2–6 ms) is much shorter than the blade sweep pass period for this turbine model at low wind speed (approximately 100 ms), an approaching bat would receive only short samples of the Doppler shift produced by the moving blades. As the extent of the shift observed in these short echoes would depend on the exact blade position at the point of echo

reflection it is useful to simulate random sampling of the rotor Doppler shift pattern using a Monte Carlo method. This would allow an estimation of the number of pulse echoes an approaching bat would need to receive in order to determine the true nature of blade movement. To do this, five single blade sweep signatures were extracted from the CW echo data set and had the true CW frequency removed by applying a second order Butterworth band stop filter. Each single signature was divided into ten equal 10 ms segments around a common point, which was taken as the position that the shift sweep crossed the true CW frequency (see Fig. 3). A fast Fourier transform (FFT) was then applied to each segment and the frequency of peak energy obtained. The series of ten values for frequency of peak energy was then averaged over

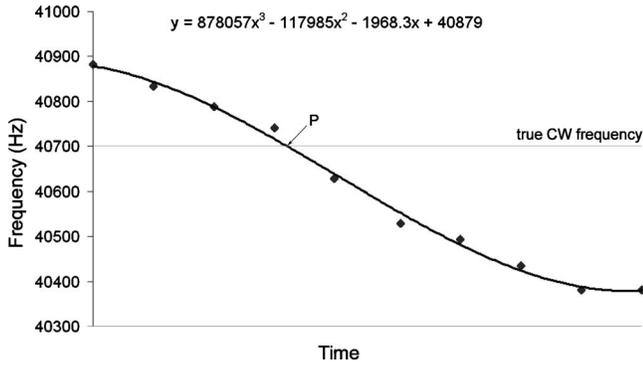


FIG. 3. Example mean Doppler shift data fitted with 3rd order polynomial curve (y). Line indicates true CW frequency; 'P' indicates crossover point. Data taken from 'horizontal' rotor ensoufflement at 0.5 m.

five blade sweeps and to this mean shift data a polynomial (3rd order) curve was fitted, as shown in Fig. 3.

To simulate CF sampling, the curve function was applied to sample the frequencies at random time intervals over the course of a single blade sweep generated using MATLAB's random number generator function. Sampled frequencies were generated in increasingly greater numbers (i.e., more echoes per blade sweep) and the mean frequency extracted until the sample size was sufficient for the resulting mean to converge to the mean shift of the signature (within an error margin of ± 10 Hz). However, some bat species employ a Frequency Modulated (FM) echolocation strategy. For FM simulations, an additional random shift of between ± 200 Hz was combined in order to take into account the more broadband nature of the FM pulse and hence the greater potential for variation in frequency of peak energy. All Monte Carlo simulations were run 20 times to obtain an average number of samples required to converge.

B. Results

Simulation results revealed that, for CF bat-like echoes, the number of samples required to converge to the mean shift per blade pass was 320 ± 121 for 'horizontal' ensoufflement, 150 ± 105 for 'lateral mid', 55 ± 16 for 'lateral top' and 100 ± 78 for 'lateral bottom'. For FM simulations, the number of samples required to converge to the mean shift per blade pass was 330 ± 123 for 'horizontal' ensoufflement, 200 ± 91 for 'lateral mid', 190 ± 143 for 'lateral top' and 150 ± 78 for 'lateral bottom'. Nearly all cases showed a high degree of variance in the number of samples required for convergence.

IV. SIMULATED BAT-LIKE PULSE ECHOES EXPERIMENTALLY REFLECTED FROM MOVING BLADES

A. Methodology

As bats employ a set duration ultrasonic pulse to 'sample' an operational rotor, it is useful to experimentally measure the information contained in such echoes reflected from turbine blades in order to compare with simulation predictions. In order to produce consistent, accurately replicable

pulses for analysis, an artificial bat echolocation pulse was simulated, modeled on the FM pulse of a common pipistrelle bat (*Pipistrellus pipistrellus*) (see Fig. 5). The equation used to create this pulse, Y , over time t , is defined as:

$$Y(t) = A(t) \cdot \lambda(t). \quad (1)$$

Time t is divided into four segments, $t_0:t_1;t_1:t_2;t_2:t_3$ and $t_3:t_{end}$. The amplitude modulation of the pulse, $A(t)$, is varied over three portions of the pulse and is defined thus:

$$A(t) = \begin{cases} A_a(t) & t \geq t_0 \leq t_1 \\ A_b(t) & t > t_1 \leq t_3 \\ A_c(t) & t > t_3 \leq t_{end} \\ 0 & \text{elsewhere,} \end{cases} \quad (2)$$

where

$$A_a(t) = A_{0a} + (t - t_0) \left(\frac{(A_{1a} - A_{0a})}{(t_1 - t_0)} \right), \quad (3)$$

$$A_b(t) = A_{0b} + (t - t_1) \left(\frac{(A_{1b} - A_{0b})}{(t_3 - t_1)} \right), \quad (4)$$

$$A_c(t) = A_{0c} + (t - t_3) \left(\frac{(A_{1c} - A_{0c})}{(t_{end} - t_3)} \right). \quad (5)$$

Here, A_{0x} is the starting amplitude of that segment and A_{1x} the ending amplitude of the same segment. Similarly, formulation of the frequency/sine wave component, $\lambda(t)$, is varied over two portions of the pulse as follows:

$$\lambda(t) = \begin{cases} \lambda_a(t) & t \geq t_0 \leq t_2 \\ \lambda_b(t) & t > t_2 \leq t_{end} \\ 0 & \text{elsewhere,} \end{cases} \quad (6)$$

where

$$\lambda_a(t) = \sin \left\{ 2\pi \left[f_{0a} + (t - t_0) \left(\frac{(f_{1a} - f_{0a})}{(t_2 - t_0)} \right) \right] (t - t_0) \right\}, \quad (7)$$

$$\lambda_b(t) = \sin \left\{ 2\pi \left[f_{0b} + (t - t_2) \left(\frac{(f_{1b} - f_{0b})}{(t_{end} - t_2)} \right) \right] (t - t_2) + \phi \right\}. \quad (8)$$

Here, f_{0x} is the starting frequency of that segment and f_{1x} the ending frequency of the same segment. Phase, ϕ , is defined as:

$$\phi = 2\pi \left(f_{0a} + (t - t_0) \left(\frac{(f_{1a} - f_{0a})}{(t_2 - t_0)} \right) \right). \quad (9)$$

A depiction of the variation in amplitude and frequency over time used to form the FM pulse by implementing Eq. (1) is shown in Fig. 4.

A pure CF pulse of the same duration was also simulated, using the same Eq. (1) but substituting λ for λ_{CF} , as follows:

$$\lambda_{CF}(t) = \begin{cases} \lambda_{CFa}(t) & t \geq t_0 \leq t_{end} \\ 0 & \text{elsewhere} \end{cases} \quad (10)$$

and

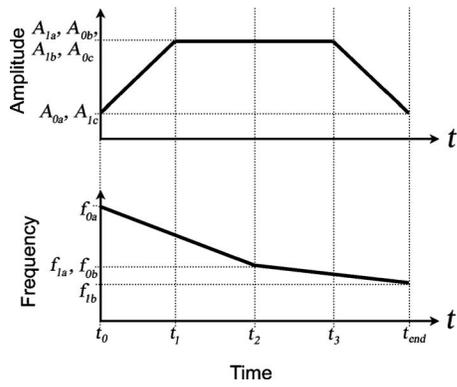


FIG. 4. Demonstrating the utilization of time components (t) in Eqs. (2)–(9) and the variation of frequency and amplitude with each segment. The frequency changes depicted here were applied only to λ in the creation of the FM pulse.

$$\lambda_{CFa}(t) = \sin\{(2\pi \cdot f)(t - t_0)\}, \quad (11)$$

whereby f is the CF.

Pulse coding was performed in MATLAB, using a frequency of 50 kHz for CF pulses and a frequency of highest intensity of 47 kHz for FM pulses (Fig. 5).

The duration of both simulated pulse types was set at 2 ms to prevent the overlap of outgoing pulse and returning echo at a reflective distance of 0.5 m (after Long *et al.*, 2009). Pulses were output via the USB-6251 DAQ card at a sampling rate of 800 kS s^{-1} , and emitted through a SRU310H (Clarion Co., Ltd., Tokyo, Japan) silk dome tweeter (frequency range 2–80 kHz, beam angle approximately 50°). This was amplified by a NIKKAI 200W (Nihon Kaiheiki Ind. Co., Ltd, Kawasaki-shi, Japan) amplifier to a level consistent with actual emitted bat pulses as per Waters and Jones (1995); 90 dB peSPL re $20 \mu\text{Pa}$ at a distance of 0.5 m from source, as measured via the calibrated microphone. The microphone was then placed in horizontal juxtaposition with the tweeter to enable recording of received echoes, sampled through the same DAQ card at 800 kS s^{-1} ; this pairing is hereafter denoted ‘source’. The source was positioned opposite the turbine in the various positions described by Fig. 1 and pulses fired at the rotor, both while blades were stationary and under operation. Horizontal measurements were taken at distances of 0.5 and 1 m, however lateral mea-

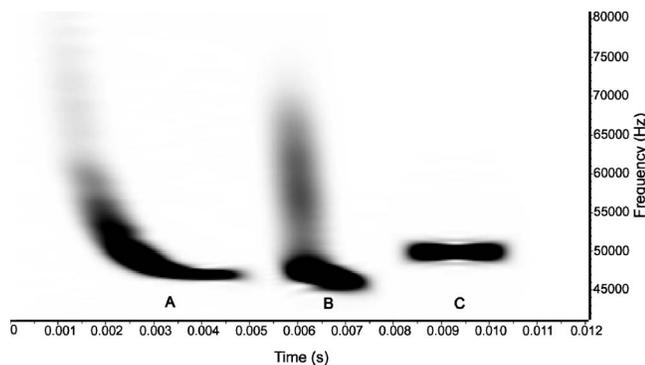


FIG. 5. (a) FFT sonogram of a real common pipistrelle pulse, (b) the short simulated FM pulse, (c) and the short simulated CF pulse. FFT length 512 points, Hanning window, 40% overlap, 0.9% linear energy scaling (sampling rate 200 kS s^{-1}).

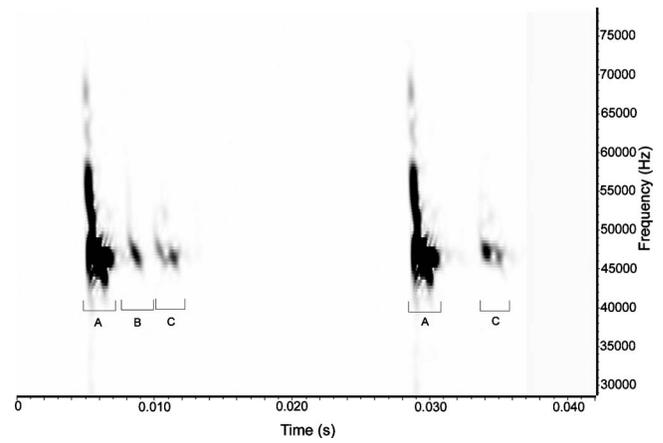


FIG. 6. Example FFT sonogram for FM pulses and echoes recorded from the ‘lateral mid’ angle at 0.5 m. (a) Outgoing pulse; (b) echo returned from blade tips; (c) echoes returned from the hub. Note that the interpulse interval has been artificially reduced in this example. Data recorded at 800 kS s^{-1} (FFT length 1024 points, Hanning window, 40% overlap, 5% linear energy scaling).

surements were taken at 0.5 m only as previous results found no echoes to be discernible from background noise for the lateral aspect at 1 m (Long *et al.*, 2009). In order to investigate for Doppler shifting and/or sound intensity reduction effects of the echoes returned from the turbine, control measurement echoes from a specular surface were taken at both distances. In all cases the time delay between outgoing pulses (interpulse interval) was set at 90 ms, consistent with a common pipistrelle bat in ‘search’ phase echolocation (Vaughan *et al.*, 1997). Again, all recorded data were saved directly to a PC in uncompressed .wav file format and were analyzed using AUDITION and MATLAB. Pulse echoes were analyzed in detail for changes to the frequency of highest sound intensity (peak frequency) using FFT data, and the percentage of sound intensity of the control specular echo was determined for each recorded echo. Statistical analyses on resulting data were performed using a paired, two-tailed t -test by comparing pulse echoes from stationary blades with those from operational blades at each angle and distance.

B. Results

A total of 1166 reflected pulses were recorded and analyzed, averaging 117 echoes per assessed angle and distance. In the majority of cases, 100% of outgoing pulses had a measurable echo returned to source, with the exception of the ‘lateral mid’ angle. In this position, only 17.3 and 13.1% of outgoing CF and FM pulses, respectively, resulted in an echo reflected back to source that corresponded to the rotor edge, despite a consistent echo being returned from the hub (Fig. 6). This was caused by the interplay between timing of pulse emission and the position of the blade tip at the point of pulse reflection (i.e., blade echoes were only returned when the blade tip was parallel to the source).

In all cases the sound intensity had much greater variance for echoes returned from the operational rotor than those from the stationary rotor (Fig. 7).

Table I describes the mean and standard deviation values for frequency of peak energy and percentage of specular re-

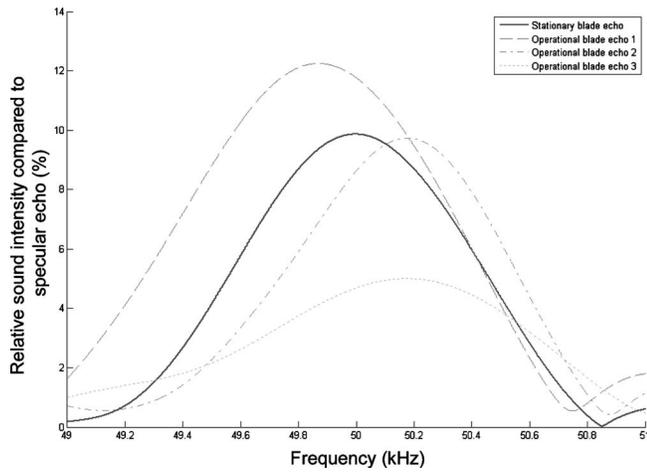


FIG. 7. Discrete Fourier transform (DFT) traces demonstrating the variation in pulse echo sound intensity returned from operational turbine blades at various positions (dashed line examples) as compared to stationary blades (solid line example). Note that the frequency shift of the experimental echo is dependent on the position of the blade at the time of reflection. Taken from simulated CF pulse samples recorded from the horizontal angle at 0.5 m (800 kS s^{-1}), calculated with a FFT algorithm.

flected sound intensity for all angles and pulse types measured. Also included are statistical results for overall Doppler shift and sound intensity information contained in echoes returned from the operational rotor (as compared to stationary rotor echoes).

V. DISCUSSION

CF tone Doppler shift signatures for blade sweeps were found to be consistent with what might be expected from the motion of the turbine rotor; i.e., on average, negative shift occurred when the turbine was ensounded from the ‘lateral top’ angle (blades predominantly moving away from source) and positive shift for the ‘lateral bottom’ aspect (blades predominantly moving toward source), although shift patterns did vary over the course of an individual blade sweep. Bats employing an FM echolocation pulse component have an apparent lack of ability to compensate for Doppler shifting (Boonman *et al.*, 2003), resulting in distance/range errors. Since many bats fly at 1%–2% of the speed of sound (Griffin, 1974), echoes returned from stationary point targets may be shifted up to 4.1% (after Boonman *et al.*, 2003) independent of additional Doppler effects from the target. Research has shown that the ‘big brown’ bat, *Eptesicus fuscus*, using FM pulses around 25 kHz, can reliably distinguish Doppler shifts (through playback recordings) only at shifts of 8% and above (Wadsworth and Moss, 2000). The turbine used in this paper produced blade tip speeds of 4.77 m s^{-1} (at 4.1 m s^{-1} wind speed) giving a Doppler shift of 2.8%, resulting in a total likely perceived shift of up to 6.9%. In addition to this, some FM bats such as *E. fuscus* are known to artificially alter the frequencies emitted by 3–6 kHz (up or down) when navigating in clutter in order to avoid emission-echo ambiguity (Hiryu *et al.*, 2010). This strategy could theoretically ‘mask’ any Doppler shifting effects caused by blade movements. It is therefore entirely possible that the Doppler shifts produced by some turbine rotor blades are not reliably detectable by

TABLE I. Experimental values for FM and CF pulse echoes reflected from stationary and operational rotor blades. ‘‘FPE’’ denotes frequency of peak energy. Ensonification angle key: H=horizontal; LT=lateral top; LM=lateral mid; LB=lateral bottom. Values in italics correspond to stationary rotor measurements.

Angle and distance to rotor blades (m)	Pulse type	Rotor stationary mean echo FPE (kHz)	Rotor stationary FPE standard deviation (Hz)	Rotor operational mean echo FPE (kHz)	Rotor operational FPE standard deviation (Hz)	Doppler shift as compared to stationary rotor echoes	Rotor stationary percentage of specular intensity standard deviation (%)	Rotor stationary mean percentage of specular sound intensity (%)	Rotor operational percentage of specular intensity standard deviation (%)	Rotor operational mean percentage of specular sound intensity (%)	Sound intensity as compared to stationary rotor echoes
H 0.5	CF	49.97	± 11	49.97	± 191	None ($t=-0.04$)	± 0.08	9.9	± 6.91	11.5	Higher ($p<0.005$; $t=-2.46$)
H 0.5	FM	47.38	± 266	46.87	± 436	Negative ($p<0.00005$; $t=10.87$)	± 0.12	5.4	± 9.47	10.9	Higher ($p<0.00005$; $t=-6.36$)
H 1	CF	50.18	± 29	49.92	± 146	Negative ($p<0.00005$; $t=19.33$)	± 0.29	9.7	± 6.16	10	None ($t=-0.46$)
H 1	FM	47.14	± 80	47.01	± 797	None ($t=1.67$)	± 0.33	16.4	± 4.3	9.8	Lower ($p<0.00005$; $t=16.86$)
LT 0.5	CF	49.1	± 29	49.92	± 212	None ($t=-0.89$)	± 0.08	2.1	± 0.75	1.8	Lower ($p<0.00005$; $t=5.14$)
LT 0.5	FM	46.9	± 94	46.94	± 423	None ($t=-1.1$)	± 0.11	4	± 0.96	2.4	Lower ($p<0.00005$; $t=18.27$)
LM 0.5	CF	50.01	± 13	49.99	± 156	None ($t=1.48$)	± 0.18	3	± 1.75	2.5	Lower ($p<0.005$; $t=2.87$)
LM 0.5	FM	46.87	± 17	47.05	± 223	Positive ($p<0.00005$; $t=-7.72$)	± 0.15	4	± 1.13	3.6	Lower ($p<0.0005$; $t=3.67$)
LB 0.5	CF	49.99	± 19	50.04	± 64	Positive ($p<0.00005$; $t=-8.1$)	± 0.44	11.8	± 1.44	9.2	Lower ($p<0.00005$; $t=18.83$)
LB 0.5	FM	46.88	± 18	46.7	± 76	Negative ($p<0.00005$; $t=26.05$)	± 0.18	3.9	± 1.31	10	Higher ($p<0.00005$; $t=-50.77$)

FM bats, leading to errors in assessing the movement and range information of operational rotors, which ultimately increases the potential for collision. Note that *E. fuscus* has a history of turbine interaction mortality (e.g., Erickson *et al.*, 2002; Arnett *et al.*, 2005; Kunz *et al.*, 2007).

The Monte Carlo simulation results showed that both CF and FM pulses required over 50 samples per blade pass to converge to the mean shift. This is extremely interesting from the point of view of an approaching bat, which would need to receive a similarly large number of reflected echoes from an operational rotor turning at low wind speeds in order to create an accurate picture of blade movement. Assuming a consistent interpulse interval of 90 ms and a pulse length of 6 ms, a pipistrelle-like bat (assumed to be stationary and close to the rotor) could theoretically ‘sample’ a single blade pass of a six-bladed rotor turning at 10.5 rad s⁻¹ just once per blade sweep cycle. Since the Doppler shift returned from this single echo sample could be anywhere along the shift pattern, this may not be enough for the bat to accurately interpret blade movement at low wind speeds. For the bat to build up a more representative picture of rotor movement (for example the 300 samples required for mean shift convergence in some cases), a pipistrelle-like bat would have to echolocate in the direction of the rotor from the same angle for around 29 s, which is biologically unlikely with normal bat flight behavior. Even assuming the pipistrelle-like bat was approaching the rotor from a maximum detectable distance of 15 m [based on the interpulse interval, after Holdried *et al.* (2005)], at a velocity of around 5 m s⁻¹ (Griffin, 1974), only around 30 pulses could be emitted before the bat reached the rotor. This may not be adequate for accurate blade motion determination.

Statistical analysis of the experimental frequency data revealed that the mean Doppler shift did not always appear to correlate with what might be expected from the shift patterns identified. As the time periods used for ‘sampling’ the operational rotor allowed a 2 ms ‘segment’ of frequency data to be extracted from the shift pattern roughly once per blade pass, these results are consistent with the predictions of the Monte Carlo simulation (i.e., a much greater number of samples are required to obtain adequate information to interpret the true nature of blade motion). The experimental data also showed a high variance in the sound intensity of echoes returned from the operational turbine rotor as compared to stationary rotor echoes, which is another potential area for misinterpretation of echoes from the bat’s perspective. Fluctuations in echo amplitude, also described as acoustic ‘glints’ (von der Emde and Schnitzler, 1986), are typically consistent with target movements and are also observed in fluttering insect echo returns (Sum and Menne, 1988) in accordance with wing beat cycle. The possibility exists that the ‘glints’ found in echo returns from an operational rotor could be acting as an acoustic ‘superstimulus’ (after Tinbergen and Perdeck, 1951) for bats, which may attract them to further investigate the rotor region. In addition to this, in many cases the echoes returned from operational blades had significantly lower sound intensity than the equivalent stationary blade echoes. This may be due to complex scattering effects caused by the movement of blade parts at the point of reflection,

which will vary depending on the exact position of the blade at the time reflection occurs. At these times, the rotor blades may therefore be less detectable to a bat under operation at low wind speeds than stationary blades.

In conclusion, operational microturbine rotor blades were found to produce specific Doppler shift return patterns consistent with blade sweep cycle, which varied according to the angle of ensonification and blade position. Frequencies were shifted by up to 6.9% by turbine rotor blades operating under low wind speed conditions (<6 m s⁻¹). Simulations revealed that around 50–300 echoes may need to be obtained by an approaching bat in order to build up an accurate perception of rotor movement, which may not be possible in the short approach time-window of the bat. In addition, some FM bats may be unable to adequately identify Doppler shift/range information in echoes returned from some turbine rotors operating in low wind speed conditions. Experimental short CF and FM pulses reflected from operational rotors had characteristics that varied significantly as compared to those reflected from stationary blades, including changes in amplitude and frequency.

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