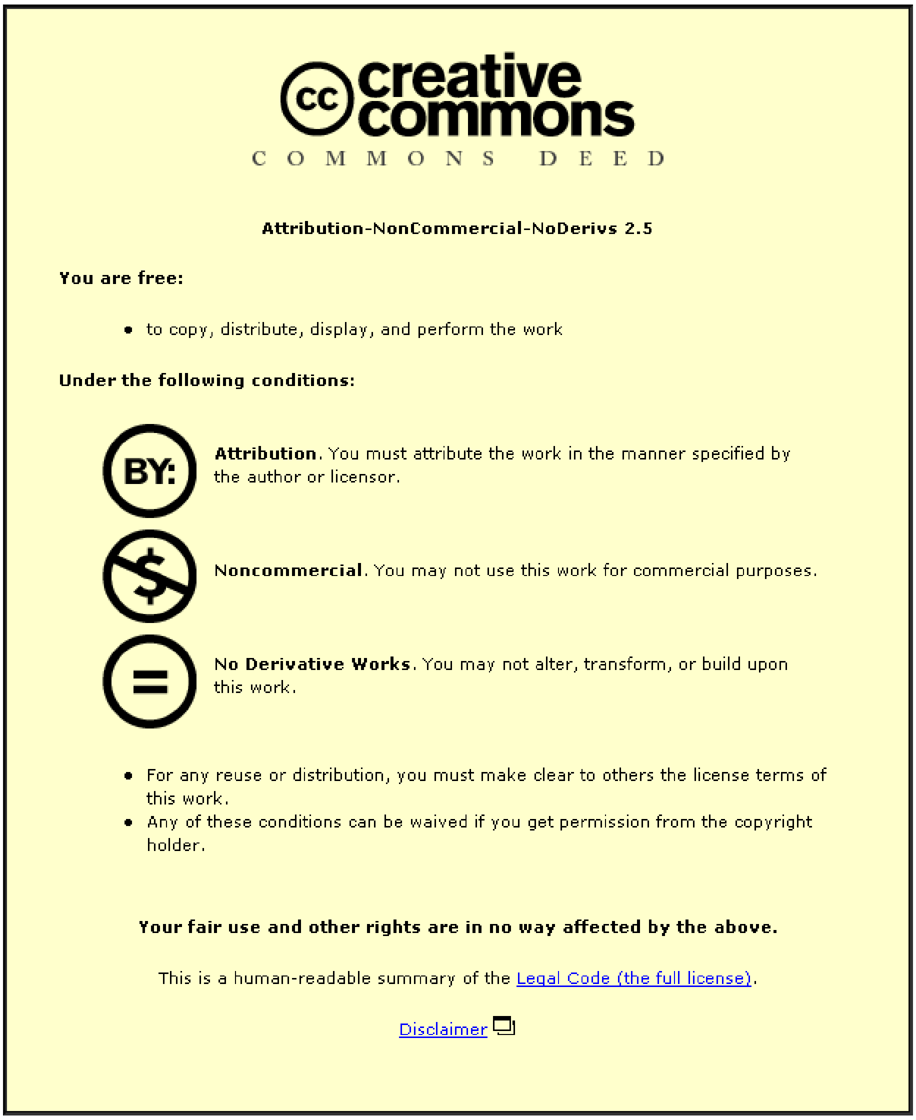
The interaction of bats (Microchiroptera) with wind turbines: bioacoustic and other investigations



The Interaction of Bats (Microchiroptera) With Wind Turbines: Bioacoustic and Other Investigations

by

Chloe V. Long, BSc (Hons)

Doctoral Thesis

Submitted in partial fulfilment of the requirements
for the award of
Doctor of Philosophy of Loughborough University

2011

“*I am inclined to believe, at least so far, that in the absence of sight there is substituted some new organ or sense which we do not have and of which, consequently, we can never have any idea."*

Lazaro Spallanzani (1793) on the discovery that bats do not rely on sight to navigate their environment. Source: Galambos, R. (1942) 'The avoidance of obstacles by flying bats: Spallanzani's ideas (1794) and later theories.' *Isis*, **34**: 132-140.

Abstract

The phenomenon of bat mortality at wind turbine installations has been generating increasing concern, both for the continued development of the wind industry and for local ecology. Bat-turbine interactions appear to be globally widespread, but are not well understood. The work outlined in this thesis primarily addresses the acoustic properties of moving turbine blades and the way in which bat-like pulses interact with them. In addition, possible factors for bat attraction to wind turbine installations are assessed. The main contributions of this thesis are (1) the formulation and application of a novel equation to rate turbine rotors in terms of bat detectability, identifying that features such as rotor angular velocity, number of blades, blade width and bat species all influence the likelihood of rotor detection; (2) passive and active ultrasonic measurements from turbine rotors in order to assess the nature of acoustic bat interaction with turning blades, showing that frequency and amplitude information in returned echoes can vary significantly, echoes may be attractive to bats as mimicry of echoes returned from flying insects, and that some turbines do not emit ultrasonic noise detectable to all bat species; (3) assessment of the Doppler shift profiles generated by moving blades in order to investigate the changing nature of frequency information returned to an echolocating bat, concluding that blades turning under low wind speed conditions may not be detectable by some bat species; (4) Monte Carlo simulation of bat-like rotor ‘sampling’ to account for the temporally short nature of reflected echoes, with the result that some bat species may not be able to achieve enough echoes to accurately interpret blade movement in the short approach time-window; (5) the creation and utilisation of artificial bat-like pulses for lab-based experimental work and (6) the investigation of insect attraction to turbine paint colours to determine the potential abundance of bat prey around turbine installations, finding that existing turbine colours are significantly attractive to insect species. By applying the conclusions of this work suggestions for the mitigation of the problem are detailed, the implementation of which may help to reduce the issue of bat mortality for both the wind industry and bat species in the future.

Acknowledgements

The author would like to thank the following people for their support over the course of the PhD:

Supervisors Drs James Flint and Paul Lepper of Loughborough University for all their time, support and draft-reading tolerance; Dr Simon Watson of CREST, Loughborough University for his valuable input and time; Drs Carol Williams of Natural England (formerly of the BCT), Lothar Bach of Freilandforschung und zool. Gutachten, Bremen, and Matthew Mason of Cambridge University for their interest and helpful feedback; Brocks Hill Environment Centre and Oadby & Wigston borough council for allowing the use of the 20 kW turbine study site; Dr Sian Williams-Worrall of the Chamistry Department, Loughborough University for her time and assistance with spectroscopy measurements; Professor Luis Ebensperger of the Pontificia Universidad Católica de Chile for his support and time; Mr. Joseph Nartey, M. Khairul Bakar, Alkis Spiliopoulos, Stefan von Pfefer, Zeke Steer, Ben Downes, Graeme George and Jacky Cheng for their project work; Dr. Emma Chung of Leicester University for helpful discussion and inviting the (prize winning!) article to *Ultrasound*; Dr. Jim Hague of the Open University for his continued love, support, feedback and patience; my parents, family and friends (special thanks to Melissa Tiley-Waters for all her time and support with Degutopia), and last (but by no means least) all the Degutopia degus for their many hours of acoustical inspiration!

Publications

List of published contributions from the author occurring during the course of the PhD:

- *Publications relating directly to bats and wind turbines*

  Long, C.V., Flint, J.A. and Lepper, P.A. (2010) ‘Wind turbines and bat mortality: Doppler shift profiles and ultrasonic bat-like pulse reflection from moving turbine blades.’ *Journal of the Acoustical Society of America*, **128**: 2238-2245, doi: 10.1121/1.3479540.

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- *Other publications*

  Mašek, T. and **Long, C.V.** (2010) ‘[Biology and nutrition of degus (*Octodon degus*)]’. *Veterinarska Stanica* (in Croatian) [article in press].

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Long, C.V. (2007) ‘Vocalisations of the degu *Octodon degus*, a social caviomorph rodent.’ *Bioacoustics*, **16**: 223-244.

- *Presentations and Invited Talks*

  – *Bat-Wind Turbine Interaction: Bioacoustic Investigations.* Midlands Bat Conference 2010, Leamington Spa, UK (Invited talk, Bat Conservation Trust).

- *Doppler Returns and Detectability of Wind Turbines from the Bat's Perspective.* National Bat Conference 2009, York, UK (Presentation, Bat Conservation Trust).

- *Wind Turbines and Bat Mortality: Interactions of Bat Echolocation Pulses with Moving Turbine Rotor Blades.* Bioacoustics 2009 Conference, Loughborough, UK (Presentation, Institute of Acoustics).

- *Pups of the Degu (Octodon degus), a Communally Nesting Caviomorph Rodent, Include Ultrasonic Frequencies in Care-Eliciting Calls.* Bioacoustics 2009 Conference, Loughborough, UK (Poster presentation, Institute of Acoustics).

- *Pups of the Degu (Octodon degus), a Communally Nesting Caviomorph Rodent, Include Ultrasonic Frequencies in Care-Eliciting Calls.* Vocal Communication in Birds and Mammals 2008 Conference, St Andrews, UK (Poster presentation).

- *Reproductive Vocalisations of the Degu (Octodon degus)*. Bioacoustics 2007 Conference, Loughborough, UK (Presentation, Institute of Acoustics).

Table of Symbols and Acronyms

Symbol	Denotes
º	Degree
º ' “	Degrees, minutes, seconds (GPS coordinates)
%	Percent
@	At
“	Inches
±	Plus/minus
Δ	Change in
$\mathbf{\Delta \underline{M}}$	Matrix of change in relevant parameters
θ	Beam half-angle
λ	Blade tip speed ratio
$\lambda_{CF}(t)$	Pulse CF waveform
λ_o	Optimal blade tip speed ratio
$\lambda(t)$	Pulse FM waveform
λ_x	Pulse waveform segment
µ	Micro
π	Pi constant (≈ 3.14)
ρ	Density
Φ	Diameter
ϕ	Phase
ω	Angular velocity
ω_{max}	Maximum angular velocity
A	Blade surface area
A_{ox}	Segment starting amplitude
A_{1x}	Segment ending amplitude
$A(t)$	Pulse amplitude modulation
A_x	Pulse amplitude segment
C_L	Lift coefficient
D	Detectability rating
D_{cut}	Detectability rating for turbine with operational cut-in
d_{targ}	Distance to target
D_s	Distance from source

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Symbol	Denotes
f	Frequency
f_{0x}	Segment starting frequency
f_{1x}	Segment ending frequency
f_{bat}	Frequency used by the bat
f_{gen}	Generated frequency
f_{out}	Output frequency
f_{true}	Actual outgoing frequency
G	Initial guess at source location
$\underline{\underline{\mathbf{G}}}$	Matrix of coordinate results
k	Tip speed ratio constant
L	Lift
n	Receiver number
n_0	Primary receiver
N	Number of turbine blades
P	Probability
P_{max}	Maximum probability
P_{min}	Minimum probability
P_R	Rated power
p_{ref}	Reference pressure
p_{rms}	Route Mean Square pressure
p_x	Instantaneous pressure level
r	Radius of rotor
R	Reflection coefficient
R_n	Distance of guess location from primary receiver
s	Doppler factor
t	Time
t_0	Pulse start time
t_{blade}	Portion of time blade sweep path occupied by blade
t_{delay}	Time delay
$\underline{\mathbf{t}}_{\mathbf{DIF}}$	Matrix of time difference results
t_{end}	Pulse end time
t_{int}	Blade-pulse interceptable duration
t_n	Pulse arrival time at receiver n
t_{n0}	Pulse arrival time at primary receiver
t_{ndif}	Difference in time of arrival

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Symbol	Denotes
t_{pulse}	Bat echolocation pulse length
t_x	Pulse time segment/relative arrival time
T_G	Guess location arrival time
T_n	Time taken for pulse to travel from guess location to n_0
v	Speed of medium/speed of sound in medium (in air ≈ 330 m s^{-1})
v_{bat}	Flight speed of bat
v_e	Speed of emitter
v_{max}	Maximum speed
v_{min}	Minimum speed
v_r	Speed of receiver
v_{rated}	Rated wind speed
v_{wind}	Incident wind speed
W	Turbine blade width
W_{max}	Blade width 2 cm from tip
W_{min}	Blade width 2 cm from hub
X	Distance from hub
X_G, Y_G, Z_G	Guess Cartesian coordinates
X_n, Y_n, Z_n	Additional receiver Cartesian coordinates
X_{n0}, Y_{n0}, Z_{n0}	Primary receiver Cartesian coordinates
$Y(t)$	Simulated bat pulse
Z	Acoustic impedance

Acronym	**Expansion**
2D	Two Dimensional
3D	Three Dimensional
4D	Four Dimensional
AC	Alternating Current
AD	Anno Domini
ANCOVA	Analysis of Covariance
BCT	Bat Conservation Trust
BWEA	British Wind Energy Association
c.	Circa
c	Centi-
CA	California (state)
CF	Constant Frequency
Co.	Company
CT	Connecticut (state)
CW	Continuous Wave
DAQ	Data acquisition
dB	Decibel
DEFRA	Department for Environment, Food and Rural Affairs
ºC	Degrees Celcius
DTI	Department of Trade and Industry
EMF	Electro Magnetic Field
EU	European Union
EWEA	European Wind Energy Association
FEmax	Frequency of highest energy/intensity
FFT	Fast Fourier Transform
FM	Frequency Modulated
FPE	Frequency of Peak Energy
G	Giga-
GLM	General Linear Model
GPS	Global Positioning System
g	gram
GUI	Graphical User Interface

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Acronym	**Expansion**
H	Horizontal (angle)
HMSO	Her Majesty's Stationery Office
hr	Hour
Hz	Hertz
ID	Identification
Inc.	Incorporated
IR	Infrared
IUCN	International Union for Conservation of Nature
k	Kilo-
kW h	Kilowatt hours
LB	Lateral Bottom (angle)
LM	Lateral Mid (angle)
LR/lc	Lower Risk/least concern
LR/nt	Lower Risk/near threatened
LS	Least Squares
LT	Lateral Top (angle)
m	Metre
MA	Massachusetts (state)
MEDD	Ministère de l'Ecologie et du Développement Durable
MH	Multi Harmonic
m	Milli-
mph	Miles per hour
μ	Micro-
$m\ s^{-1}$	Metres per second
MT	Microturbine
MW	Megawatt
n	Sample number /size
N	Newtons
nm	Nanometres
NB	Narrow Bandwidth
OK	Oklahoma (state)
Pa	Pascals
PC	Personal Computer
pSPL	Peak Sound Pressure Level
peSPL	Peak Equivalent Sound Pressure Level

Continued overleaf…

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Acronym	Expansion
rad.	Radians
re 20 µPa	Relative to 20 microPascals
RF	Radio Frequency
RH	Relative Humidity
RPM	Rotations Per Minute
s	Second
S	Samples
T	Turbine
TX	Texas (state)
UK	United Kingdom
US	United States
USA	United States of America
UV	Ultraviolet
VC	Video Camera
VUA2c	Vulnerable to extinction, category A2c
W	Watt
yr	Year

In this thesis, sound pressure level (SPL) is defined as:

$$\mathrm{SPL} = 20\log_{10}\left(\frac{p_{rms}}{p_{ref}}\right)$$

Where p_{rms} is the root mean square of the pressure values and p_{ref} the reference pressure level, typically 20 µPa.

List of Figures

List of Tables

Contents

6. Site Survey Practice and Mitigation 140

7. Conclusions and Further Work 171

Appendix 176

Turbines in the Lake District, C.V. Long (2009)

1

Introduction

Bioacoustics is the term used to describe the production or interaction of sound within the natural environment. Most commonly the term is applied to the study of the vocal sounds produced by animals for communication or navigation, although it is increasingly common for bioacousticians to investigate how human-generated noise may be propagating through and altering natural phenomena. The human race has always had a close relationship with sound, for example through the emotional connections of music, to the vocal complexities of language; however we are only able to perceive a very small part of the acoustic spectrum. The human hearing range extends from about 20 Hz to 20 kHz as determined by the ability of tiny stereocilia hairs in our ears to react to sound waves of frequencies within this range (e.g. Engström & Borg (1983)). Frequencies below 20 Hz are termed ‘infrasonic’ and are used by some animals such as elephants for long-distance communication (e.g. Payne *et al.* (1986)), while frequencies above 20 kHz are termed ‘ultrasonic’ and are utilised by echolocating species such as dolphins and bats (e.g. Norris *et al.* (1961); Griffin (1974)). This will be discussed in more detail in the following chapter.

1.1 Addressing the Issue

Bats have existed on this planet, in some recognisable form or another, for about the last 60 million years (Teeling *et al*., 2005). Although humans, by contrast, have been around for only the last 200,000 years (Cela-Conde & Ayala, 2007), as a species we have had more of an impact on life on Earth than any other. As we endeavour to shape the environment around us and utilise the resources presented to us, we are not always able to consider the direct or indirect implications to the other forms of life that share the planet. Gradually we are coming to realise that these consequences of our actions, however small, can quickly grow to become major problems that affect the delicate natural balance. This can have far-reaching consequences, both for ourselves and the rest of the ecosystem we inhabit.

A topical example of such an indirect effect is the impact of wind turbines on flying wildlife. Humans have been harnessing the power of the wind for over 2000 years (Hills, 1994), although only in relatively recent years has technology enabled us to do so on an industrial and global scale. Over the past century human energy consumption has risen sharply, and the demand for cleaner, low-polluting renewable energy sources has increased almost exponentially in the last decade due to concerns over global climate change (see Figure 1.11).

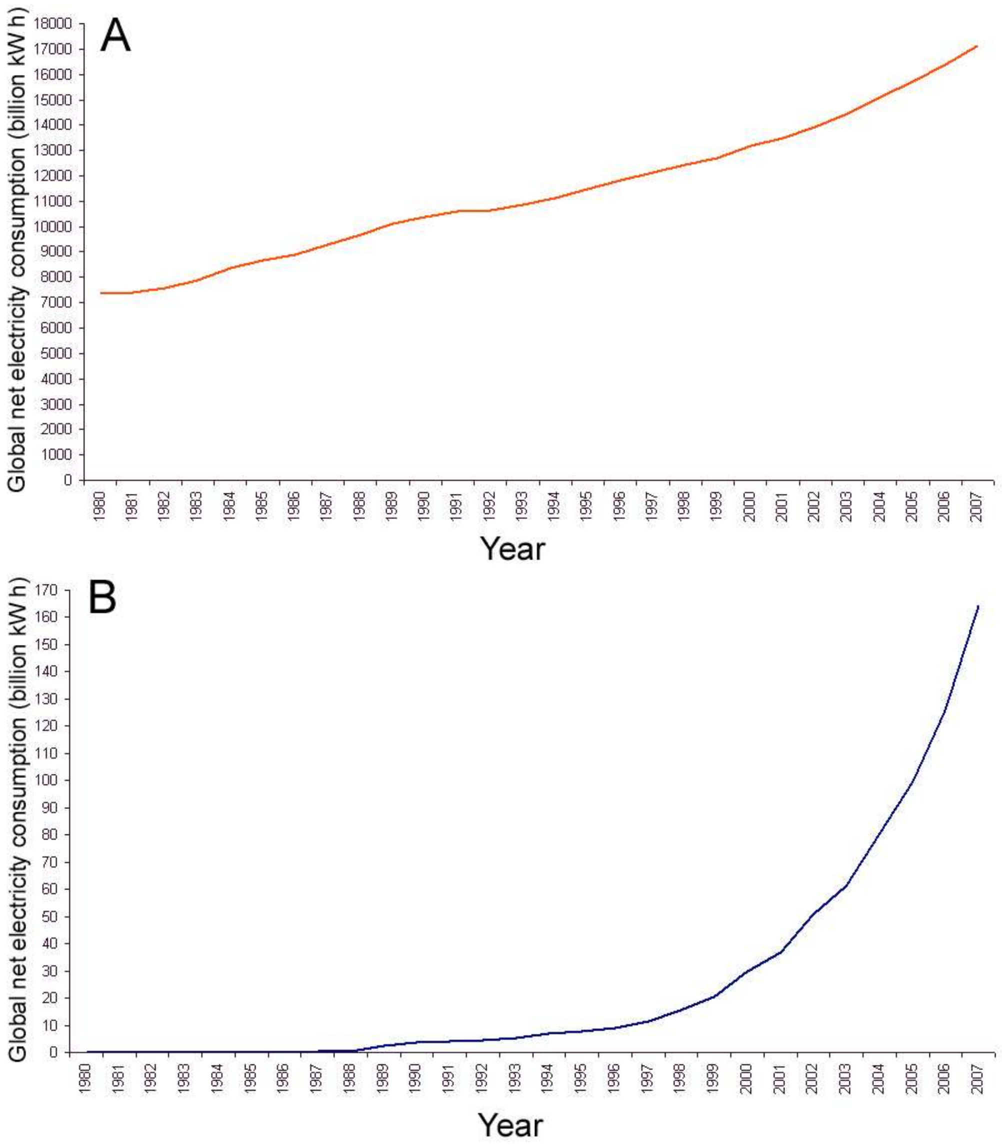

Figure 1.11- Depicting global trends in electricity consumption between 1980-2007. A: Total global electricity consumption over the past 27 years; B: Global electricity consumption from wind power generation over the same period. Plotted using data from the Energy Information Administration (2008).

Wind energy has contributed significantly to meeting power needs in a more ‘green’ manner and is expected to play an even bigger role in the future, however there have been casualties of this success. As wind turbines have become more widespread the phenomenon of wildlife-turbine mortality has become more abundant. Although initial awareness was brought about through documented avian mortalities and bird-turbine interaction studies, concern has been growing over bat mortalities at wind installations, as hundreds of carcasses have been reported to be retrieved at some wind plants in just one night (e.g. Kerns & Kerlinger (2004)). In the future, should this trend of turbine growth and bat deaths be allowed to continue unchecked, it is feared this could lead to local population decline, and in the worst cases, species extinctions. Because insectivorous bats play a crucial role in nocturnal insect control and are a vital part of the ecosystem (e.g. Hutson *et al.* (2001)), and because it seems likely that wind energy will continue to expand in the future, it is most important to investigate this phenomenon and to look into mitigation possibilities, for the future of both bats and wind power generation. This thesis aims to contribute to the knowledge in this area so that wind turbine designers and planners can make a more informed choice.

1.2 Objectives

The main objectives of the work set out in this thesis are to investigate (a) why bats appear to fly in the vicinity of wind turbine rotors, (b) why and how, when they are present, they interact with moving turbine rotor blades and (c) how bat impacts with turbines may be mitigated. Bats have evolved highly specialised and sophisticated methods of obtaining situational awareness in their environment, by producing sound and listening for reflected echoes. From a human point of view, this method of navigation is quite alien and we do not fully understand the exact processes bats use to do so. For this reason it is necessary to investigate how the vocalisations produced by bats may be interacting with moving turbine parts. In the long term, this will contribute to a better understanding of the information presented to bats about the turbine structure. By applying the results to what is already known about bat echolocation, it may be possible to diagnose problematic turbines or installations and offer detailed mitigation advice. From the point of view of this thesis, the focus will mainly be on objectives (a) and (b), with some practical suggestions to address (c).

1.3 Thesis Overview

The thesis is divided into chapter sections in the following order: **Chapter 2** provides a literature review covering the subjects of bats and echolocation, the historical use of wind power and current information on bat-wind turbine interactions, while the following three chapters detail the experimental work done in this area. Because bats, as aerial animals, have such a unique method of navigating and interpreting their environment, the primary focus of the work described in **Chapters 3** and **4** will be the acoustical interaction of ultrasound with the main bat ‘danger zone’ of the turbine, the rotor. **Chapter 5** approaches the issue from a slightly different angle, investigating the possibility that turbines may be visually attractive to insect prey, which is a potentially important concept for mitigation. It is hoped that the implementation of some or all of the mitigation options discovered through this work could help to significantly reduce bat-turbine fatalities at wind installations in the future, which will be detailed in **Chapter 6** along with information regarding bat site-use assessments at planned turbine sites. Finally, **Chapter 7** concludes the work and highlights some suggestions for future study in this area.

1.4 Contributions of This Thesis

The following is a summary of the original contributions to knowledge made by the author; further details can be found in Chapters 3 to 6.

- The formulation of an equation to ‘rate’ wind turbine rotors in terms of bat detectability, based on predicting the likelihood of echolocation pulse reflection during rotor operation.

- The application of the ‘rotor rating’ equation to existing models of wind turbines and microturbines in order to assess the physical properties of the rotor that have the most impact on bat detectability.

- Passive acoustic measurements of selected turbine rotors to assess ultrasound emission levels and blade fault anomalies.

- Active acoustic Doppler shift measurements of moving microturbine blades, in order to predict the likely degree of frequency shift presented to an approaching bat in a rotor-reflected echo, and how a bat might interpret this.

- Monte Carlo simulation of the bat-like sampling of moving turbine blade frequency shifts, in order to assess the random nature of frequency information presented to an approaching bat.

- The formulation and coding of simulated bat-like pulses, for acoustic experimental application.

- Active acoustic measurement of reflections produced by insonating moving microturbine blades with simulated bat-like pulses, in order to assess the way in which bat pulses may be interacting with operational turbine rotors.

- The experimental assessment of the relative insect attractiveness of different turbine paint colours in order to investigate colour as a possible factor in bat-turbine interaction.

- The coding of an interactive GUI to aid in the identification of British bat species monitored through recorded echolocation data.

- The coding of a system to locate and track a bat’s flight path in 4D using a multilateration technique with Least Squares solution.

- Outlining mitigation options aimed at reducing the issue based on the findings of this work and a novel acoustic aposematic deterrent.

1.5 References

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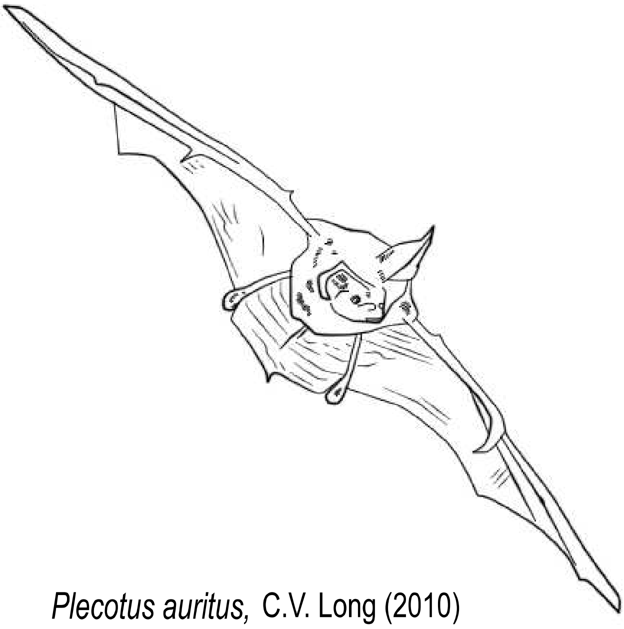

Plecotus auritus, C.V. Long (2010)

2

Background

The bat is arguably one of the most remarkable animals on the planet. Not only has it evolved a feature unique amongst mammals- powered flight- it has also adapted to fill a specific evolutionary niche expertly. In fact, bats have been so successful in exploiting this niche that they have become one of the largest mammal orders, making up around one-fifth of all mammalian species (Tudge, 2000). The order Chiroptera, to which bats belong, translates from Greek as 'hand-wing', referring to the adaptation of the bones in the 'hands' of the bat into wing-like appendages, covered by an extraordinarily thin membrane of skin. It is thought that bats originally evolved from shrew-like insectivores, gliding from treetops to catch insect prey some 64 million years ago (Teeling *et al*., 2005). During this time, competition from the newly evolving birds would have put great evolutionary pressure on the hunting success of bats. Since the vast majority of birds would have been diurnal and poorly adapted to hunt at night, this created a nocturnal niche which bats have so expertly exploited. In fact, fossil records suggest that bats have changed little in the last 40-50 million years (Gunnell & Simmons, 2005), a time when echolocation is thought to have developed during a period of diversification of insect species (Teeling *et al*., 2005), with the majority of bat species remaining insectivorous and nocturnal (although a small percentage are sanguivorous, frugivorous, piscivorous, nectarivorous or diurnal). These bats were until recently classed as Microchiroptera, or ‘micro bats’, as opposed to the larger, generally diurnal and fruit-eating Megachiroptera. In fact, recent molecular sequencing has revealed the order Chiroptera to be monophyletic, with two suborders ‘Yinpterochiroptera’ and ‘Yangochiroptera’, the latter of which contains the majority of insectivorous species (Teeling *et al*., 2005). The ability of insectivorous bats to locate and hunt down aerial prey on the wing, in near or total darkness, has long fascinated humans, and the mysteries of their nocturnal behaviour have given them something of a bad name in the folklore of many cultures. It was not until the 1790’s that the mysteries of the bat began to be unravelled, by the Italian Biologist Lazaro Spallanzani. During experiments, Spallanzani noticed that nocturnal birds, such as owls, were unable to navigate in absolute darkness and frequently collided with objects. Bats, however, did not have the same problems, even when artificially blinded. Further investigation revealed that bats were rendered completely helpless when either their ears or mouth were covered, and this convinced Spallanzani that hearing was a vital part of the bat’s ‘sixth sense’ (Galambos, 1942). Sadly, Spallanzani died in 1799 and his theories were largely rejected by the scientific community in favour of the idea that bats navigated by touch. In fact Spallanzani’s work fell into such obscurity that it was not until 1920 that Hamilton Hartridge, inspired by underwater sonar systems used in the first World War, proposed that bats might be reliant on the receiving of high frequency echoes for navigation (Hartridge, 1920). It is from this work that the discovery of bat ‘echolocation’ was made, a subject that has fascinated scientists in its complexity but which remains largely mysterious to the present day.

2.1 The Principles of Echolocation

After Hartridge’s initial speculation that bats may use high frequency sound for navigation purposes, in 1938 it was Donald Griffin, an American zoologist, who became one of the first people to listen to and record these sounds (Griffin, 1974). The experiments that followed led Griffin to coining the term ‘echolocation’ to describe the process of producing a sound and interpreting the reflected echo to assess the immediate environment (Griffin, 1944).

Despite most species having good eyesight, bats are now widely recognised for having a finely-tuned ability to both emit ultrasonic pulses and interpret the resulting echoes from both moving and stationary targets with high accuracy. They achieve target detection, localisation and classification using a variety of methods to enhance the information extracted from the echoes of their emitted ultrasonic pulses. For a bat to be able to utilise echolocation, two basic elements are needed- an emitter and a receiver. All echolocating bat species employ the use of high frequency sound pulses in the ultrasonic region (20 kHz and above; frequencies used by bats typically range between 22-110 kHz). Although the energy contained in the sound pulse at these frequencies is readily attenuated and cannot cover large distances, the resolution it provides is very fine. This is particularly important for bats hunting very small insect prey (for example mosquitoes which have a body size between 2-10 mm), where the wavelength of the sound pulse should be equal to or less than the circumference of the target in order for a strong specular reflection to occur (Figure 2.11). This occurs due to Rayleigh scattering, where targets that appear as point sources (i.e. are small in comparison to wavelength) scatter the wave in all directions rather than reflecting directly back toward the source of the wave.

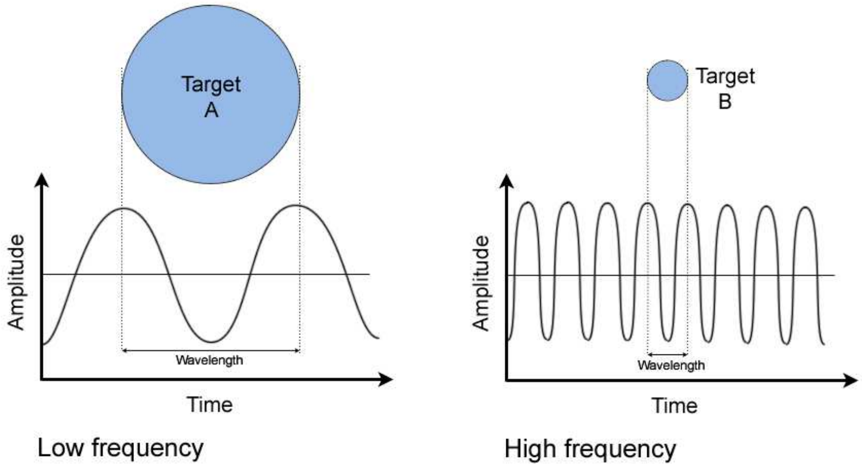

Figure 2.11- Demonstrating how the size of the wavelength affects the size of the target capable of being detected at a specific frequency. The wavelength should be equal to or less than the target circumference in order for a strong echo reflection to occur. The high frequency example could therefore be used to detect both targets A and B, while the low frequency may detect target A only.

Bats are therefore able to produce these high frequency sounds via specialised membranes in the larynx, and emit them from the mouth and/or nose in the direction of the target object. Figure 2.12 provides an example of how some bat species, such as those in the family Phyllostomidae, use a fleshy membrane around the nose, or ‘noseleaf’, to implement beam directivity. Research by Zhuang & Müller (2006) using modelling techniques revealed that the shape of the furrows and cavities within the noseleaf created acoustical resonances which could be modified by the bat to shape and direct the ultrasonic beam.

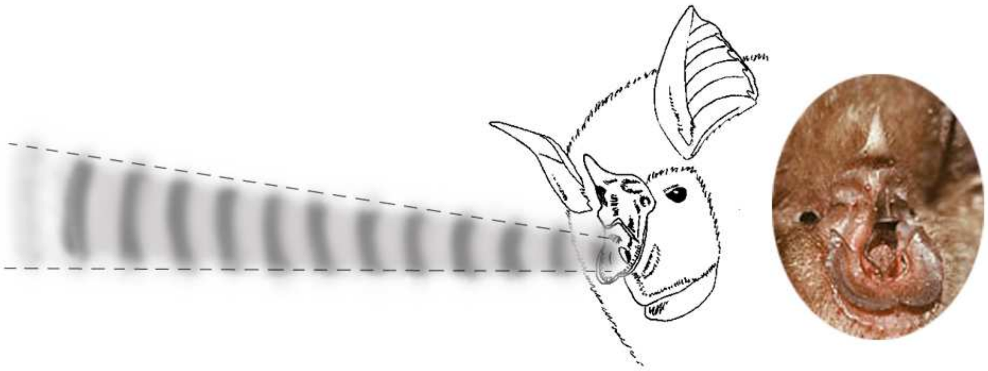

Figure 2.12- While some bats emit ultrasonic pulses through the mouth, others emit them through the nose and these species, such as the greater horseshoe bat (*Rhinolophus ferrumequinum*) pictured, have evolved elaborate 'noseleafs' to further adapt the pulse into a narrow beam (image source: Long, 2009).

The frequency of the sound produced depends not only on the average prey size hunted by each species, but also on the body size of the bat and hence the relative size of the vocal cords and length of the vocal tract. For example, the common pipistrelle (*Pipistrellus pipistrellus*), which feeds predominantly on small Diptera (flies ≈5 mm) (Vaughan, 1997), has a typical body length of 35 mm (Greenaway & Hutson, 1990) and echolocates in the region of 45-76 kHz (wavelength 4.3-7.3 mm). In contrast the noctule (*Nyctalus noctula*) feeds predominantly on Coleoptera (beetles >10 mm) (Poulton, 1929), has a typical body length of 75 mm (Greenaway & Hutson, 1990) and echolocates in the region of 22-47 kHz (wavelength 7-15 mm). However, in actuality the relationship between echolocation and prey size may be a little more complex, with the diets of some larger bats such as the parti-coloured bat (*Vespertilio murinus*) (body length 57 mm (Starikov *et al.*, 2009), echolocation frequencies 24-38 kHz (Schaub & Schnitzler, 2007)) consisting primarily of small Diptera rather than the larger prey items expected (Rydell, 1992). This may be due to the higher complexity of echoes returned from insects than might be predicted by similar returns from basic spherical objects (Waters *et al*., 1995), such as wing beat effects (e.g. Von der Emde & Schnitzler, 1986). For some insectivorous bats, therefore, low frequency pulses may not necessarily limit prey size to larger items.

In addition to this, the bats must be able to accurately detect the reflected echoes as they are bounced off a target. This has resulted in the evolution of some specialised ear adaptations, which effectively act as acoustic ‘horns’, with most bats having highly manoeuvrable ears to receive the incoming echoes at an optimal angle and having an unusually large portion of the cochlea involved with detecting high frequencies (Iwata, 1924). Some species have developed extremely large ears in comparison to the body such as the brown long-eared bat, *Plecotus auritus* (Figure 2.13), which uses low intensity pulses to both hawk and ‘glean’ (i.e. pick off) insects from foliage. It has been hypothesised that this may be linked to the hearing ability of some tympanate moth species (Waters & Jones, 1995), which can detect higher energy echolocation pulses and adopt an evasive strategy (e.g. Roeder, 1974).

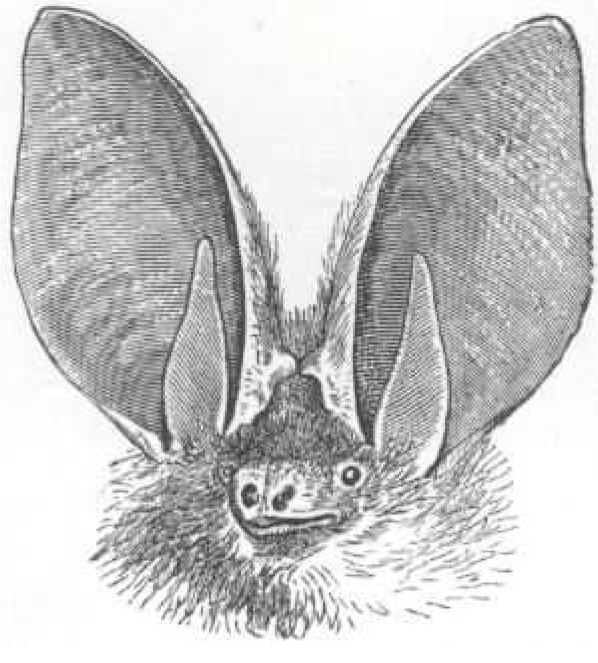

Figure 2.13- Some bat species have exaggerated ears to maximise the information that can be extracted from low-intensity echoes. Here the ears of the brown long-eared bat (*Plecotus auritus*) also have an elongated projection in front of the ear canal (the tragus), which creates acoustic side-lobes at specific frequencies (Müller, 2004; Leonard, 2006) which the bat uses to enhance localisation of targets (Wotton & Simmons, 2000) (image source: Sterndale, 1884).

Figure 2.14 provides two examples of bat ear diversity in accordance with hunting strategy. Having a binaural receptor system is also crucial to target localisation, as the timing of reception of an echo to each ear allows the bat to determine the direction of pulse reflection (see below).

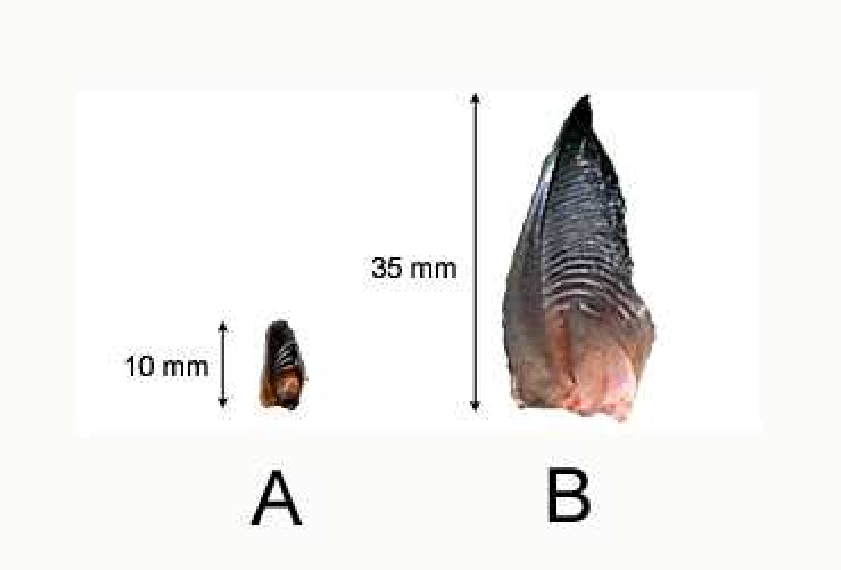

Figure 2.14- Scale representation of two types of bat ear morphology; A - Soprano pipistrelle *Pipistrellus pygmaeus* ear and B – Brown long-eared ear. The pipistrelle ear is less than 1/3 of the size of the long-eared, since this species uses much higher-intensity echolocation pulses (image source: Long, 2009).

When a hunting bat produces an echolocation pulse, vibrations in the larynx of the bat transfer energy to adjacent particles such as air molecules in the trachea and mouth. This results in the formation of a pressure wave, with particles being exposed to periods of compression, followed by periods of rarefaction, in the direction of the wave (termed a ‘longitudinal wave’). Sound waves propagate from the mouth/nose and are subject to spherical spreading to some extent (see Figure 2.15).

Figure 2.15- Waves propagate from the bat in the direction of the prey target, where a reflected echo occurs.

When the wavefront reaches an insect target, although to a degree the wave is transmitted through the target, a reflected echo occurs and is transmitted back to the bat. This reflection arises due to differences in the properties of the particles that make up the insect as compared to the properties of the particles that make up the atmosphere in which the sound wave was transmitted. This difference may be defined in terms of characteristic acoustic impedance, Z (N s m^{-3}), based on the density of the material, ρ (kg m^{-3}), and the speed of sound within that material, v (m s^{-1}):

$$Z = \rho v \tag{2.11}$$

To determine the reflection coefficient, R, at a boundary, the following equation can be employed for a 0° angle of incidence:

$$R = \left(\frac{Z_2 - Z_1}{Z_2 + Z_1} \right)^2 \tag{2.12}$$

Where Z_1 represents the acoustic impedance of air, and Z_2 the acoustic impedance of the insect target's exoskeleton or wings. The reflection coefficient can be multiplied by 100 to obtain the percentage of energy reflected as compared to the original wave's energy. Note that the boundary reflection can either be in phase or in antiphase with the original wave, however if $Z_2 = Z_1$ then impedance is matched and the wave will be transmitted only. Once the bat has received an echo, the time delay between initial pulse transmission and echo reception, t_{delay}, can be used to determine the distance to the target, d_{targ} (m), at the time of reflection as follows:

$$d_{t\arg} = \frac{1}{2}(v\,t_{delay}) \tag{2.13}$$

Where v is the speed of sound in air (≈ 330 m s^{-1}). Bats are apparently able to extract much more detailed information from the returned echo, including target size, nature and features, some of which are discussed below.

It is usual for the pressure level of a sound wave (reflected or otherwise) to be measured in terms of Sound Pressure Level (SPL), in decibels (dB). For airborne acoustics, the following equation describes it:

$$\mathrm{SPL} = 20\log_{10}\left(\frac{p_{rms}}{p_{ref}}\right) \tag{2.14}$$

Where p_{rms} is the root mean square of the pressure values (in N m^{-2} or Pa), and p_{ref} the reference pressure level, typically 20 μPa. Equation 2.15 describes the formulation of p_{rms}, where p_x represents instantaneous pressure level and n the number of values.

$$p_{rms} = \sqrt{\frac{{p_1}^2 + {p_2}^2 + \cdots + {p_x}^2}{n}} \tag{2.15}$$

It is often desirable to calculate the maximum SPL of a bat's echolocation pulse; one method of doing so is to calculate the peak SPL (pSPL). This method involves measuring the highest instantaneous pressure level at any one point in the pulse (no matter how long this level is represented over the entire pulse duration). A more favourable method is to calculate the peak equivalent SPL (peSPL). This method makes use of measurements of peak-to-peak values of the sine wave of the pulse, averaged over a set time interval, and compares an equivalent continuous, fixed-frequency sine wave of the same value with that of a sine wave of known SPL. Since the emitted pulses in some species can be extremely loud, often in excess of 90 dB peSPL re 20 µPa (Waters & Jones, 1995), the muscles in the inner ear of FM species protect the sensitive hearing of the bat by contracting to close the ear during pulse emission (Henson, 1965).

Bats typically use one of two distinct classifications of echolocation; constant frequency pulses (CF) or frequency modulated pulses (FM). Figure 2.16 provides example sonograms of both pulse types. Some bats use only one of these for their echolocation, some use a combination, and some are able to change their echolocation strategy depending on the hunting environment. Such bats to change strategy notably include some members of genus *Tadarida*, for example the Mexican free-tailed bat *T. brasiliensis*, which includes more harmonics in high clutter environments and distinctly CF pulses in open environments (Simmons *et al*., 1979). FM bats use short frequency sweeps of around one octave, always starting at a high frequency and ending at a lower frequency. For targets the size of a small insect this sweep will include the fluctuations in intensity due to Rayleigh scattering, where shorter wavelengths are more strongly reflected according to target size, which may be utilised by bats for target identification (Griffin, 1974).

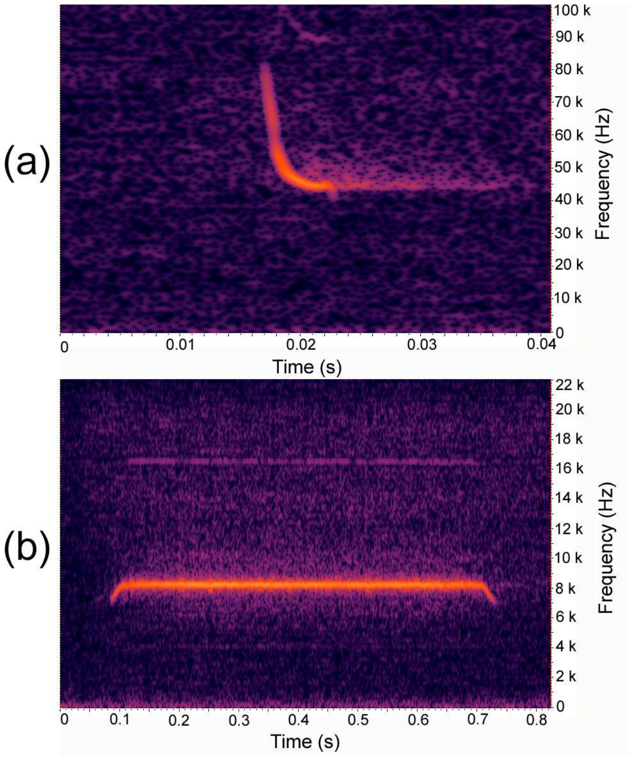

Figure 2.16- (a): An example FM pulse recorded from a common pipistrelle (*Pipistrellus pipistrellus*). Note how the frequency changes from high to low, ending in a short, almost CF, portion. The frequency of highest energy for this species is typically around 47 kHz. (b): An example CF pulse recorded from a greater horseshoe bat (*Rhinolophus ferrumequinum*). The short FM start and end portions are clearly shown, with the long CF portion at around 80 kHz. Note that this pulse was recorded using a frequency division bat detector (factor of 10), so the frequency appears lower than actual. FFT settings: Hanning window, FFT length 256 points, 75 % overlap (image source: Long, 2009).

The directionality patterns of an FM pulse vary widely with each individual frequency component of the pulse, since each frequency has different intensities at varying angles from the bat's head, meaning each frequency will differ in the chance it is reflected back toward the bat. Higher frequencies tend to be concentrated more in the forward (0°) direction (Griffin, 1974). The nature of the FM pulse may also greatly enhance localisation since the ears may receive different frequencies (due to the time delay between the ears) depending on target location. In contrast, CF bats have a much longer pulse duration, usually with a slight FM portion at the start and end of the pulse. Bats employing this mode of echolocation must therefore overcome the problem of identifying a faint echo whilst simultaneously emitting a pulse, due to temporal overlap. For this reason, CF bats rely heavily on the Doppler effect, whereby the frequency of the returning echo changes in accordance with the movement of the target (Equation 2.16).

$$\Delta f = \left(\frac{v + v_r}{v - v_e} \right) f \tag{2.16}$$

Here f is the outgoing frequency, v the speed of sound, v_r the speed of the receiver and v_e the speed of the emitter. For a rebounded pulse echo, the Doppler shift is enhanced as the frequency is affected by both the speed of the source and of the target on the return to the receiver. As noted by Griffin (1974), most bats fly at around 1-2 % of the speed of sound in air, so only a 3-4 % change in frequency is possible from a stationary target. In theory this is adequate for a detectable change in pitch for a CF bat; an FM bat may have much greater difficulty detecting Doppler shift in some or all of the outgoing frequencies. Experiments by Von der Emde & Schnitzler (1986) and Sum & Menne (1988) have demonstrated the ability of both CF and FM bats to detect and distinguish fluttering targets (analogous to the wingbeats of an insect), possibly by listening for the acoustic ‘glints’ produced by insect wings in repeated patterns as they reach a position that reflects echoes back to the bat more directly (see Figure 2.17). Bats are therefore able to utilise a variety of auditory cues to interpret the properties and movement of a target.

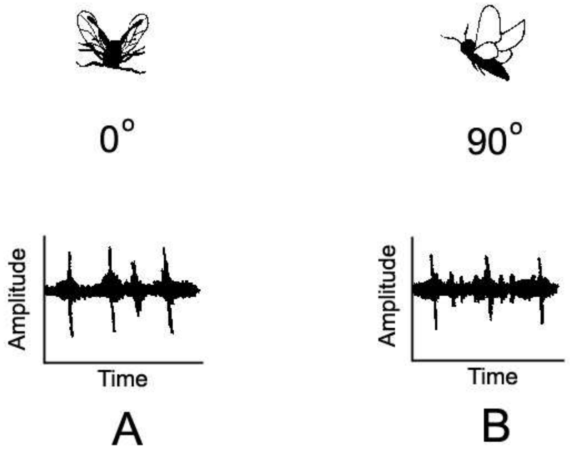

Figure 2.17- Representations of the acoustic glint patterns reflected from insects in flight. Waveform A represents the glint pattern from a beetle flying directly toward the microphone (0º), while waveform B represents that of a moth flying side-on to the microphone (90º).

Although both patterns appear very similar, bats are able to use the small discrepancies in glint frequency to distinguish prey targets (adapted from Kober & Schnitzler, 1990; image source: Long, 2009)

As first identified by Griffin (1974), the most important features of the echolocation pulses of the bat are as follows:

1. The duration- This is particularly important for FM bats as a short pulse duration is required in order to receive the echo from the emitted pulse after it has been sent out, without a temporal overlap. Because of this, the duration of the pulse changes according to distance to the target, since the time between emitted pulses decreases as the bat approaches its prey (see Figure 2.18). Increasing the pulse rate also enhances the acuity of each available echo, while a lower sweep rate increases the chance that a specific frequency discrepancy is detected in the echo (Boonman & Ostwald, 2007).
2. The intensity- The emitted pulse has to have a high intensity in order to maximise the energy contained in the returning echo. Echoes reflected from a target will have much less energy according to the size of the target, its properties, the scattering of the pulse, the degree of attenuation of the sound and distance and angle of the target.
3. The frequencies used- These must be compatible with the size of the target and the distance to be covered, and will also affect the frequencies that are returned to the bat in the echo after Doppler shifting. This is particularly important for determining speed and movement direction information.
4. Variation of frequency and intensity over time- As an FM bat approaches a target, the frequency of greatest intensity becomes higher, shortening the wavelength to allow more energy to be reflected from the small target. Pulses simultaneously become more broadband to maximise the information that can be obtained from the echoes, as shown in Figure 2.18. In the terminal phase, pulses may then become more narrowband again (Simmons *et al*., 1979) which may help to enhance perception of target Doppler/velocity information. As identified by Boonman and Ostwald (2007), pulse bandwidth limits the separation

between emitted pulses as it creates some optimum whereby the bat can most efficiently separate multiple echo returns, but increasing the bandwidth improves the resolution of returned echoes.

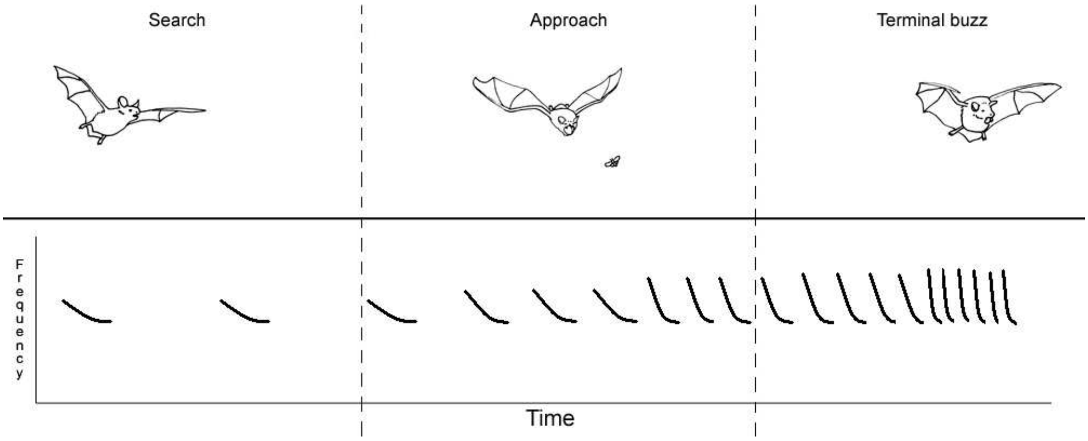

Figure 2.18- Demonstrating the change in pulse quality as an FM bat detects and captures an insect. The sequence is divided into three segments after Griffin *et al*. (1960), the ‘search’, ‘approach’ and ‘terminal buzz’ phases. During searching, the bat emits a narrowband pulse at fairly low repetition. When an insect is detected and is approached, the pulse repetition rate gradually increases and the pulses become more broadband. Just prior to capture of the insect, the pulses are as close together as possible to rapidly localise the target without temporal overlap of pulse and echo, producing a ‘feeding buzz’ (image source: Long, 2009).

It is clear that bats have been able to adapt their echolocation ability primarily for the purpose of locating, pursuing and capturing small prey targets in a variety of natural habitats. However, a number of different hunting methods have evolved, leading to diversification in echolocation methods, which include ‘gleaning’ (picking off insect prey from leaves and other surfaces), ‘aerial hawking’ (hunting in open spaces) and even ‘trawling’ (hunting along the surface of the water for insects or even fish (e.g. Altenbach (1989))). Because bats have such specific hunting strategies, they may become ‘victims of their own success’ in terms of adaptation to new environmental challenges, especially those that have appeared rapidly through human development. The implications of this will be discussed in the following sections.

2.2 Wind Power

The mechanical harnessing of wind energy has historically been employed by a vast number of cultures since records began (Hills, 1994). In many countries, wind is an abundant resource, seasonally predictable (although variable) and readily harnessed even with basic technology. In fact, the earliest use of a wind-powered structure has been credited to Hero of Alexandria (c. 50-70 AD), who recorded the use of a ‘windmill’ to drive air via a pump into an altar organ (Woodcroft, 1851) (Figure 2.21).

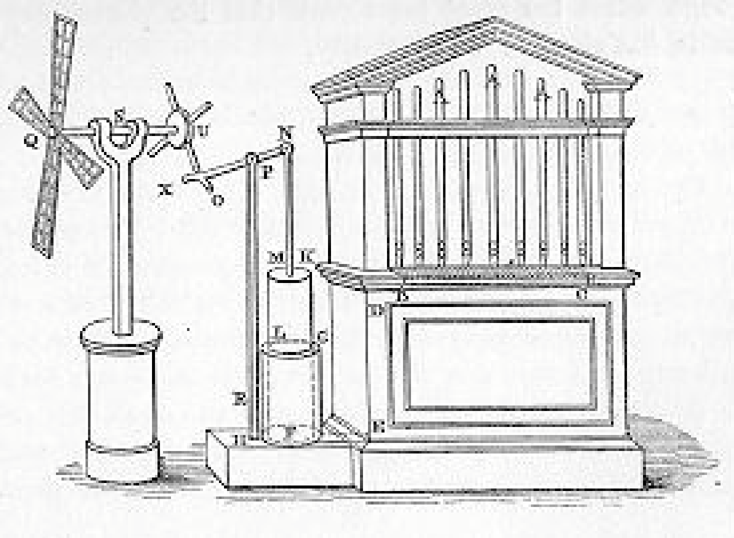

Figure 2.21- Hero’s ‘windmill’ powered altar organ (image source: Woodcroft, 1851).

Other early writings from Persia indicate the use of wind ‘mills’ in the truest sense; around 644 AD a technician constructing windmills was reported to have murdered the head of state in a dispute over the taxation of the structures (White, 1962). Sistan, in modern day Iran, was particularly renowned as the ‘land of winds’ and for harnessing this power for milling and pumping water c. 950 AD (Klemm, 1959). Windmill usage thereafter became widespread in Europe c. 1100 AD and China c. 1250 AD (Hills, 1994). From then on, windmill design evolved gradually to become more efficient and diverse, with windmills being used not only for milling, but also land drainage and, later, industry (initially through the Dutch wind-powered sawmill, c. 1600 (Hills, 1994)).

The first record proposing the harnessing of electrical energy from the wind occurred in 1881 by Sir William Thomson, a Scottish physicist and engineer (Wolff, 1888), although at the time such developments were not yet feasible due to lack of technological advancement. By the mid to late 1880’s a few small trial rigs were set up for wind DC generation in Massachusetts, USA (Hills, 1994) and by 1890 one notable large-scale ‘windmill dynamo’ had been installed by Charles F. Brush of Cleveland, Ohio (Figure 2.22), to provide power to his estate.

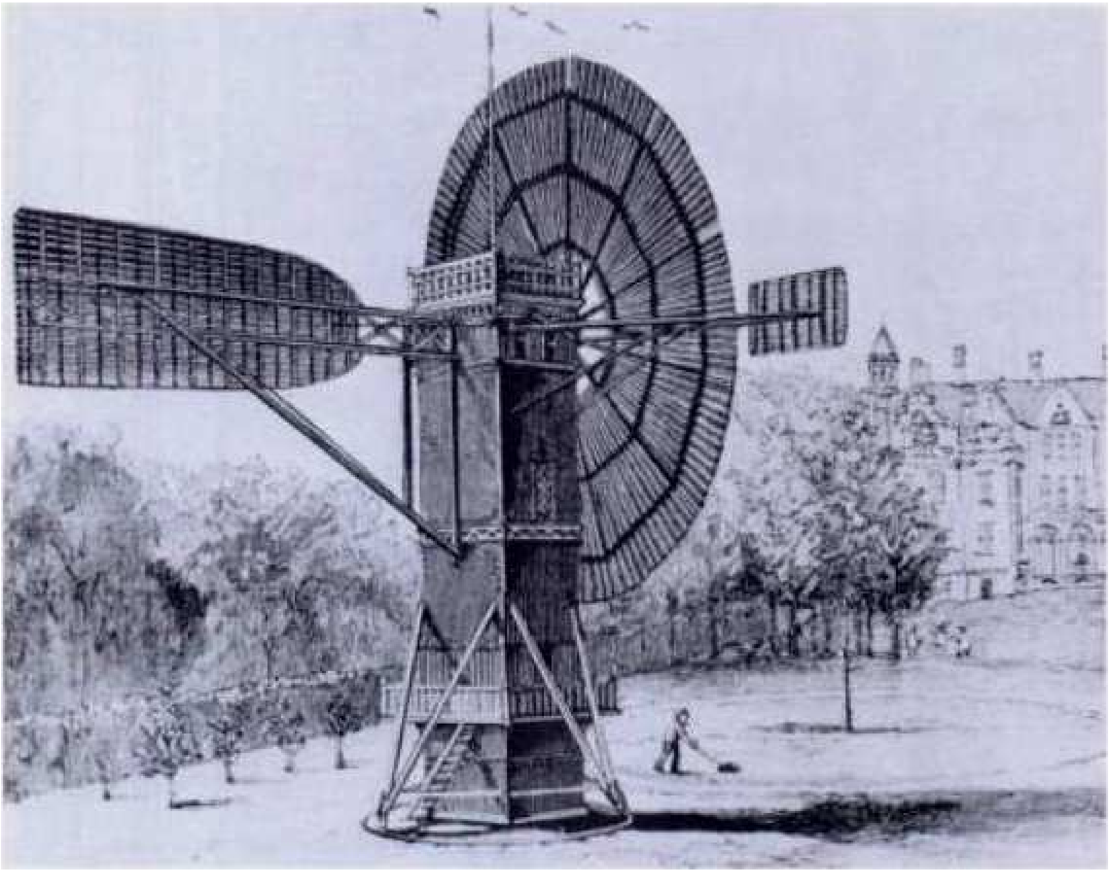

Figure 2.22- Depicting one of the first windmills to generate electricity on a large scale, the ‘windmill dynamo’ of Charles F. Brush (image source: Anon., 1890).

One of the early pioneers to study and trial the use of wind-generated power was Danish scientist Poul La Cour. From 1891 La Cour systematically trialled and improved upon windmill designs for agricultural power generation, and from here their popularity began to grow, despite the remaining problem of regulating the speed of the dynamo (Hills, 1994). The real breakthrough in wind power development came at the end of the first World War, through research inspired by aeroplane propeller design in Europe. In 1926, Russian engineers Sabinin and Yurieff, and German engineer Bilau, designed four-bladed propeller-like windmill rotors (Hills, 1994), using a wind tunnel to create a more aerodynamic and efficient design, which greatly improved generation capabilities. However, it was not until 1941 in Vermont, USA that the first ‘wind turbine’ was connected to the electrical grid using AC (Koeppl, 1982). Shortly thereafter development was halted by the onset of World War two, but began anew, albeit slowly, in the early 1950’s. Edward W. Golding, a British Electrical Engineer, summarises the progress in 1954:

> “Some two percent of the sun’s energy falling on the Earth is converted into wind energy and it has been estimated that even the small fraction of this total which could conceivably be captured would be equivalent to that produced annually by the burning of some 1,500 million tons of coal. But this capturing has not yet begun on any significant scale. No precise calculation of the present annual energy produced from the wind can be made in the absence of records of the capacities of wind power installations in different parts of the world…”

The oil crisis of 1973 spurred renewed interest into alternative methods of energy generation, with the governments of several countries providing tax incentives for wind installations, including the USA, UK, Denmark and Germany (Ibenholt, 2002). These subsidies, coupled with new technological advancement in materials and design, triggered rapid growth of the wind industry from this period up to the present day. Toward the end of the 1990’s, wind power had become the fastest growing global energy technology with an annual growth rate of around 30 % (BWEA, 2001), boosted by the promotion of the ‘green’ credentials of wind turbines. This has become particularly important over the last decade as more substantial measures have been taken to reduce carbon emissions worldwide; in 2008, 43 % of all new power installations in the EU were wind turbine installations (EWEA, 2009), in line with government targets. It is expected that wind power will therefore play a crucial role in future energy production, so it is vital that any potential problems which may provide an obstruction to development be well understood in order for mitigation and solutions to be implemented. This will be discussed in the following chapter.

2.2.1 Turbine Structure and Function

Turbines are typically categorised into two main groups, vertical-axis and horizontal-axis, relating to the angle of the rotor mounting in relation to airflow. By far the most common turbine design is horizontal-axis (see Figure 2.23), which will be the focus of this work.

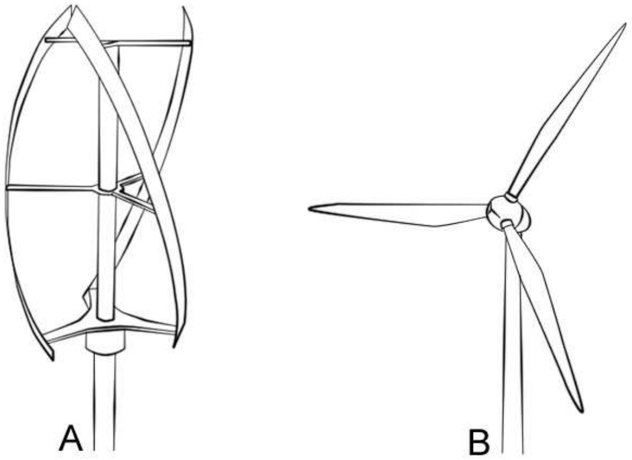

Figure 2.23- Vertical-axis wind turbine (A), with blades turning parallel to airflow, and horizontal-axis wind turbine (B), with blades turning perpendicular to airflow.

Horizontal-axis wind turbines rely on propeller-like blades to create lift, L (kg m s^{-2} (N)), in incident airflow of velocity, v (m s^{-1}), which is also dependent on air density, ρ (kg m^{-3}), blade surface area, A (m^2) and the lift coefficient, C_L:

$$L = \frac{1}{2}\rho v^2 A C_L \tag{2.21}$$

Although generation with a single blade is possible, these tend to be unstable and audible in the human range of hearing (Hau, 2006), so it is much more common for turbines to have two or three blades (although five and six blade machines are also used). Blades are fixed symmetrically around the rotor 'hub' where the internal gearing system used to generate power is housed directly behind the hub, in the nacelle. The speed of rotation of the blades relative to wind speed is paramount to energy generation efficiency; too slow a rotation and the incident airflow is largely unaffected, while too fast a rotation causes the incident airflow to be disrupted entirely and most of the energy dissipated (Twidell & Weir, 1986). Blade tip speed is defined as $r\omega$, where r is the radius of the rotor swept region (in m) and ω the angular velocity (in rad. s^{-1}), and this is equal to λv_{wind} (where λ is the tip speed ratio and v_{wind} the incident wind speed (in m s^{-1})). The tip speed ratio is that of the speed of the blade tip as compared to the speed of the oncoming wind. This optimal rotation speed requirement results in the formulation of an optimal blade tip speed ratio, λ_o, defined by Twidell & Weir (1986) as:

$$\lambda_o = \frac{2\pi}{kN} \tag{2.22}$$

Where k is a constant ≈ ½ and N is the number of blades. It is therefore apparent that the speed at which the turbine blades travel is directly proportional to, and interdependent on, the relationships of rotor diameter, angular velocity, tip speed ratio and wind speed. Typically, turbines operate within a set range of wind speeds up to a maximum, at which point a braking system is employed to decelerate or ‘feather’ the blades and stop the turbine rotor to prevent damage. All turbines are given a maximum ‘rated’ power capacity at a set wind speed (Figure 2.24), which is normally 12 m s^{-1} (Twidell & Weir, 1986).

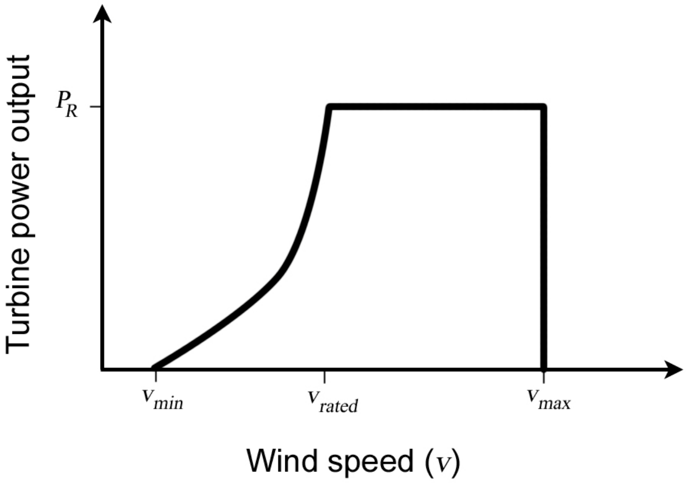

Figure 2.24- Generalised representation of the power output of a wind turbine according to wind speed. The rated power, P_R, is produced at the rated wind speed, v_{rated}. Also shown is the minimum wind speed required for power generation, v_{min}, and the maximum wind speed, v_{max} (adapted from Twidell & Weir, 1986).

For some of the large scale turbines with rotor diameters of 80 m or more, the blade tip speeds at the rated wind speed can reach in excess of 90 mph. However, not all turbines are built on such a huge scale, and in recent years there has been a surge of interest in the ‘microgeneration’ of power for domestic use, through small scale wind turbines, collectively termed ‘microturbines’. Such turbines have a rotor diameter of 2 m or less, although typical blade tip speeds at the rated wind speed can still be in excess of 100 mph due to high angular velocity. An understanding of the importance of blade speed to wind turbine function is pivotal to understanding the problem discussed in the following section.

2.3 Bats and Wind Turbines

Although wind turbines have undergone rapid development over the last 30 years, it is only relatively recently that their impact on wildlife has been brought to scientific and public attention, perhaps due to their increasingly widespread deployment over a wider range of habitats than ever before. The phenomenon asserted itself with incidents of bird strike at early experimental large scale turbine installations in the 1980's (Erickson *et al*., 2005), with studies into bird mortality at wind plants developing throughout the US well into the late '90's and beyond. As the majority of bird-strike surveys were conducted during the day, when most birds are active, it was not until early 2000 that bat-strike at wind plants began to be noticed during ground carcass surveys, with many hundreds of bat carcasses turning up, at some plants outnumbering bird carcasses by almost 7:1 (Kerns & Kerlinger, 2004). Further study revealed that the phenomenon of bat-turbine mortality was widespread throughout the US and reports of similar incidents began to appear from Europe and other countries worldwide. In fact, the first documented bat-turbine incident occurred at an Australian wind plant in the 1970's, where twenty two white-striped free-tailed bats (*Tadarida australis*) were found dead around turbine bases over a period of four years (Hall & Richards, 1972), although this report remained largely ignored until some thirty years later.

Bat-turbine interaction presents a very different problem to that relating to birds. Bats are somewhat unique with regard to habitat (Westaway, 2007) and their reliance on acoustic cues to navigate, with current data suggesting that bats are much more vulnerable to turbines than birds (Tuttle, 2004), despite records for avian fatalities having been kept for longer. Visual turbine effects problematic to birds such as blade motion smear (Hodos, 2003) are thought to have little relevance to bats and the ability of birds to 'hear' turbines (e.g. Dooling, 2002) is likely to be entirely dissimilar to the acoustic profile of a turbine presented to a bat. The involvement of bats with wind turbines has today become the more prominent and urgent area of study, but remains the most difficult to prove in the field (Harbusch & Bach, 2005).

2.3.1 Key Studies of Bat-Turbine Interaction

Although most data on bat-turbine mortality comes from the US, European bat-turbine studies are on the increase. The following subsections describe the findings of several key studies regarding bat-turbine interaction. The field is dominated by the assessment of large scale turbines and wind farms; the impact of microturbines on bat species has yet to be studied in detail although incidents of bat-microturbine mortality have been reported in the UK (BCT, 2007).

Bach (2001)

Germany

Bach investigated the indirect impact of 70 planned turbines (30 m hub height, rotor diameter 30 m) on local bat species at a proposed hedge-rich wind plant site in Germany (Windpark Nidlum). In some cases the hedges were only 10 m from the nearest turbine; hedgerows are used by many bat species for foraging and navigation (e.g. Verboom & Huitema, 1997). After installation of the turbines, a significant reduction in the number of serotines (*Eptesicus serotinus*) hunting in the area was observed, although serotines were still occasionally observed hunting in the immediate vicinity of the turbines. The number of observed serotines flying around the turbine site post turbine erection decreased during the study, despite the number of serotines in the wider area remaining constant throughout. This seems to suggest that the installation of the turbines directly impacted the local serotine population in that area. However, it was also noted that during turbine construction, a number of hedgerows had to be removed and there was a large amount of scrub clearance, which could also have had a direct impact on the serotines' hunting environment in this area. Conversely, the number of hunting common pipistrelles (*Pipistrellus pipistrellus*) in the turbine study area was actually observed to significantly increase after construction. The total area utilised by this species also increased during the course of the study. Common pipistrelles in the area were not noticed to avoid the active turbines in the same way as the serotines did. A further interesting finding of this study was that the common pipistrelles were observed to alter their reactions to the turbines with varying wind direction. When turbine rotors were parallel to the hedgerow along which pipistrelles were hunting, the bats did not alter their flight path at 2-10 m in height and would not approach the turbine closer than 4-10 m. On the other hand, when rotor blades were perpendicular to the hedgerow, the pipistrelles were observed to dive underneath the rotor region to a height of 0.5-1 m (Figure 2.31), although possible reasons for this were not given.

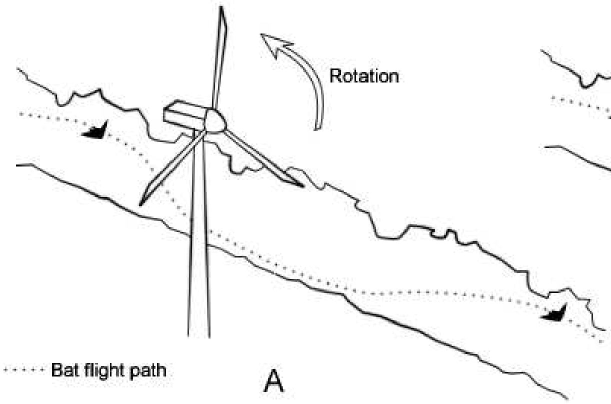

Figure 2.31- Demonstrating how the flight path of the common pipistrelle along a nearby (<10 m) hedgerow changes in accordance with rotor angle; perpendicular (A) and parallel (B). Note that the dip in flight path A when the rotor blades are perpendicular occurs in both directions along the hedgerow (Bach, 2007) (Adapted from Bach & Rahmel, 2004).

Erickson *et al*. (2002)

North America

This industry report documented several species’ mortality figures for a variety of wind plants, including Minnesota (613 bat fatalities year^{-1}), Wyoming (138 bat fatalities year^{-1}) and Oregon (28 bat fatalities year^{-1}). The authors stated that bat-turbine collisions during the US bat breeding season were almost non-existent, despite some large populations documented in close proximity to US turbine plants.

Johnson et al. (2003)

North America

This study documented 184 bat collision fatalities at a wind plant in Minnesota between 1996-1999, most of which were Hoary bats *Lasiurus cinereus* and eastern red bats *L. borealis*. The mortality rate was estimated at 0.07-2.04 fatalities per turbine per year, and it was suggested that most fatalities were migrant rather than resident breeding bats. While 24 % of all US bat species have been discovered in turbine collisions, Hoary bats account for nearly half of these (Erickson *et al*., 2002; Johnson & Kunz, 2004). Hoary bats use multiharmonic echolocation calls with a FM-CF structure (having both a frequency modulated and a constant frequency component), consistent with foraging in open air but near obstacles (Barclays, 1986). They are, however, considered poorly manoeuvrable in flight and this may put them at higher risk (Erickson et al., 2002). Other species of bat killed by turbine interactions in the US include silver-haired (*Lasionycteris noctivagans*), northern long-eared (*Myotis septentrionalis*), western red (*Lasiurus blossevillii*), Brazillian free-tailed (*Tadarida brasiliensis*), long-eared myotis (*Myotis evotis*) and seminole (*Lasiurus seminolus*) bats (Johnson & Kunz, 2004; Kunz *et al.*, 2007; Arnett *et al.*, 2005), as well as big brown (*Eptesicus fuscus*), little brown (*Myotis lucifugus*) and eastern pipistrelle (*Perimyotis subflavus*) bats (Erickson *et al*., 2002; Kunz *et al.*, 2007; Arnett *et al.*, 2005). None of these US species reported are currently endangered (Johnson & Kunz, 2004), although it is entirely possible that other bat species are being killed at different times of the year to those previously studied (Arnett *et al.*, 2005) since year-round assessments are scarce.

Kerns & Kerlinger (2004)

North America

An industry study of a wind farm in west Virginia monitored forty four turbines of approximately 116 m to highest point of blade tips. A total of 475 bat carcasses (the most common of which was the eastern red bat; a total of 42.1 % of all bat carcasses) were collected during the study period of April to November, with the majority of these found between August and September (92.5 %). This peak may have been linked to the seasonal migration of certain species. Twelve of the turbines studied were lit with red strobe lights, although no significance with regard to lighting was found here. Most bat carcasses were collected after warm, low wind speed nights.

Dürr & Bach (2004)

Germany

In Germany, all published data relating to bat and bird turbine mortality is held in a national database at the Landesamt Brandenburg (Staatliche Vogelschutzwarte). In 2004 Dürr & Bach performed analysis on all the bat data held, which listed 207 bat-turbine mortality incidents from ten species throughout Germany, up to the date of the study. It was found that the most frequently killed species was the noctule (*Nyctalus noctula*) (47.8 %) and Nathusius' pipistrelle (*Pipistrellus nathusii*) (19.3 %), with the genus *Pipistrellus* alone contributing to 31.5 % of all recorded bat fatalities in Germany. The fact that noctules as a species had the highest mortailty rate is interesting, since bats in the genus *Pipistrellus* are generally considered to be more common with a widespread distribution throughout Europe (e.g. Mayer & Von Helversen, 2001). It is therefore possible that certain bat species, for reasons as yet unknown, are at a greater risk of turbine mortality than others. A marked mortality peak was observed between June-August, although the data may have been skewed since carcass surveys were not regular or evenly distributed throughout the year. The data demonstrated that most bat carcasses were found under turbines that were less than 50 m from wooded areas, however dead bats were also reported at distances up to 200 m between the turbine site and the nearest forest. Of the 292 turbines investigated, it was found that mortality occurred around all types of turbine with a hub height over 51 m. No mortality was found to occur when the rotor hub height was below 50 m, although this was thought to be due to the smaller turbines in the study being positioned along shoreline where bat densities were very low. Bat deaths were found to occur regardless of the rotor diameter (those in the study measured 21-90 m), although there appeared to be no correlation between the rotor size and the number of bats killed at that site.

Arnett *et al*. (2005)

North America

Arnett and colleagues investigated two wind energy plants (a total of 64 turbines), in Pennsylvania and west Virginia, for 6 months (July-September) of the year of study. In addition, thermal imaging camera observations were taken during August night monitoring to provide 2,398 recorded object passes, of which 41 % were bats, 20 % were insects, 1 % were birds and 35 % were unidentified. Detailed analysis of thermal images showed that bats were both attracted to and investigated the moving (and stationary) blades, and were in some cases directly struck by them. There were even captured shots of bats attempting to or actually landing on stationary blades and towers, and it was hypothesised that the bats were curious about investigating the turbines as potential roost sites or gleaning opportunities. It was found that there were significantly more adult male bat fatalities (~60 %) than adult females (~25 %), juvenile males (<10 %) or juvenile females (<5 %) ($p<0.0001$), and that bat fatalities were highly variable throughout the study. This may indicate a variation in site use by male and female bats, which could have interesting implications for population impacts on a larger scale. As with other US studies, most bats observed and killed were Hoary and eastern red bats. No bat carcasses were found around the one turbine not in operation during the course of the study. Nightly bat passes ranged from 9 - 291 turbine^{-1}. The highest recorded carcass injury type was wing damage (20 %), whereas 42 % had no visible sign of external injuries. A small percentage of carcasses had lacerations to the head or back; some bats were found grounded around the turbines but alive, and were later released. An average of 0.8 bat carcasses were found per turbine per night during the study. Analysis of site fatality distribution revealed that 88.5 % of all carcasses were discovered within 40 m of the turbine bases.

Baerwald *et al*. (2008)

Canada

Hoary and silver-haired bat carcasses were retrieved from a wind farm in Canada and post mortem carcass examinations conducted to look for evidence that changes in pressure (barotrauma) could be causing bat deaths rather than direct physical blade strike. Of 188 carcasses, 46 % had no evidence of external injury that could cause death (such as broken bones, lacerations, etc.). Of these, 57 % had internal haemorrhaging and 17 bats with lung tissue examined histologically demonstrated lesions consistent with barotrauma. The authors concluded that it is possible that some bats are killed by pressure fluctuations behind turbine blades, although there is strong video evidence that bats are also being struck directly by blades (e.g. Arnett *et al.*, 2005).

Arnett *et al.* (2009)

North America

This study focussed on the effect on bat mortality of changing the operational cut-in wind speeds of turbine rotors of twelve turbines at a wind plant in Pennsylvania, between the months of July to October. The number of bat fatalities was almost five and a half times greater at turbines with a standard default operational cut-in at a wind speed of 3.5 m s^{-1}, and it was found that operational cut-ins for turbines at wind speeds above 5 m s^{-1} were most beneficial in lowering the number of bat deaths.

2.3.2 Wind Turbine Bat Mortality Projections

Based on research findings including the key studies mentioned in the last section, several projections as to the numbers of bats likely to be fatally involved in wind turbine interaction have been produced for various locations. According to Johnson & Kunz (2004), the overall average projection for wind farms in north America is 3.4 bat fatalities per turbine per year, or 4.6 bats per MW per year, with the highest estimated impact being in the eastern states. Kunz *et al.* (2007) suggest the number of bats killed in the eastern US ranges from 15.3 to 41.1 fatalities per MW per year, with much lower mortality rates reported for the western US, 0.8 to 8.6 fatalities per MW per year. However, much more data exist for eastern America, and other reasons for variability include lack of systematic, universal monitoring/carcass searching techniques, local habitat/climate variation and environmental location of turbines. Further investigation is needed concerning these factors, as bat mortality figures from Canada are reportedly similar to those for the eastern US (Kunz *et al.*, 2007). Current data from Europe seems to similarly reflect that of north America (MEDD, 2004); Table 2.31 lists the projected yearly mortality rates calculated using numbers from the current literature.

Projected figure	Species fatality	Projection context	Location	Author(s)
0.07-2.04	Bat deaths	Turbine^{-1} yr^{-1}	USA (Minnesota)	Johnson *et al*. (2003)
3.40	Bat deaths	Turbine^{-1} yr^{-1}	USA (Entire)	Johnson & Kunz (2004)
4.60	Bat deaths	MW^{-1} yr^{-1}	USA (Entire)	Johnson & Kunz (2004)
~3.07	Bat deaths	Turbine^{-1} yr^{-1}	USA (Minnesota)	Erickson *et al*. (2002)
2.00	Bat deaths	Turbine^{-1} yr^{-1}	USA (Wyoming)	Erickson *et al*. (2002)
0.74	Bat deaths	Turbine^{-1} yr^{-1}	USA (Oregon)	Erickson *et al*. (2002)
15.30-41.10	Bat deaths	MW^{-1} yr^{-1}	USA (Eastern)	Kunz *et al.* (2007)
5110.00	Bat deaths	Wind Plant^{-1} yr^{-1}	France	MEDD (2004)
328.50	Bat deaths	Turbine^{-1} yr^{-1}	USA (West Virginia)	Arnett *et al.* (2005)
259.15	Bat deaths	Turbine^{-1} yr^{-1}	USA (Pennsylvania)	Arnett *et al.* (2005)
1.00-6.00	Bat deaths	Microturbine^{-1} yr^{-1}	UK	BCT (2007)
1.00-6.00	Bat deaths	Turbine^{-1} yr^{-1}	Croatia	Zagmajster *et al*. (2007)
Up to 40.00	Bat and bird deaths	Turbine^{-1} yr^{-1}	France	MEDD (2004)

Table 2.31- Projected mortality rates for various turbine sites taken from current literature. All figures calculated to give annual projection, although not all reported figures were taken from studies conducted regularly throughout the entire year. Not all studies included a figure corrected for scavenging or carcass retrieval error.

It is important to note that of the few studies done to assess bat mortality at turbine sites, the figures given may underestimate the actual fatality rates per turbine due to lack of systematic studies conducted throughout the year, and lack of annual repeatability (Bach & Rahmel, 2004; Tuttle, 2004; Kunz *et al.*, 2007). Reports that produce small figures for bat mortality rates can be misleading due to assessment error (Tuttle, 2004) as bats may be overlooked during carcass searches due to their small size and inconspicuous colouration (Kunz *et al.*, 2007), and studies previously designed for bird carcass searches may have initially disregarded bat bodies. Potential problems exist when estimating turbine mortality rates based on carcass retrieval due to scavenging predators and inefficiency of searcher (Morrison, 2002), but most contemporary studies typically include a retrieval error correction to allow for this. However, few studies include carcass searching at ‘control’ sites, i.e. sites away from turbine locations, in order to test the typical abundance of bat carcasses in more ‘standard’ locations.

2.3.3 The Potential Impact on Bat Populations

While it is clear that wind turbines are responsible for mortality in several bat species, what is not clear are the long-term effects of this on local bat populations. There are 834 recognised species of microchiropteran bats globally, 44 % of which are threatened or near-threatened species (Hutson *et al*., 2001). In the UK alone there are 17 species of bats, all of which are protected under UK and European law by the Wildlife and Countryside Act (HMSO, 1994), with the UK having at least 2 “vulnerable” species and 3 “near-threatened” species (Hutson *et al*., 2001). Table 2.32 lists the species of bats found in the UK and their conservation status.

Bat Species	Call Duration (ms)	Frequency Range (kHz)	Frequency With Most Energy (kHz)	Interpulse Interval (ms)	Call Type	Bat Size	Prey Type	Worldwide Status
Bechstein’s *Myotis bechsteinii*	3.3	35-108	61	96.4	FM	Span- 28 cm Body- 45 mm	Woodland spp. Diptera (flies) Lepidoptera (butterflies, moths and skippers) [6]	VUA2c
Brandt’s *Myotis brandtii*	4.2	32-103	51	86.2	FM	Span- 24 cm Body- 40 mm	Diptera [6]	LR/lc
Daubenton’s *Myotis daubentonii*	6.2 [3]	32-85	49	69.8	FM	Span- 25 cm Body- 45 mm	Diptera [6]	LR/lc
Greater mouse-eared *Myotis myotis*	*6.0 [2]*	*22-86 [2]*	*37 [2]*	*?*	*FM*	*Span- 40 cm* *Body- 70 mm*	*?*	*LR/nt*
Whiskered *Myotis mystacinus*	3.0	34-102	53	86.2	FM	Span- 24 cm Body- 40 mm	Swarming Diptera [6]	LR/lc
Natterer’s *Myotis nattereri*	3.8	23-115	53	67.1	FM	Span- 28 cm Body- 45 mm	Diptera [6]	LR/lc
Barbastelle *Barbastella barbastellus*						Span- 27 cm Body- 45 mm	Lepidoptera [6]	VUA2c
Call type 1	2.5 [1]	30-38 [1]	33 [1]		FM			
Call type 2	4.1	29-47	38	63.8	FM			
Brown long-eared *Plecotus auritus*	2.5	27-56	45	104.2	FM (MH)	Span- 25 cm Body- 45 mm	*Noctua* spp. moths [5] Lepidoptera [6]	LR/lc
Grey long-eared *Plecotus austriacus*	5.8 [2]	18-45 [2]	28 [2]	104.2	FM (MH)	Span- 25 cm Body- 45 mm	*Noctua* spp. moths [5] Lepidoptera [6]	LR/lc
*** Nathusius’ pipistrelle** *Pipistrellus nathusii*	6.9 [2]	36-62 [2]	41 [2]	103.0	FM (ending CF)	Body- 52 mm	Diptera [6]	LR/lc
*** Common pipistrelle** *Pipistrellus pipistrellus*	5.6	45-76	47	93.0	FM (ending CF)	Span- 22 cm Body- 35 mm	Diptera [6]	LR/lc
*** Soprano pipistrelle** *Pipistrellus pygmaeus*	5.8	53-86	55	81.0	FM (ending CF)	Span- 22 cm Body- 35 mm	Diptera [6]	*Not listed*

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Bat Species	Call Duration (ms)	Frequency Range (kHz)	Frequency With Most Energy (kHz)	Interpulse Interval (ms)	Call Type	Bat Size	Prey Type	Worldwide Status
*** Serotine** *Eptesicus serotinus*	8.8	25-55	31	116.0	CF	Span- 36 cm Body- 64 mm	Diet varies depending on habitat, but may prefer Coleoptera (beetles) [6]	LR/lc
*** Leisler's** *Nyctalus leisleri*	8.5	25-54	29	226.0	FM/NB	Span- 30 cm Body- 64 mm	Diptera [6]	LR/nt
*** Noctule** *Nyctalus noctula*				336.0		Span- 36 cm Body- 75 mm	Coleoptera [5]	LR/lc
Call type 1	11.5 [1]	26-47 [1]	27 [1]		FM			
Call type 2	13.8	22-33	22		NB			
Lesser horseshoe *Rhinolophus hipposideros*	31.7	93-111	110	79.9	CF (FM start and end)	Span- 25 cm Body- 40 mm	Coleoptera [5], [6] Noctuid moths [5] Lepidoptera [6]	LR/lc
Greater horseshoe *Rhinolophus ferrumequinum*	37.4	69-83	81	83.0	CF (FM start and end)	Span- 34 cm Body- 64 mm	Coleoptera [5], [6] Noctuid moths [5] Lepidoptera [6]	LR/nt

Table 2.32- Parameters of all 17 species of UK bat (note that the greater mouse-eared bat may be extinct in Britain). Species marked with a * and listed in bold are considered to be at highest risk of wind turbine mortality due to their aerial hawking foraging strategy [7]. Echolocation values averaged from [1] and [2], except where referenced independently. Body size values obtained from [3]. Worldwide conservation status as listed in the 2006 IUCN Red List [4]. VUA2c indicates the species is vulnerable, expecting a 20% decline in population over the next 10 years/3 generations due to loss of habitat. LR/nt indicates the species is lower risk but near threatened. LR/lc indicates the species is lower risk of least concern. Note that all British bat species are protected due to recent declines in UK population levels. Call types and interpulse intervals obtained from [3], abbreviations: FM- frequency modulated; CF- constant frequency; MH- multi-harmonic; NB- narrow bandwidth.

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British bats are in need of special protection as there have been extensive reports for the recent decline in many UK and European bat populations (Wickramasinghe *et al*., 2003). There is well-documented evidence for the decline of the *Rhinolophus* species in Europe, which for the greater horseshoe bat (*R. ferrumequinum*) alone is believed to be a 90 % decrease in the UK over the past 100 years (Hutson *et al*., 2001). The UK Biodiversity Group (1998) identifies at least four European bat species resident in the UK as being in urgent need of sustainable conservation. Rodrigues *et al*. (2006) point out that many of the UK bat species are known to fly in the open or above canopy level, and could therefore be at particular risk of turbine interaction. Betts (2006) identifies the British bat species at highest risk from turbine mortality as the noctule, Leisler's bat, the serotine, the common pipistrelle, the soprano pipistrelle (*Pipistrellus pygmaeus*) and Nathusius' pipistrelle, based on their reliance on an aerial hawking feeding strategy (Vaughan *et al*., 1997), and evidence of interaction with turbines in Europe. These species are highlighted (***** bold font) in Table 2.32.

Bats are particularly susceptible to population instabilities due to their slow generation rates; usually only one bat pup is born to each female per year, and young adult bats do not become reproductively active until they are 10-15 months old (Hutson *et al*., 2001), although bats are relatively long-lived with some individuals reaching ages of up to 30 years (Hutson *et al*., 2001). It should be considered that total mortalities in the first year of life may be as high as 40-50 % (Hutson *et al*., 2001), independent of turbine incidents. The potential impact of increased bat mortality rates through turbine collisions on already threatened bat populations, therefore, is high, and thus the importance of research in this area does not need further underlining. However, it must be considered that turbines not only pose a direct risk to bats through fatal interaction, but also an indirect risk due to loss of foraging habitat, interruption of commuting routes and disturbance of roost sites (Williams, 2007), as well as potentially affecting the positioning of roosts and breeding sites (Bach, 2001; Cryan, 2008). Modification of the landscape during construction of turbines (such as creating clearings in a forest as in some eastern US sites) may be creating favourable foraging habitats for a variety of bat species (Arnett *et al.*, 2005), but habitats may also be significantly altered with negative foraging effects during turbine construction (Bach & Rahmel, 2004). Bats are known to be affected by the loss of foraging sites, such as removal of hedgerows and the heavy use of anthelmintics in livestock (Hutson *et al*., 2001; Wickramasinghe *et al.*, 2003). According to Bach (2001) there are four main ways that turbines could potentially impact bat populations; a) via disturbance caused by ultrasound emissions; b) through collisions with rotor blades; c) via barrier effects caused by loss of flight corridors (which could cause abandonment of roosts in the long term (MEDD, 2004)) and d) through loss of hunting grounds.

It may be that, over time, bats could learn to avoid turbines, presumably either behaviourally in the short-term, or evolutionarily in the long-term. This of course would depend on the selection pressure being sufficiently high for all bat species, and also that there is no positive gain for the bat to be close to a turbine (such as good foraging); however, it should be considered that bats may not have diversified appreciably over the last 50-60 million years (Griffin, 1974), so may be slow to adapt to change in evolutionary terms. Most bat species visit the same foraging sites every year (Bach & Rahmel, 2004), so it may be possible for bats to learn to avoid permanent turbines in these areas (or remember the rotor swept regions, which would nevertheless result in loss of foraging habitat). All these have the potential to impact the various bat species in different ways; for example forage loss may have a more significant impact on brown long-eared bats which have a very specific hunting range (Bach & Rahmel, 2004), whereas other species (such as Natterer's bat (*Myotis nattereri*)) have a much wider range of hunting opportunities (Bach, 2001). Positioning of turbines will also affect the species involved; for example turbines placed along a hedgerow are much more likely to affect common pipistrelles (*Pipistrellus pipistrellus*) (Bach, 2001) which use these features for navigation. It has been suggested that turbines positioned along river valleys, upland rivers, upland passes or coastlines (Rodrigues *et al*., 2006) would pose particular problems to bat populations, and although off-shore turbines tend to be positioned 12 km away from shore (Westaway, 2007), it is difficult to assess the impact of these on migrating populations (although some species are known to forage as much as 5 km from coastlines (Harbusch & Bach, 2005). In relation to microturbines, it has been hypothesised that these pose the highest risk of bat collision if placed close to a roost or on a “flyway” (BCT, 2006). Turbines are increasingly encroaching on bat habitats (Bach & Rahmel, 2004), and Harbusch & Bach (2005) suggest the situation is most critical for turbines situated in or near wooded areas. It is recommended that turbine sites should avoid known bat migration routes, commuting routes (minimum of 200 m), foraging habitats (minimum 200 m), known summer and winter roosts (minimum 500 m), forests (minimum 200 m) and mountain passes in order to reduce the likely impact on bat populations, and areas for potential turbine sites need to be assessed for their use by different species in order to minimise impacts on populations (MEDD, 2004).

There are a small number of reports that contest the impact of turbines on bats; Erickson *et al*. (2002) claim that only a small fraction of detected bat passes around a turbine actually result in collisions, and that there appears to be little correlation between activity and mortality. The observed US mortality rate is claimed not to be sufficient for local bat populations to decline (Erickson *et al*., 2002), but the effect on migratory populations remains unknown (although it could potentially be significant (Rahmel *et al*., 2004)), and it is likely that mortality rate figures given in some studies were underestimated (Kunz *et al*., 2007; Tuttle, 2004). In any case, turbines are known to have directly affected 14 species of bats throughout Europe and 10 species in Germany alone (Bach & Rahmel, 2004), including species also resident in the UK. The number and frequency of bat-turbine impacts is much greater than for any other tall man-made structures (Arnett *et al*., 2005), which is raising increasing concern. Wind turbine projects have the potential to impact susceptible species on a global scale (MEDD, 2004); Kunz *et al*. (2007) are quoted as saying: “significant cumulative impacts of wind energy development on bat populations are likely”. However, as pointed out by Bach & Rahmel (2004), it is impossible to make an assumption on the effect that turbine mortality will have on individual bat species or populations, since so little is currently known about bat populations or why they interact with turbines. What is known is that insectivorous bats play an important role in insect control (Hutson *et al*., 2001), and the knock-on effects of any reduction in bat populations on insect species levels (or other insectivore populations) could have dramatic consequences. Because insects have such a rapid generation rate, even a relatively minor reduction in predator levels could lead to large insect population increases, with consequences that can include crop damage (Settle *et al.*, 1996) and higher prevalence of insect-borne disease transmission (for example, malaria) (Breidenbaugh *et al.*, 2009). It is therefore important, not only for the protection of bat populations, but also for the continued growth of the wind industry, for further investigation to be conducted into the phenomenon of bat interaction with wind turbines in order for mitigation strategies to be developed and deployed with necessary haste. Such investigations form the basis of the following chapters.

2.4 Summary

The problem of flying wildlife mortality at wind turbine installations has been reviewed in this chapter. Bats in particular are known to be fatally involved with moving turbine rotor blades and at some wind farms many hundreds of bats are being killed each night at certain times of year. There is evidence that bat mortality may be comparable to or exceeding avian mortalities. Bats are known to be particularly susceptible to sudden population reductions due to their slow generation rates, and also present a unique problem due to their use of echolocation to determine the nature of objects in the environment. Because wind power is a low-polluting, renewable energy source it is important for future global energy provision and has undergone rapid development over the last century, with notable growth in recent decades. This growth has lead to an increase in the concern of the impact such structures could have on bat populations, which are an important part of the ecosystem, in particular with regard to insect control. There is an urgent need to therefore determine the underlying causes of the phenomenon of bat mortality at wind installations in order to develop mitigation strategies to reduce the impact for both the wind industry and bats as a species.

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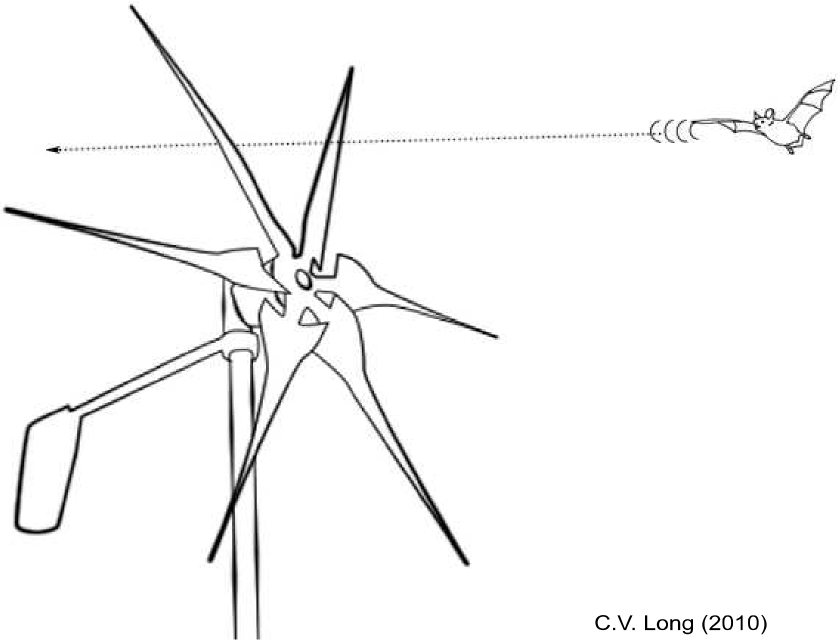

C.V. Long (2010)

3

Theoretical Interaction of Echolocation Pulses with Turbine Rotor Blades

The studies in Chapter 2 support the assertion that wind turbines are responsible for bat fatalities. Recent studies have indicated that bats may not only be foraging in the vicinity of turbine rotors (Ahlén, 2004; Horn *et al*., 2008), but also actively investigating turbine towers and blades, both moving and stationary (Horn *et al*., 2008). In addition, it has been suggested that bats become ‘trapped’ in the wake vortex of operational rotors (Horn *et al*., 2008) which is when barometric trauma caused by pressure changes can also lead to fatality (Baerwald *et al*., 2008). Bats present a particularly interesting problem from an acoustic point of view, since they rely primarily on sound to navigate the environment, both actively and passively. Because bats produce pulses of ultrasound which are temporally fleeting, it is potentially useful to be able to determine the likelihood that any one emitted bat pulse could be reflected, in theory, from a blade as the rotor turns. This section presents equations derived from basic mechanics which aim to quantify this. By applying these equations to existing turbine models, further insight may potentially be gained into the way that bats might be perceiving wind turbines. Furthermore, this may indicate possible areas for mitigation, with the aim of creating a ‘rotor rating’ system which can be implemented in the consideration of new turbine designs.

3.1 Methodology

3.1.1 Equation formulation

A series of equations can be formulated that take into account the basic mechanical features of the operational turbine rotor that will influence the likelihood that any one incoming bat echolocation pulse will be intercepted by the turbine blades, therefore having the chance to be reflected and detected by an approaching bat. No attempt is made here to characterise the actual reflected pulse in terms of acoustic field intensity or any experienced Doppler shifts. However, the equation provides a basic framework for assessing the bat's chance of detecting the turbine blades. If a turbine has N blades, turns with angular velocity ω rad. s^{-1} and has a nominal blade width ('chord length') W m, the time period t of rotation from one leading blade edge to the next leading edge is given as follows:

$$t = \frac{2\pi}{\omega N} \tag{3.11}$$

Assuming a small point sampled over an infinitely small period of time, the probability, P, of the point intercepting a blade at distance from hub, x (m), will be

$$P = \frac{WN}{2\pi x} \tag{3.12}$$

During time t, at any one point along the blade sweep path (and assuming the curvature of the path arc is roughly consistent with blade width), the amount of time when the path is occupied by a blade, t_{blade}, is calculated as follows:

$$t_{blade} = \frac{WN}{2\pi x} . \frac{2\pi}{\omega N} = \frac{W}{\omega x} \tag{3.13}$$

However, should that point on the blade sweep path be sampled over a longer finite duration, t_{pulse}, more consistent with that of a bat echolocation pulse, the probability of interception will inevitably be higher. If $t_{pulse} \geq t\text{-}t_{blade}$ (the period minus the blade pass time), P = 1 and interception will definitely occur. If $t_{pulse} < t\text{-}t_{blade}$, the interceptable duration, t_{int} will be

$$t_{\text{int}} = t_{blade} + t_{pulse} \tag{3.14}$$

Therefore the portion of time when the pulse will be intercepted by a blade and could potentially be reflected, hence the probability of interception, is given by:

$$P = \frac{t_{\mathrm{int}}}{t} = \frac{(t_{blade} + t_{pulse})}{t} = \frac{N}{2\pi}\left(\frac{W}{x} + \omega t_{pulse}\right) \text{for } t_{\mathrm{int}} < t \tag{3.15}$$

Note that the actual probability cannot exceed 1, therefore for the case of $t_{int} \geq t$ there is certainty that the blade will intercept the pulse and P=1. Figure 3.11 provides a graphic representation of equation elements.

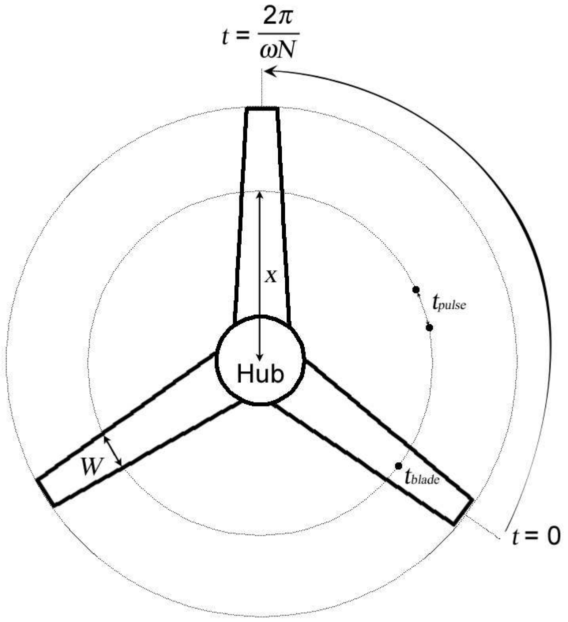

Figure 3.11- Graphic representation of equation parameters t, x, W, t_{blade} and t_{pulse}.

The equation is intended to be applied from the point of view of a bat approaching the rotor head-on (toward blade faces), but may also be applied to blade tips for bats approaching the rotor side-on (the equivalent of setting x equal to the rotor radius). This basic equation forms the basis for the conclusions in the following sections.

3.1.2 Equation application

Equation 3.15 was applied to known physical parameters of a selection of existing variable speed turbines and microturbines in such a way as to obtain two sets of probability values per turbine over incrementing operational wind speeds. These two data sets corresponded to two values of W in relation to x, W_{min} being the width of each blade 2 cm from the turbine blade tips, and W_{max} being the width of each blade 2 cm from the hub (blades were assumed to taper linearly). Probabilities were calculated from wind speeds, v, of 0 m s^{-1} (rotor stationary) up to the maximum operational wind speed, v_{max}, for that turbine. Manufacturer's data were consulted in order to determine maximum angular velocity, ω_{max}, and v_{max} for each turbine model. By dividing ω_{max} by v_{max} a conversion factor could be obtained (Table 3.21). This was used to determine the values of ω from v, assuming the conversion factor remains constant. Thus the relationship between wind speed and rotational velocity was assumed to be linear. For any given turbine, a graph of the probability of pulse interception vs. wind speed can therefore be plotted, which is hereafter termed the 'detectability profile'. In order to facilitate turbine rotor classification, each turbine was also assigned a single numerical value or 'detectability rating', D, as defined in Figure 3.12. This was obtained by taking an average of the probability values for W_{max} and W_{min} at wind speeds between 1-6 m s^{-1} and then integrating the area under the curve. The reason for selecting this particular range of low-speed wind was in light of findings by Arnett *et al*. (2008) and Horn *et al.* (2008), that bat mortality is greatest on low wind speed nights with significantly fewer bat casualties on nights with wind speeds greater than 6 m s^{-1}. For turbines with a minimum wind speed operational cut-in, only the wind speed values for which the rotor was operational were selected for integration (up to 6 m s^{-1}). This has the effect of boosting the detectability rating for turbines with operational cut-ins (see Figure 3.12), since stationary blades are fully detectable and present little hazard to an approaching bat (Long *et al*., 2009).

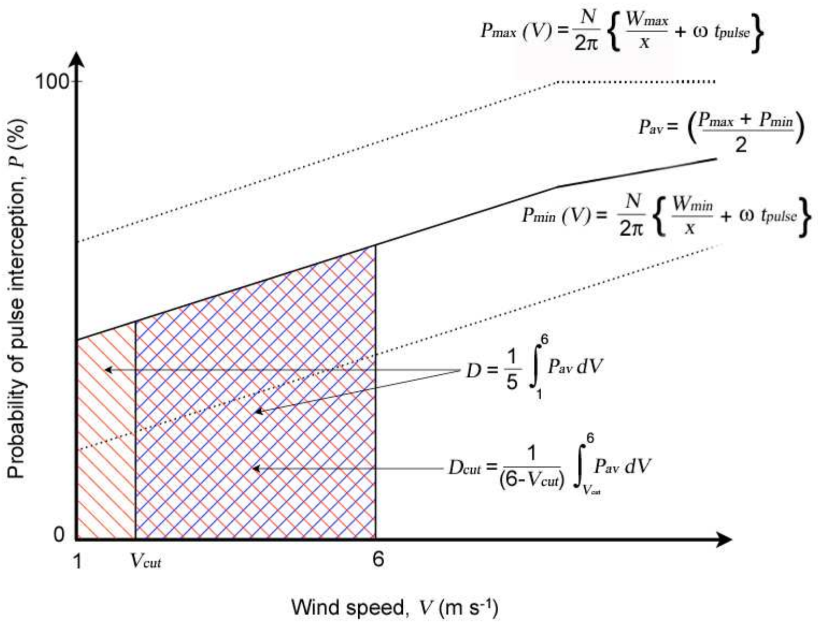

Figure 3.12- Demonstrating the derivation of the ‘detectability rating’. Dotted lines represent the detectability profiles of P_{max} and P_{min} for a given turbine, relating to the values of W and x. D represents the formulation of the detectability rating for a turbine, while D_{cut} represents the formulation of the detectability rating for a turbine with an operational cut-in. The resulting detectability rating is a percentage, 0 % being the worst score and 100 % being the best in terms of chance of pulse interception.

Note that, unless otherwise stated, the value of t_{pulse} applied was consistent with the call length of a common pipistrelle (*Pipistrellus pipistrellus*) bat in ‘search phase’ echolocation (5.6 ms, averaged from Parsons & Jones (2000) and Obrist *et al*. (2004)).

3.1.3 Data analysis

After applying Equation 3.15 to a data set of existing turbine and microturbine model parameters and obtaining detectability ratings, the data were examined for significant trends in the relationship between the different physical parameters and detectability rating. Data were analysed using the GLM ANCOVA module of Statistica 5.1 (Statsoft, Inc., OK, USA). ‘Detectability rating’ was chosen as the dependent variable, while either ‘rotor diameter’, ‘blade number’, ‘operational cut-in speed’ or ‘power output’ were selected as independent variables. In all cases the relevant equation elements from ‘rotor diameter', 'blade number', 'maximum rpm', 'min blade width' and 'max blade width' were selected as covariates.

Turbines were considered to fall into the following categories; 'microturbine' (rotor diameter, Φ <=2 m), 'small' (2< Φ <=10 m), 'medium' (10< Φ <=30 m) and 'large' (Φ >30 m).

3.2 Results

Before applying Equation 3.15 to turbine rotors it is possible to predict the physical features most likely to increase the probability of pulse interception. Since the probability is directly proportional to both the number of blades, blade width, rotational velocity and bat transmission pulse length, increasing the value of any or all of these parameters will increase the probability of pulse interception. It can also be assumed that the turbine blade tip region is likely to be less detectable to an approaching bat, since the probability of interception is inversely proportional to the distance from the hub at which the rotor is sampled. In addition, the equation infers greater detectability at higher wind speeds, consistent with the findings of Arnett *et al*. and Horn *et al.* (2008).

Table 3.21 provides the relevant physical parameters for a selection of turbine and microturbine models which were applied to Equation 3.15 to produce a series of detectability ratings and profiles. These data provided the basis for statistical analysis as follows:

3.2.1 Effect of Blade Number

Data from the different turbine makes and models confirm that a greater number of rotor blades significantly increases the chance of pulse interception at low wind speeds ($p<0.005$; $F_{[3,25]} = 7.13$), as demonstrated in Figure 3.21.

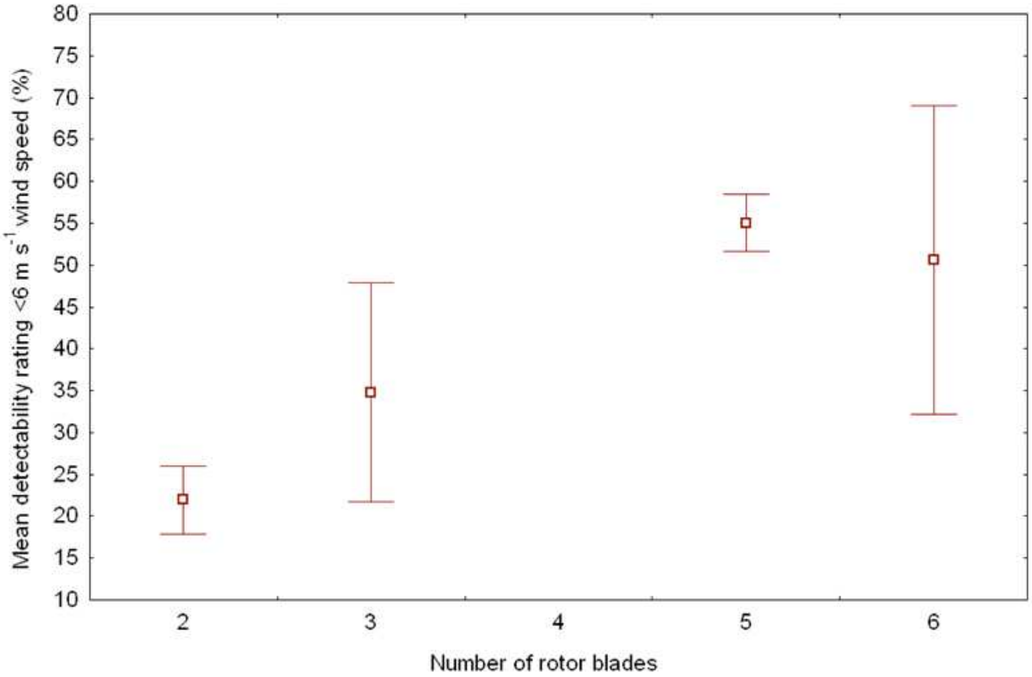

Figure 3.21- Variation in mean detectability rating for low wind speeds according to the number of rotor blades. Boxes indicate means with ± standard deviation whiskers.

Best achievable detectability rating does appear to be linked to the number of blades, although it should be considered that there were relatively few examples of five and six blade models in the data set and that many of these were microturbines. While blade number was correlated positively overall with probability of pulse interception, it is not always the case that a greater blade number alone will produce a better detectability rating, as demonstrated by the six blade microturbine model T1 and the three blade microturbine model T5 (Table 3.21). Here, although the six blade model might be expected to fare better than the three blade model, it is the three blade T5 that has the higher detectability rating. This is due to the fact that the three blade model has much wider blades near to the hub and also rotates at a higher angular velocity for each given wind speed than the six blade example.

3.2.2 Effect of Operational Cut-in

From the equations given in Figure 3.12, manufacturer-designed operational cut-ins might be predicted to improve the overall detectability rating for turbines with this feature. Results from the data set did not confirm or refute the suggestion that operational cut-ins are beneficial to overall detectability rating ($F_{[3,24]}$ = 0.22). This could be due to the lack of available data for large scale turbines without an operational cut-in feature, or microturbines with a cut-in feature for comparison. However, it is clear that applying an operational cut-in to the same model of turbine will enhance its detectability rating, since as wind speed and therefore rotor angular velocity increases, the rotor becomes more detectable (as demonstrated in Figure 3.12). Figure 3.22 highlights the effect of operational cut-in on the resulting detectability profile, using an example of a microturbine (T7) and larger, medium scale cut-in turbine (T22) (which remains at a constant probability of reflection until the blades begin to rotate above the cut-in wind speed), with similarly low detectability ratings.

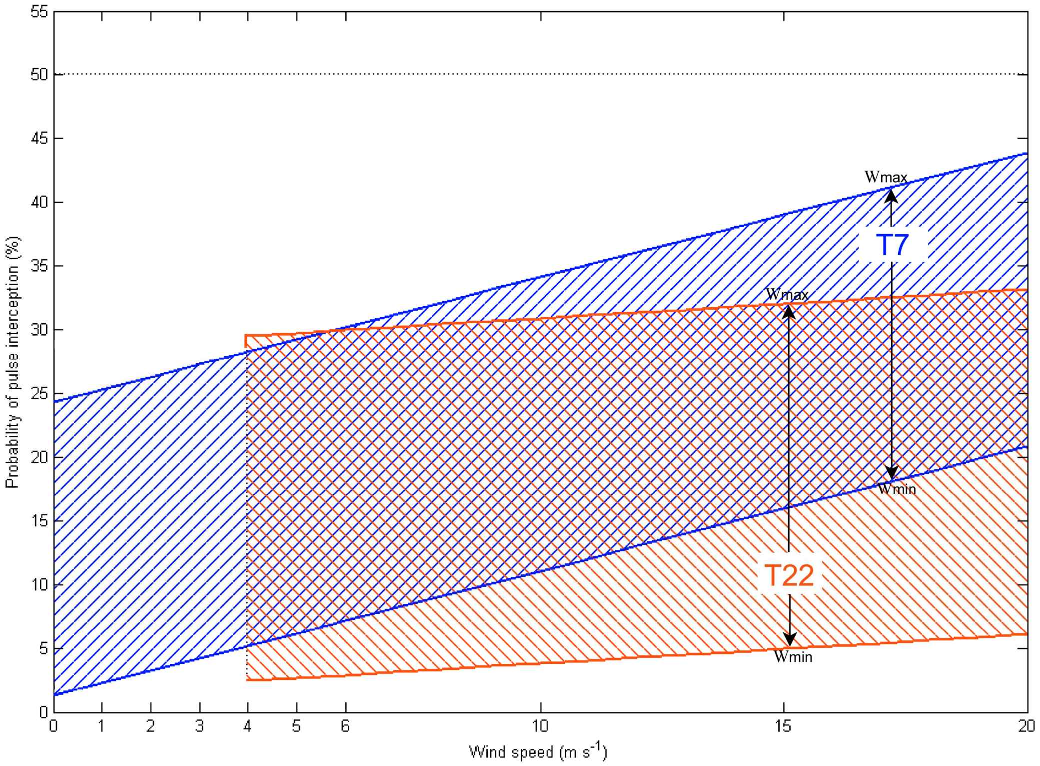

Figure 3.22- Detectability profile for two low-rating examples T7 and T22, demonstrating the effect of an operational cut-in (T22) on detectability profile, represented by the dotted line at 4 m s^{-1}. Each profile consists of two parallel lines, the upper representing the probability of pulse interception toward the hub and the lower representing the probability of pulse interception toward the blade tips.

While T7 generally has a better detectability profile than T22 at higher wind speeds, it must also be considered that in the low wind speed ‘danger zone’, the stationary rotor of T22 presents a much smaller risk to approaching bats than the turning rotor of T7, as not only is there less chance of injury but, in terms of the signal strength of the returning echo, stationary blades may also be more detectable (Long *et al*., 2009). Since recent research by both Baerwald *et al*. and Arnett *et al*. (2009) suggested that implementing operational cut-ins can significantly reduce bat mortality (up to 87 %) at wind installations, this is one feature to be seriously considered for mitigation.

3.2.3 Effect of Power Output and Rotor Diameter

There was no statistically significant correlation in the data set between rotor diameter ($F_{[18,10]} = 0.91$) or power output ($F_{[25,2]} = 0.7$) and detectability rating, although Figure 3.23 (overleaf) demonstrates a trend for increasing detectability rating with higher power capacity and larger rotors. The fact that rotor diameter/power output appears to be correlated with detectability rating may be linked with the lower likelihood of large turbine models to have fewer than three blades, and the relatively larger width of large turbine blades toward the rotor hub. On the other hand, the fact that larger rotors result in much lower probabilities of interception near the blade tips as compared to smaller rotors means that this result must be treated with caution.

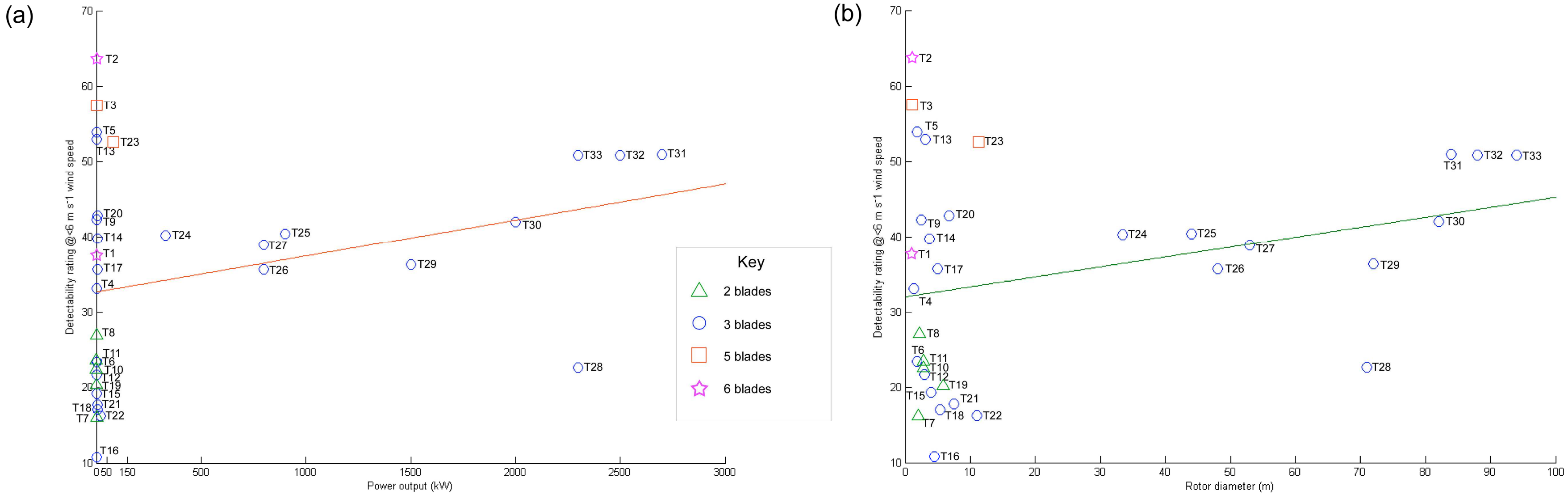

Figure 3.23- Scatterplots showing the effect of turbine power capacity (a) and rotor diameter (b) on detectability rating at low wind speeds. Plot lines indicate linear trend.

Effect of Bat Species

Bat pulse length was also predicted to affect detectability; the pulse length of a bat's echolocation call can vary widely between individual bat species. Although the pulse length of a common pipistrelle has been used here as standard, the effect of applying another bat species' pulse length to the same turbine is shown in Figure 3.24.

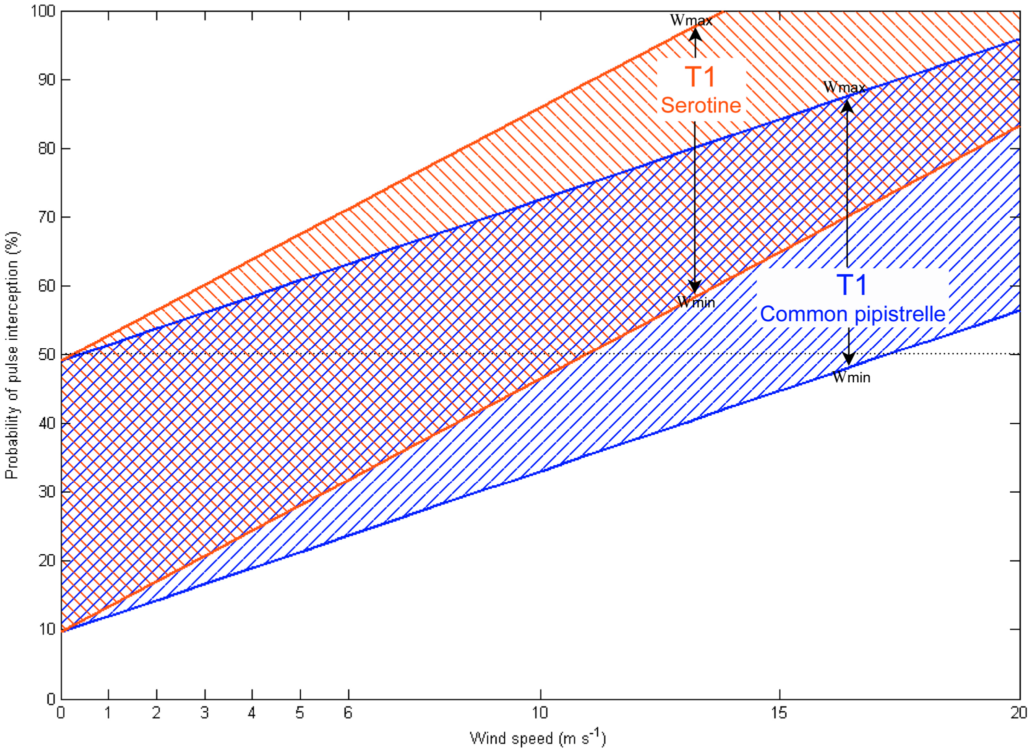

Figure 3.24- Demonstrating the effect of bat species' pulse length on detectability profile. Here the same model of microturbine, T1, is used and pulse lengths for either the common pipistrelle (5.6 ms) or the serotine (*Eptesicus serotinus*; 8.8 ms) are applied.

Whilst both species have a similar detectability profile at very low wind speeds, as wind speed increases and so rotor velocity increases, the profile of the serotine bat has a higher probability of pulse interception, particularly at higher wind speeds. This is due to the longer pulse duration of this species. Bat species with shorter echolocation pulses are therefore less likely to have pulses intercepted by moving blades (i.e. their potential for pulse reflection and therefore detection is lower).

Turbine model code	Rotor diameter (m)	Number of blades	Conversion factor of ω to wind speed (rad. m^{-1})	RPM range	Operational cut-in wind speed (m s^{-1})	Blade width min (m)	Blade width max (m)	Rotor height range (m)	Power capacity (kW)	Detectability rating @ 1-6 m s^{-1} wind speed (%)
T1	**0.91**	**6**	**4.5**	**0 – 837**	**-**	**0.044**	**0.071**	**< 10**	**0.3**	**37.6**
T2	0.93	6	7.9	0 – 1500	-	0.062	0.096	< 10	0.1	**63.7**
T3	1.1	5	6.3	0 – 1200	-	0.037	0.1	< 10	0.4	**57.5**
T4	1.35	3	9.8	0 – 1875	-	0.05	0.09	< 10	0.1	**33.1**
T5	1.8	3	8.4	0 – 1600	-	0.027	0.207	6 – 12	1	**53.8**
T6	1.85	3	6.5	0 – 1250	-	0.065	0.13	< 10	0.2	**23.4**
T7	2	2	5.8	0 – 1100	-	0.039	0.097	12	0.6	**16.2**
T8	2.2	2	5.2	0 – 1000	-	0.065	0.146	12	0.8	**27.1**
T9	2.4	3	7	0 – 1333	-	0.1	0.171	12	0.75	**42.3**
T10	2.7	2	5.8	0 – 1100	-	0.06	0.139	12	1.5	**22.7**
T11	2.7	2	4.7	0 – 900	-	0.055	0.164	12	3	**23.6**
T12	3	3	4.1	0 – 775	-	0.076	0.12	< 10	0.5	**21.7**
T13	3.12	3	4.1	0 – 775	-	0.069	0.185	12	1.4	**52.9**
T14	3.7	3	4.7	0 – 900	-	0.082	0.245	12	6	**39.8**
T15	4	3	3.2	0 – 610	-	0.1	0.14	10 – 12	1	**19.2**
T16	4.5	3	2.9	0 – 556	-	0.1	0.14	10 – 12	2	**10.8**
T17	5	3	2.4	0 – 450	-	0.138	0.23	18	5.6	**35.7**
T18	5.4	3	1.2	0 – 230	-	0.067	0.201	9 – 15	5	**17.1**

Continued overleaf…

…Continued

Turbine model code	**Rotor diameter (m)**	**Number of blades**	**Conversion factor of ω to wind speed (rad. m^{-1})**	**RPM range**	**Operational cut-in wind speed ($m\ s^{-1}$)**	**Blade width min (m)**	**Blade width max (m)**	**Rotor height range (m)**	**Power capacity (kW)**	**Detectability rating @ 1-6 $m\ s^{-1}$ wind speed (%)**
T19	5.6	2	1.3	0 – 245	-	0.104	0.332	18	6	**20.2**
T20	6.8	3	1.9	0 – 367	-	0.13	0.37	12 – 15	5	**42.8**
T21	7.5	3	1.6	0 – 309	-	0.13	0.37	18 – 20	7.5	**17.8**
T22	11	3	0.9	33 – 163	4	0.175	0.247	13 – 20	20	**16.2**
T23	11.3	5	0.8	13 – 145	1.8	0.276	0.579	40 – 50	90	**52.6**
T24	33.4	3	0.2	18 – 45	3	0.458	2.177	37 – 50	330	**40.2**
T25	**44**	**3**	**0.1**	**12 – 34**	**2**	**0.651**	**2.536**	**45 – 55**	**900**	**40.4**
T26	48	3	0.1	16 – 30	2	0.751	3.286	50 – 76	800	**35.7**
T27	52.9	3	0.1	12 – 29	2	0.447	3.843	60 – 73	800	**38.9**
T28	71	3	0.1	6 – 22	2	0.862	2.317	57 – 113	2300	**22.6**
T29	**72**	**3**	**0.1**	**2.5 – 14.1**	**3.5**	**0.686**	**2.229**	**62 – 80**	**1500**	**36.3**
T30	82	3	0.1	6 – 20	2	1.4	4.218	78 – 138	2000	**42**
T31	84	3	0.1	5 – 18	3.5	1.577	4.617	70 – 58	2700	**51**
T32	88	3	0.1	5 – 16.5	3.5	1.34	4.612	85	2500	**50.8**
T33	94	3	0.1	5 – 14.9	3	1.532	4.435	100 – 120	2300	**50.8**

Table 3.21- Physical properties of a selection of turbine and microturbine models alongside the resulting detectability rating at low wind speeds for each. Models are listed in the order of increasing rotor diameter. Turbines listed in bold font (grey highlights) are models previously linked with bat morality incidents.

3.3 Discussion and Conclusions

It is important to consider that this equation has been derived from basic principles and may not take into account detailed features of each rotor. The model assumes that a) rotor blades are specular to the incident pulse (i.e. lack curvature that may influence the direction of echo return); b) acoustic scattering or Doppler shifting effects are negligible; c) there are no additional effects due to a wider beam angle of an incoming pulse and d) that the pulse length of the particular bat species is consistent.

Clearly there is a complex interplay between the physical requirements of turbine design and the application of the detectability equation. From the data set, small turbines T13 and T16, and microturbines T2 and T7 provide a useful comparison; both T13 and T16 are of a similar scale, however T13 has a detectability rating almost five times higher than that of T16. The limiting physical properties of T16 are the comparatively low RPM range (and so rotational velocity at each given wind speed) and the smaller blade width toward the hub. Microturbine T7 has a rating four times lower than that of microturbine T2, and here the limiting features include the small number of blades of T7 (2 as compared to 6 for T2), the lower RPM range and the smaller blade width toward the tips. It is therefore clearly important to consider all the key rotor features that are linked to probability of pulse interception rather than focussing on any one element of design.

It is interesting to note that all the turbine models in the data set which have previously been linked to bat mortality (those listed in bold font in Table 3.21) have a very similar detectability rating of around 40 %. It may be inferred that any turbines in the table with a rating of 40 % or less could be viewed as being potentially hazardous to bats. In light of this it may be desirable to implement design modifications which aim to surpass this rating in order to present bats with the best possible chance of detecting and avoiding the rotor.

The reason for selecting the pulse length of a common pipistrelle as the standard length for calculations was partly due to the widespread distribution of this bat species throughout Europe, and partly because it is one of the bat species previously identified by Betts (2006) as being at high risk of wind turbine interaction due to its aerial hawking feeding strategy (therefore spending much time foraging for insects above hedgerow height in open spaces). When applying the detectability equation it must therefore be considered which bat species are most abundant at the proposed site of installation, and of these to select the species with the shortest pulse duration.

One factor Equation 3.15 does not take into account is the beam width of the outgoing bat pulse. This is likely to also be relevant to the predicted detectability of the turbine blades, since it will affect the proportion of the rotor that is insonated with any one pulse. This, however, will vary depending on the distance of the bat from the rotor at the time of pulse emission, and will also be affected by acoustic attenuation, spreading losses and the complex scattering that may be occurring in the rotor region (Long *et al*., 2009). Equation 3.15 can be modified to take an estimation of beam angle into account, assuming distance from source, D_s, and beam half angle, θ:

$$P = \begin{cases} \dfrac{N}{2\pi}\left(\dfrac{W + 2D_s \tan\theta}{x} + \omega t_{pulse}\right) \text{for } t_{\text{int}} < t \\ 1 \qquad \text{for } t_{\text{int}} \geq t \end{cases} \tag{3.31}$$

The maximum distance at which a large object such as a turbine will be detectable by a bat will vary depending on species. For a common pipistrelle, this may be anywhere within 15 m (based on the correlation of interpulse interval (around 90 ms for *P. pipistrellus*) to maximum detection range, after Holderied *et al*. (2005)), however this will vary depending on the nature of the target. Beam angle also varies depending on species and type of echolocation; while many bats producing frequency modulated (FM) type calls emit pulses primarily through the mouth (for example *Eptesicus fuscus* produces a beam angle of around 40° (Wotton & Jenison, 1997)), some constant frequency (CF) species emit pulses through elaborate noseleafs which may enable them to alter the beam angle spontaneously (Zhuang & Muller, 2006). As an example, applying a distance, D_s, of 0.5 m and a beam angle of 40° to Equation 3.31 will shift the detectability profile, and so the detectability rating, of a turbine by +26 %. Clearly more empirical evidence is needed for individual bat species and acoustic pulse-blade interaction before Equation 3.31 can be confidently implemented in turbine rotor ratings.

Further consideration may need to be given to the RPM range of different turbine models. For example, it is possible for some of the larger turbines to have an RPM that increases linearly with wind speed but not all the way up to the maximum operational wind speed when that turbine furls; this information may not always be supplied by the manufacturer. For such turbines, it is more usual for the rotor RPM to increase linearly up to a certain wind speed (for example 10 m s^{-1}) and then remain constant. It is possible to implement such an assumption and re-work the resulting detectability profile for one of the large-scale example turbines, T33. Figure 3.31 demonstrates the modification to the resulting profile:

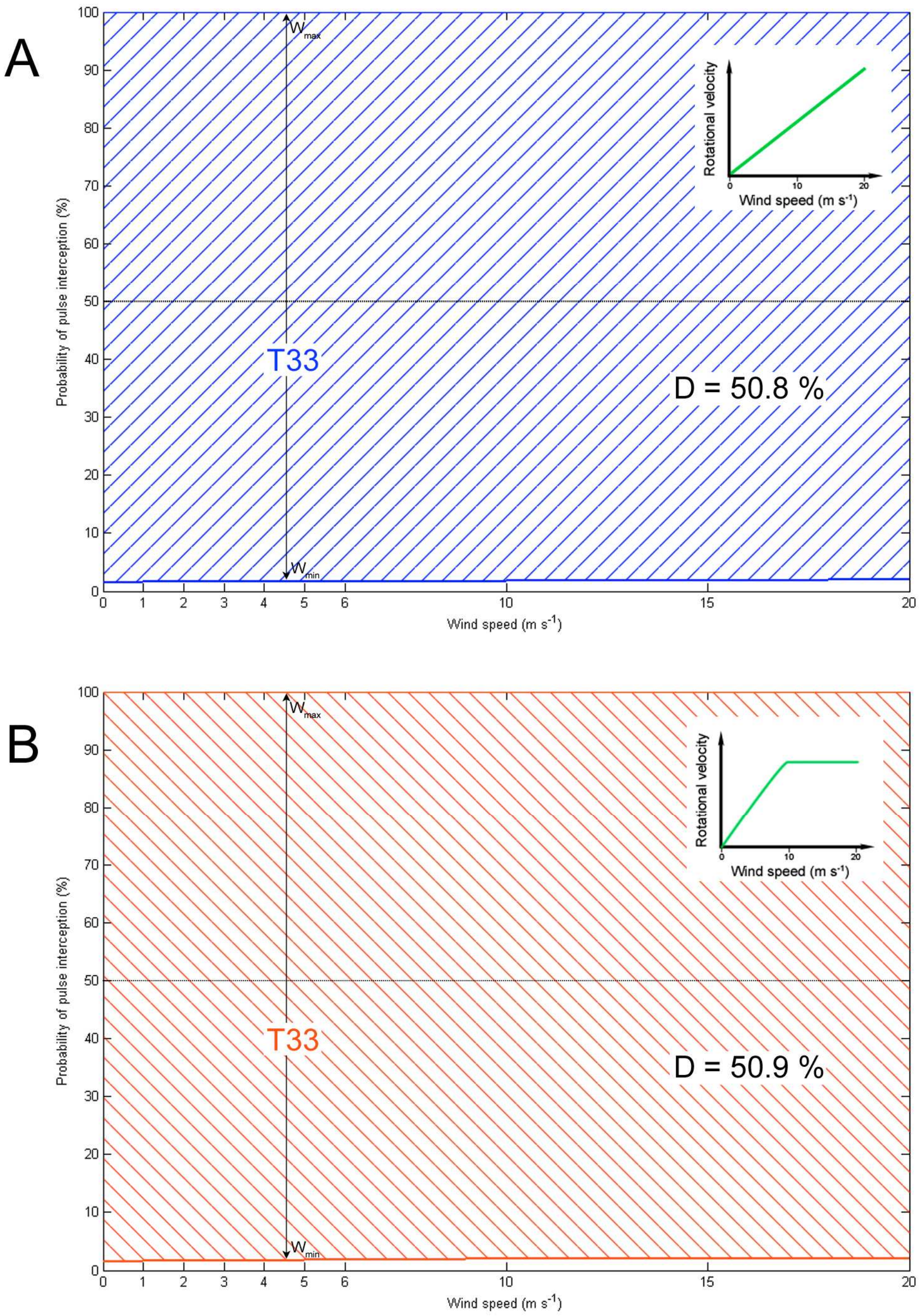

Figure 3.31- Detectability profile for example large-scale turbine T33 demonstrating the implementation of a modified rotational velocity vs. wind speed profile (B) rather than assuming a purely linear relationship (A). Inset in each profile is a graph indicating the rotor speed against wind speed relationship, as well as the overall detectability rating, D.

Implementing this type of rotor speed vs wind speed relationship therefore has the effect that above 10 m s^{-1} the detectability profile remains constant, and for the example of T33 at low wind speeds, has only a small effect on the resulting detectability profile.

It may also be beneficial to consider the distribution of wind speeds, i.e. the likelihood that the rotor would be exposed to a certain wind speed at any one point in time. This will of course vary according to turbine location, but it is possible to consider this distribution with the following example. The data provided in Figure 3.32 utilise a data set for yearly wind speed distribution in Orkney, north Scotland, taken from Barbour (1984). These data were fitted with a Weibull distribution, in MATLAB, which is commonly used to fit wind speed data; further information can be found in Deaves & Lines (1997) and Seguro & Lambert (2000).

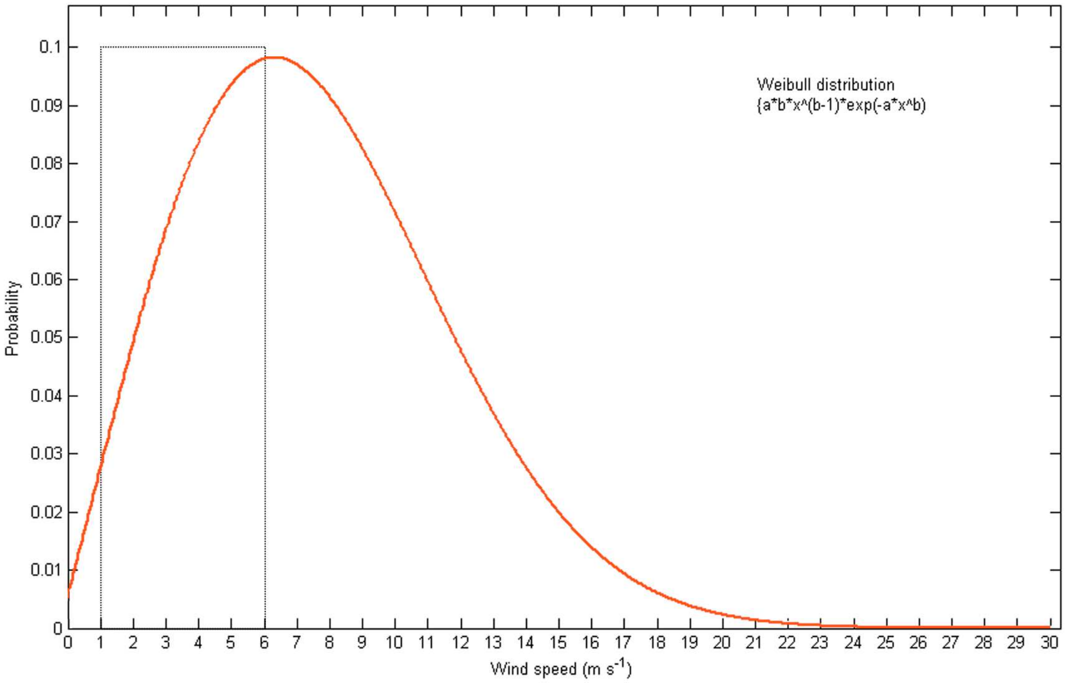

Figure 3.32- Weibull distribution of yearly wind speed data in Orkney, taken from Barbour (1984) and fitted in MATLAB. Dotted box indicates values relevant to the detectability rating, D. Inset is the distribution equation, where a=0.0099 and b=2.095.

It is then possible to use the relative probability values for each given wind speed between 1-6 m s^{-1} to weight the detectability rating, D, accordingly, thus producing a rating that takes into account wind speed distribution at that particular site (i.e. includes the probability that a bat will encounter the rotor turning at a particular RPM). The detectability equation (D, Figure 3.12) is thus modified as follows:

$$D = \frac{\int_1^6 P_{av}(v)\, Vel(v)\, dv}{\int_1^6 Vel(v)\, dv} \tag{3.32}$$

Where $Vel(v)$ is the Weibull distribution of wind velocities. By weighting the data of some example turbines (T1, T11 and T22) in this way, the resulting detectability ratings are modified as follows:

Turbine	**Detectability rating @ 1-6 m s^{-1} wind speed (%)**	**Weighted detectability rating @ 1-6 m s^{-1} wind speed (%)**
T1	37.6	39.4
T11	23.6	24.2
T22	16.2	16.2

Table 3.31- Demonstrating how Detectability rating, D, changes after weighting data according to the Weibull distribution of wind speeds at a given location.

Table 3.31 highlights that applying such weighting may slightly increase the overall detectability rating of the turbine, particularly in locations with a median wind speed of around 6 m s^{-1} as in the example distribution. For turbines T1 and T11 this increase is around 1-2 %, however T22 (which has an operational cut-in at 4 m s^{-1} wind speed) does not appear to be affected by this particular weighting. This may demonstrate that the detectability rating is insensitive to the precise form of the wind speed distribution.

One additional factor that is not considered by the detectability equation is the turbine rotor height. Bat activity is known to vary at different heights in accordance with behaviour, species, habitat and foraging opportunities (e.g. Menzel *et al*., 2005; Collins & Jones, 2009). Research by Barclay *et al*. (2007) found that bat mortality at wind installations increases exponentially with rotor height, putting bats foraging at altitude and migrating bats at a higher risk of turbine interaction. As migrating bats may be at a particular disadvantage in terms of likelihood of rotor detection due to their infrequent pulse emission rates (van Gelder, 1956), rotor height appears to be another key consideration in limiting bat-turbine fatalities.

In conclusion, we find that by applying this basic equation to various turbine models, the detectability profile of a wind turbine rotor may be affected by a number of physical parameters that could, within certain constraints, be modified to improve the detectability rating as defined in this paper. Increasing turbine blade width, number of blades, rotational velocity (particularly at low wind speeds) and implementing operational cut-ins up to wind speeds of 6 m s^{-1} are all suggested to help mitigate the problem of bat-turbine mortality. The application of the detectability equation to new turbine designs could help to improve the detectability profile in order to provide bats with the best possible chance of detection/avoidance in the low wind speed danger zone. However, it must be made clear that there are numerous issues regarding the detection of blades by an individual bat; this method provides an elementary calculation to model the likelihood that a blade will be detected by an approaching bat. Finally, it is underlined that it is important to consider local variables such as habitat, rotor height and bat species when applying the equation to turbine models intended for installation.

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S.A. Hadfield-Hill & C.V. Long (2010)

4

Acoustic Measurements of Turbine Rotors

The issue of bat interaction with wind installations presents a unique problem from an acoustic point of view, since bats rely heavily on sound and the use of echolocation to navigate their environment. 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 chapter, three approaches to the problem are adopted; the first section 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 two then looks into the short bat-like sampling of these frequency shifts in simulation, and in section three bat-like pulses are used to experimentally assess information contained in echoes reflected from an operational turbine rotor. The final section briefly investigates ultrasonic emission from the rotor region. Since bats rely on frequency and amplitude information within each echo to extract the relevant parameters of the object (Griffin, 1974), the findings of this chapter may aid better understanding of the problems faced by bats in the vicinity of turbine rotors and potential mitigation opportunities.

4.1 CF Tone Doppler Shift Signatures from Moving Blades

4.1.1 Methodology

A six-blade, tethered microturbine (rotor diameter 0.91 m) placed in a 2.5 x 2.5 x 4 m 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 less than 6 m s^{-1} (Arnett *et al.*; Horn *et al.*, 2008)) measured by anemometer (HHF81, OMEGA engineering, Inc., CT, USA). 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 seconds, 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 CW CF (Continuous Wave, Constant Frequency) source tone of 40.7 kHz. This was emitted via a MA40B8R (Murata Manufacturing Company, Ltd., Kyoto, Japan) transducer, through a tone generator, situated opposite the turbine. According to manufacturer specifications, transducer beam angle was 50º, similar to the beam angle of some bat species (e.g. the FM bat *Eptesicus fuscus* at 40º (Wotton & Jenison, 1997)), giving a beam diameter of approx. 0.4 m at 0.5 m distance. The transducer was placed in horizontal juxtaposition with a calibrated, flat response ¼" 40BF microphone (see Appendix for data sheet) 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 insonated by the transducer. The turbine rotor was then insonated during operation at one of the following angles to the source, a) 'horizontal', b) 'lateral top', c) 'lateral mid' or d) 'lateral bottom' (Figure 4.11), accurately aligned with the assistance of a low power laser. The reflected echo was recorded and time-synchronised 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 second period, which enabled exact blade movements and positions to be correlated 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.

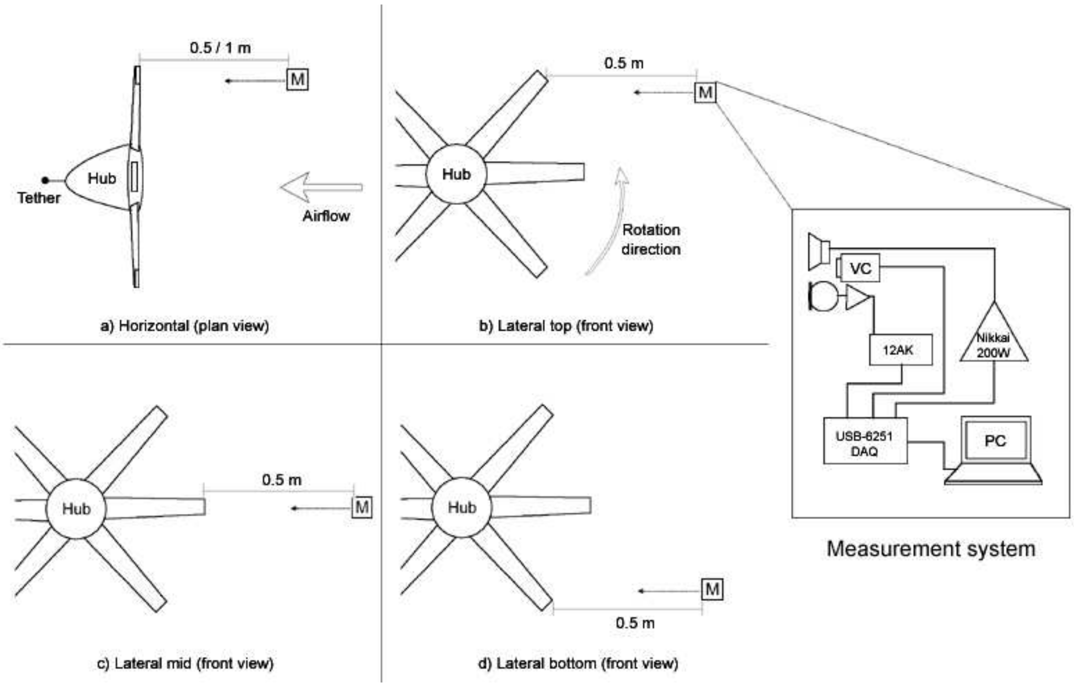

Figure 4.11-Schematics for experimental set up indicating the different angles of turbine insonation; ‘horizontal’ (a), ‘lateral top’ (b), ‘lateral mid’ (c) and ‘lateral bottom’ (d). ‘M’ denotes measurement equipment in all cases (inset) and ‘VC’ denotes ‘Video Camera’.

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 analysed using MATLAB 2009b (The MathWorks, Inc., MA, USA). The recorded sound files were temporally corrected to allow for the delay in the reflection of sound back to the microphone from the blade in order for recordings to tie in with video footage. To do this, the speed of sound in the anechoic chamber was first verified by recording and measuring the time delay of a fixed-duration FM pulse after emission and reflection from a specular surface at a distance of 1 m (speed of sound was verified at 342 m s^{-1} at 30.9 % relative humidity, 21.2 ℃). Assuming time delay = distance/speed of sound, the data recorded at 0.5 m was temporally corrected by 1.5 ms.

4.1.2 Results

Moving turbine blades were found to produce Doppler shift signatures that varied according to the angle of rotor insonation and blade position at the point of reflection. Figure 4.12 describes the Doppler shift signatures for all angles insonated, indicating the blade positions resulting in shift portions for each blade sweep.

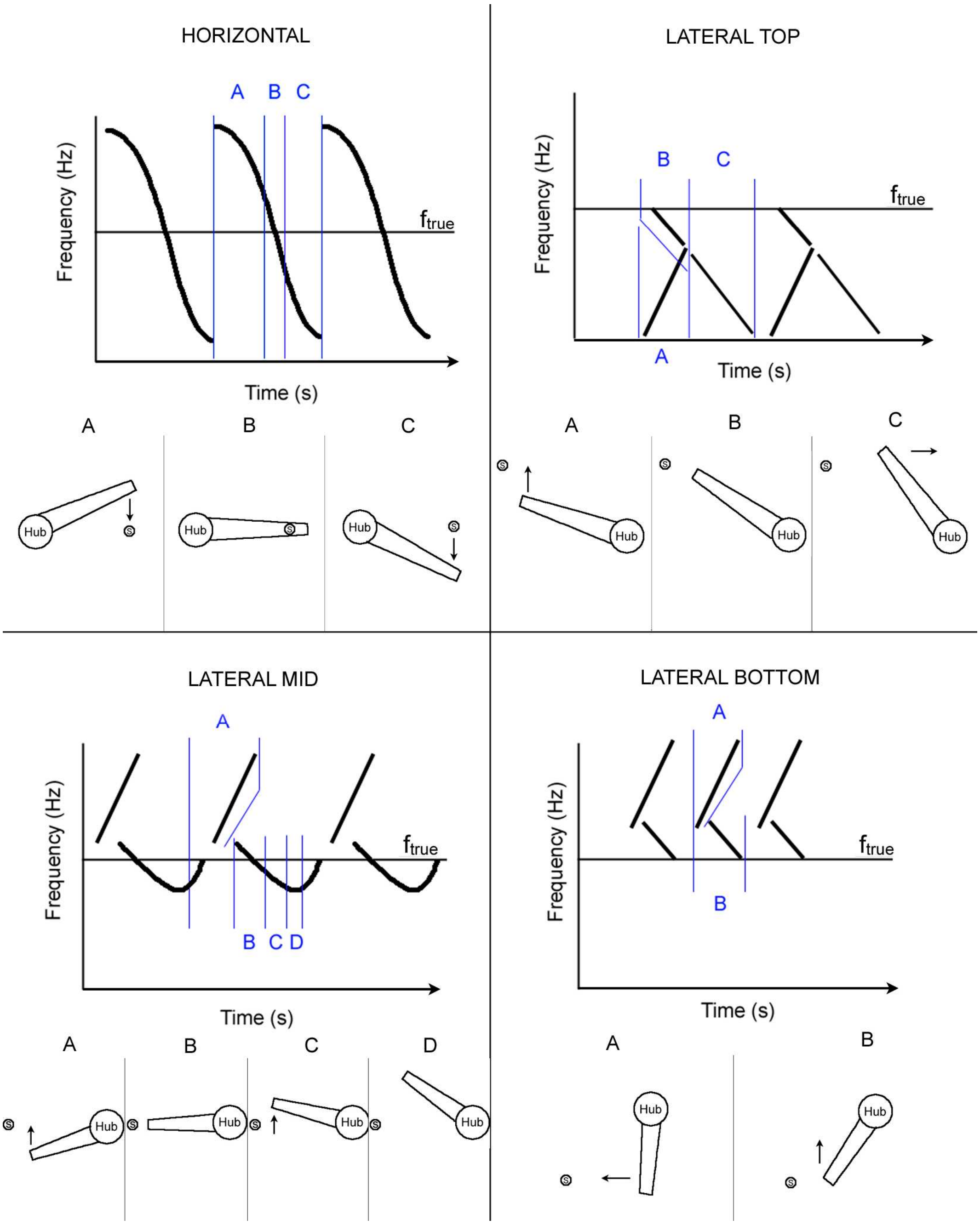

Figure 4.12- Representative Doppler shift echo signatures for turbine blade sweeps insonated from four different angles with an outgoing ultrasonic CF tone (40.7 kHz). Patterns taken from FFT data recorded at 1250 kS s^{-1} (FFT length 16384 points, Hanning window, 75 % overlap, 2 % linear energy scaling). '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).

In Figure 4.12 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. Figure 4.13 provides an example of how the video camera footage tied in with the Doppler shift sweep profile.

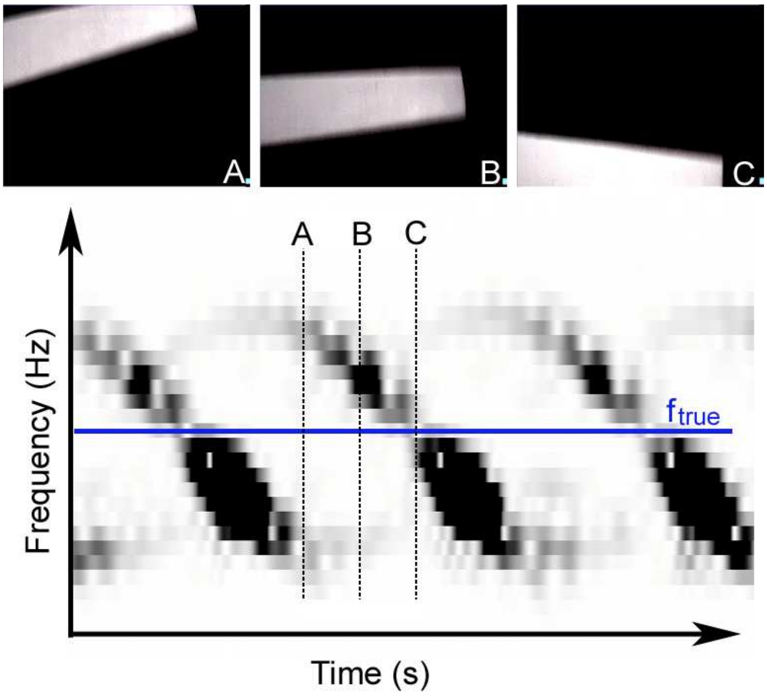

Figure 4.13- Showing three sequential video camera frames of a moving turbine blade (top) taken from the 'horizontal' aspect, and corresponding Doppler shift sweep FFT profile (bottom). The three frames represent segments 'A' and 'B' of the profile in Figure 4.12. Solid line denoted 'f_{true}' indicates actual outgoing frequency; dashed lines A, B and C correspond to the time intervals of each respective video frame. In all cases the measurement source was situated immediately below the video camera. Sonogram FFT length 16384 points, Hanning window, 75 % overlap, 0.3 % linear energy scaling.

The extent of the Doppler shift deviation from the mean shift varied between angles; ‘horizontal’ shift ranged between ± 325 Hz, ‘lateral top’ shift ranged between ± 595 Hz, ‘lateral mid’ shift ranged between ± 785 Hz and ‘lateral bottom’ shift ranged between ± 730 Hz. Overall, sound reflected from the operational rotor from the horizontal aspect demonstrated slight negative Doppler shift, from the lateral top aspect demonstrated negative shift, from the lateral mid aspect demonstrated slight positive shift and from the lateral bottom aspect demonstrated positive shift.

4.2 Monte Carlo Simulation of Bat-Like Pulse Echo Doppler Shift

4.2.1 Methodology

Since an incoming bat-like echolocation pulse (approx. 2-6 ms) is much shorter than the blade sweep pass period for the turbine model used in experimental work at low wind speed (approx. 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. 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 Figure 4.21). A 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 five blade sweeps and to this mean shift data a polynomial (3rd order) curve was fitted, as shown in Figure 4.21.

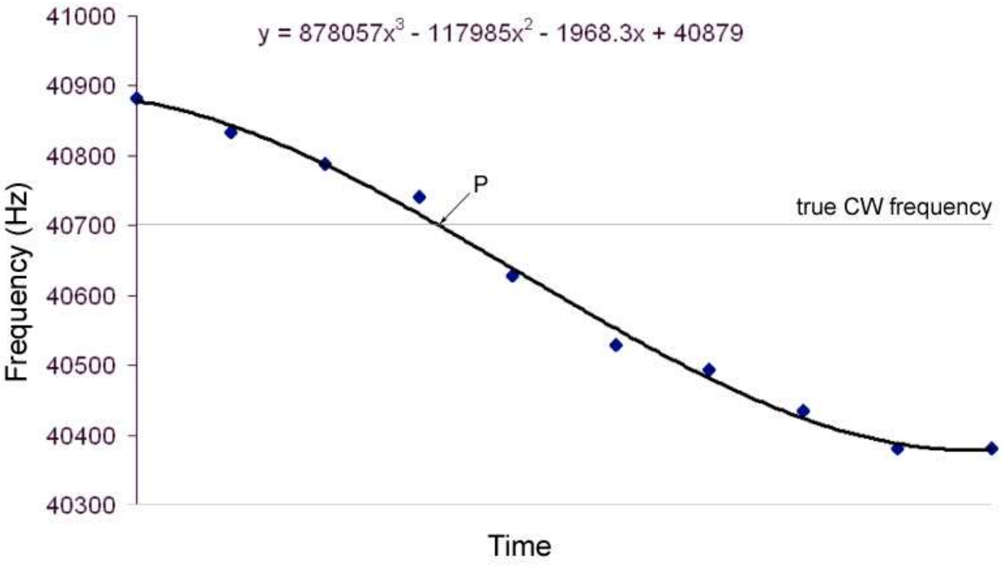

Figure 4.21- Example mean Doppler shift data fitted with 3rd order polynomial curve (y). Line indicates true CW frequency; ‘P’ indicates crossover point. Data taken from ‘horizontal’ rotor insonation at 0.5 m.

To simulate CF sampling, the curve function was applied to sample the frequencies of a single blade sweep, at random time intervals 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 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 a number of times to obtain an average number of samples required to converge.

4.2.2 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’ insonation, 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’ insonation, 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. Figure 4.22 provides CF and FM examples of the Monte Carlo convergence graphs.

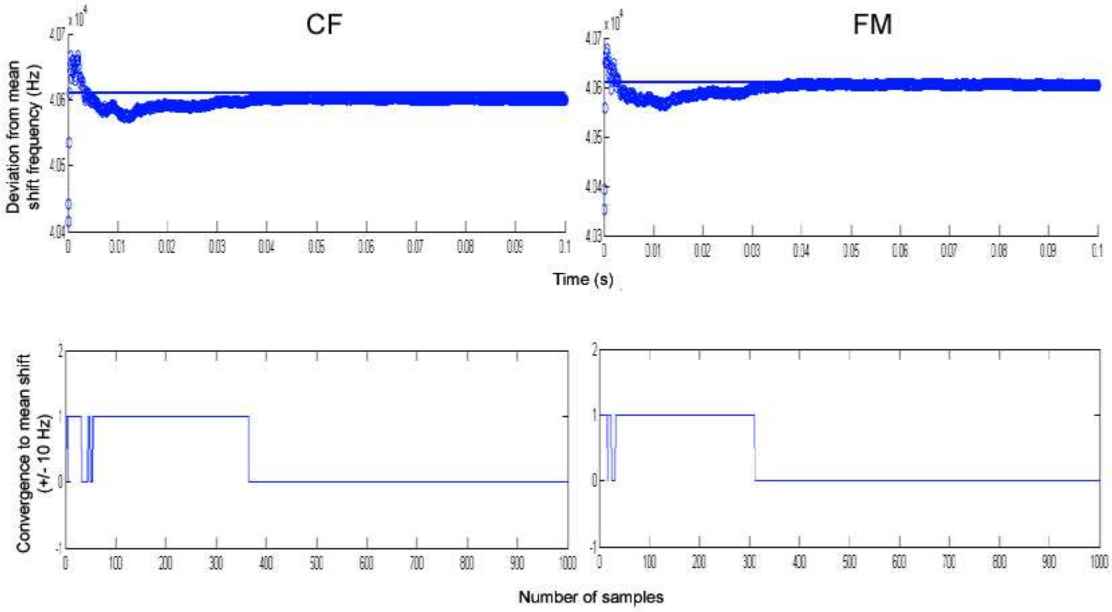

Figure 4.22- Example Monte Carlo convergence graphs for CF and FM pulses based on the Doppler shift blade sweep curve for the ‘horizontal’ aspect. Upper graphs indicate the deviation of the frequencies sampled from the mean shift frequency over the course of the sweep. Lower graphs indicate the number of samples required for convergence to the mean shift (in both cases 1=not converged, 0=converged).

4.3 Simulated Bat-Like Pulse Echoes Experimentally Reflected from Moving Blades

4.3.1 Methodology

As bats employ a finite 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 repeatable pulses for analysis, an artificial bat echolocation pulse was simulated, modelled on the FM pulse of a common pipistrelle bat (*Pipistrellus pipistrellus*) (see Figure 4.32). The equation used to create this pulse, Y, over time t, is defined as:

$$Y\ (t) = A(t) \cdot \lambda(t) \tag{4.31}$$

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:

$$A(t) = \begin{cases} A_a(t) & t \geq t_0 \leq t_1 \\ A_b(t) & t > t_1 \leq t_3 \\ A_c(t) & t > t_3 \leq t_{end} \\ 0 & \text{elsewhere} \end{cases} \tag{4.32}$$

Where

$$A_a(t) = A_{0a} + (t - t_0)\left(\frac{(A_{1a} - A_{0a})}{(t_1 - t_0)}\right) \tag{4.33}$$

$$A_b(t) = A_{0b} + (t - t_1)\left(\frac{(A_{1b} - A_{0b})}{(t_3 - t_1)}\right) \tag{4.34}$$

$$A_c(t) = A_{0c} + (t - t_3)\left(\frac{(A_{1c} - A_{0c})}{(t_{end} - t_3)}\right) \tag{4.35}$$

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:

$$\lambda(t) = \begin{cases} \lambda_a(t) & t \geq t_0 \leq t_2 \\ \lambda_b(t) & t > t_2 \leq t_{end} \\ & \\ 0 & \text{elsewhere} \end{cases} \tag{4.36}$$

Where

$$\lambda_a(t) = \sin\left\{2\pi\left[f_{0a} + (t-t_0)\left(\frac{(f_{1a}-f_{0a})}{(t_2-t_0)}\right)\right](t-t_0)\right\} \tag{4.37}$$

$$\lambda_b(t) = \sin\left\{2\pi\left[f_{0b} + (t-t_2)\left(\frac{(f_{1b}-f_{0b})}{(t_{end}-t_2)}\right)\right](t-t_2)+\phi\right\} \tag{4.38}$$

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

$$\phi = 2\pi\left(f_{0a} + (t-t_0)\left(\frac{(f_{1a}-f_{0a})}{(t_2-t_0)}\right)\right) \tag{4.39}$$

A depiction of the variation in amplitude and frequency over time used to form the FM pulse by implementing Equation (1) is shown in Figure 4.31.

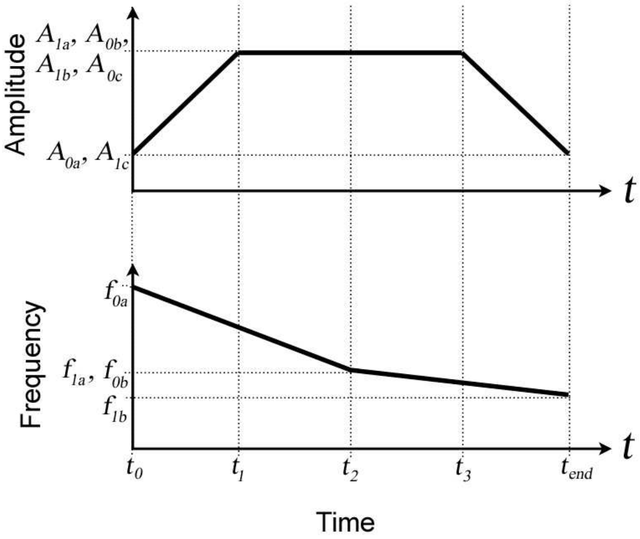

Figure 4.31- Demonstrating the utilisation of time components (*t*) in Equations 4.32-4.39 and the variation of frequency and amplitude with each segment. The frequency changes depicted here were applied only to λ in the creation of the FM pulse.

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

$$\lambda_{CF}(t) = \begin{cases} \lambda_{CFa}(t) & t \geq t_0 \leq t_{end} \\ \\ 0 & \text{elsewhere} \end{cases} \tag{4.310}$$

And

$$\lambda_{CFa}(t) = \sin\left[(2\pi \cdot f)(t - t_0)\right] \qquad (4.311)$$

Whereby f is the CF frequency. Pulse generation 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 (Figure 4.32).

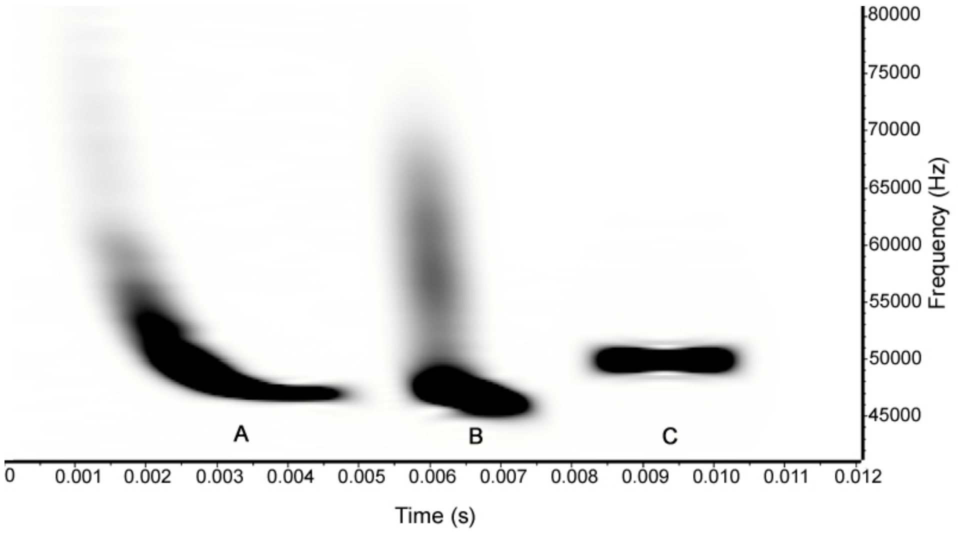

Figure 4.32- FFT sonogram of a real common pipistrelle pulse (A), the short simulated FM pulse (B) and the short simulated CF pulse (C). FFT length 512 points, Hanning window, 40 % overlap, 0.9 % linear energy scaling (sampling rate 200 kS s^{-1}).

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 approx. 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 & Jones (1995)); 90 dB peSPL re 20 µPa 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 in Section

4.1 (Figure 4.11) and pulses fired at the rotor, both while blades were stationary and under operation (see Figure 4.33).

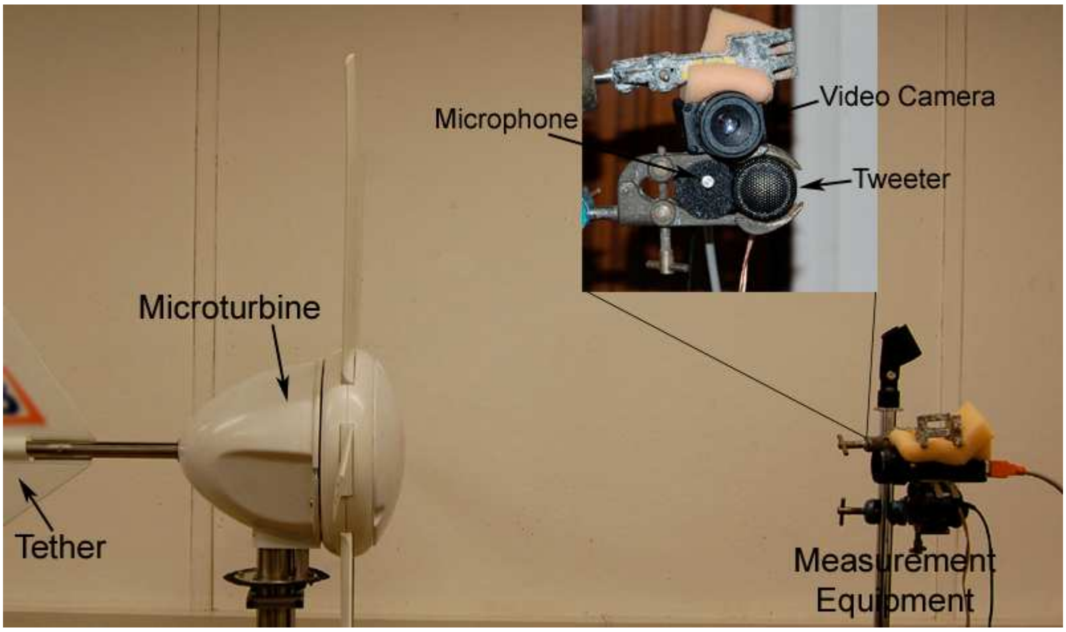

Figure 4.33- Equipment set-up for bat-like pulse echo testing, demonstrating the positioning of the turbine and measurement equipment (‘source’) for the ‘horizontal’ aspect.

Horizontal measurements were taken at distances of 0.5 and 1 m, however lateral measurements 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 analysed using Audition and MATLAB. Pulse echoes were analysed 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.

4.3.2 Results

A total of 1166 reflected pulses were recorded and analysed, averaging 117 echoes per assessed angle and distance. In the majority of test configurations, 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 a measurable echo reflected back to source that corresponded to the rotor edge, despite a consistent echo being returned from the hub (Figure 4.34). This was caused by the interplay between the 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).

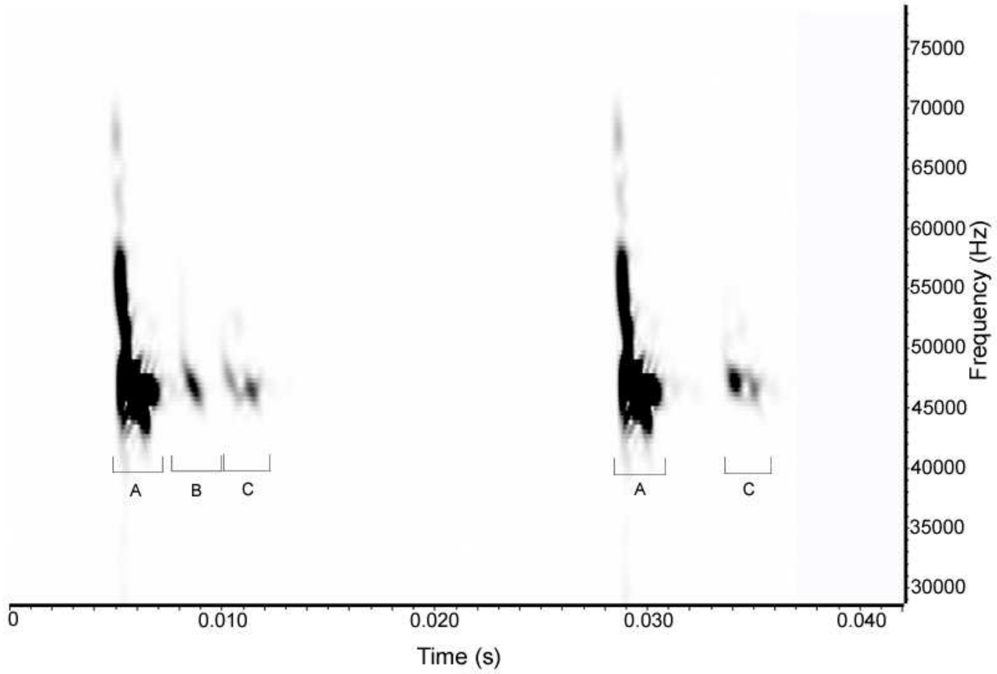

Figure 4.34- Example FFT sonogram for FM pulses and echoes recorded from the 'lateral mid' angle at 0.5 m. A: outgoing pulse; B: echo returned from blade tips; C: echoes returned from the hub. Note that the interpulse interval has been artificially reduced in this example. Data recorded at 800 kS s^{-1} (FFT length 1024 points, Hanning window, 40 % overlap, 5 % linear energy scaling).

In all cases the sound intensity had much greater variance for echoes returned from the operational rotor than those from the stationary rotor (Figure 4.35).

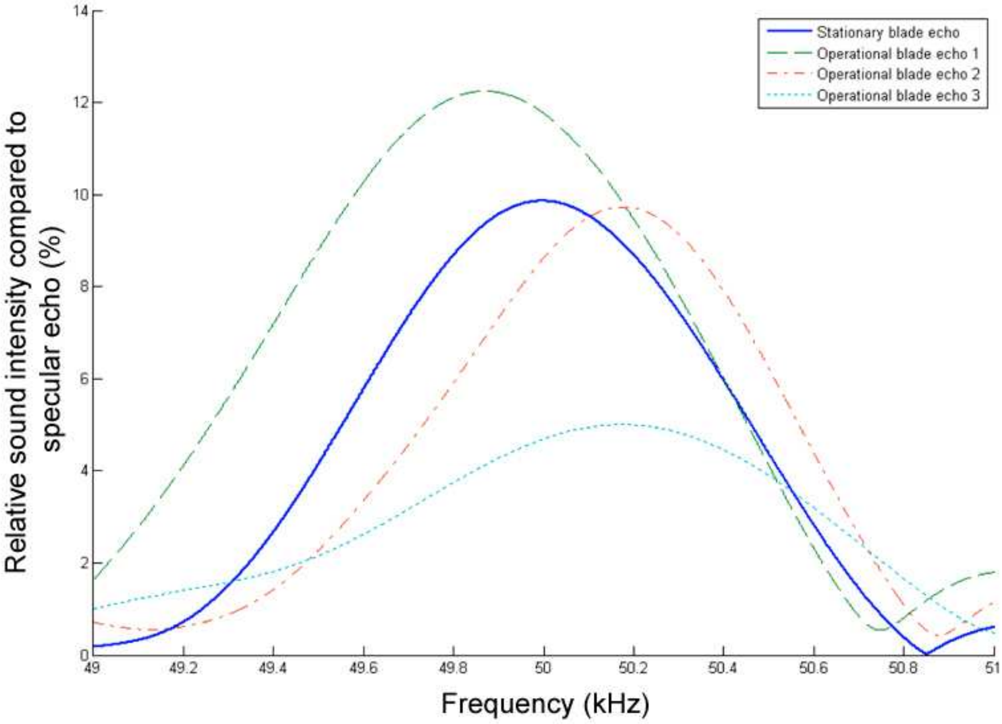

Figure 4.35- DFT traces demonstrating the variation in pulse echo sound intensity returned from operational turbine blades at various positions (dashed line examples) as compared to stationary blades (solid line example). Note that the frequency shift of the experimental echo is dependent on the position 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.

Table 4.31 overleaf describes the mean and standard deviation values for frequency of peak energy and percentage of specular reflected 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).

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 mean percentage of specular sound intensity (%)*	*Rotor stationary percentage of specular intensity standard deviation (%)*	Rotor operational mean percentage of specular sound intensity (%)	Rotor operational percentage of specular intensity standard deviation (%)	Sound intensity as compared to stationary rotor echoes
H 0.5	CF	*49.97*	*± 11*	49.97	± 191	None (*t*=-0.04)	*9.9*	*± 0.08*	11.5	± 6.91	Higher (p<0.05; *t*=-2.46)
H 0.5	FM	*47.38*	*± 266*	46.87	± 436	Negative (p<0.00005; *t*=10.87)	*5.4*	*± 0.12*	10.9	± 9.47	Higher (p<0.00005; *t*=-6.36)
H 1	CF	*50.18*	*± 29*	49.92	± 146	Negative (p<0.00005; *t*=19.33)	*9.7*	*± 0.29*	10	± 6.16	None (*t*=-0.46)
H 1	FM	*47.14*	*± 80*	47.01	± 797	None (*t*=1.67)	*16.4*	*± 0.33*	9.8	± 4.3	Lower (p<0.00005; *t*=16.86)

Continued overleaf…

…continued

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 mean percentage of specular sound intensity (%)***	***Rotor stationary percentage of specular intensity standard deviation (%)***	**Rotor operational mean percentage of specular sound intensity (%)**	**Rotor operational percentage of specular intensity standard deviation (%)**	**Sound intensity as compared to stationary rotor echoes**
LT 0.5	CF	*49.1*	*± 29*	49.92	± 212	None (*t*=-0.89)	*2.1*	*± 0.08*	1.8	± 0.75	Lower (p<0.00005; *t*=5.14)
LT 0.5	FM	*46.9*	*± 94*	46.94	± 423	None (*t*=-1.1)	*4*	*± 0.11*	2.4	± 0.96	Lower (p<0.00005; *t*=18.27)
LM 0.5	CF	*50.01*	*± 13*	49.99	± 156	None (*t*=1.48)	*3*	*± 0.18*	2.5	± 1.75	Lower (p<0.005; *t*=2.87)
LM 0.5	FM	*46.87*	*± 17*	47.05	± 223	Positive (p<0.00005; *t*=-7.72)	*4*	*± 0.15*	3.6	± 1.13	Lower (p<0.0005; *t*=3.67)

Continued overleaf…

…continued

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 mean percentage of specular sound intensity (%)***	***Rotor stationary percentage of specular intensity standard deviation (%)***	**Rotor operational mean percentage of specular sound intensity (%)**	**Rotor operational percentage of specular intensity standard deviation (%)**	**Sound intensity as compared to stationary rotor echoes**
LB 0.5	CF	*49.99*	*± 19*	50.04	± 64	Positive (p<0.00005; *t*=-8.1)	*11.8*	*± 0.44*	9.2	± 1.44	Lower (p<0.00005; *t*=18.83)
LB 0.5	FM	*46.88*	*± 18*	46.7	± 76	Negative (p<0.00005; *t*=26.05)	*3.9*	*± 0.18*	10	± 1.31	Higher (p<0.00005; *t*=-50.77)

Table 4.31- Experimental values for FM and CF pulse echoes reflected from stationary and operational rotor blades. ‘FPE’ denotes frequency of peak energy. Insonation angle key: H = horizontal; LT = lateral top; LM = lateral mid; LB = lateral bottom. Values in italic font (highlighted in grey) correspond to stationary rotor measurements.

4.4 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 insonated 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.*, 2000), resulting in distance/range errors. Since many bats fly at 1-2 % of the speed of sound (Griffin, 1974), it is possible to calculate the Doppler shift percentage from stationary point targets by implementing the following equation, defined by Boonman *et al.* (2000):

$$s = \frac{1 + v_{bat} / v}{1 - v_{bat} / v} \tag{4.41}$$

Where s is the Doppler factor, v_{bat} the flight speed of the bat and v the speed of sound in air. Therefore, echoes returned from a stationary target may be shifted up to 4.1 % 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 & Moss, 2000). The turbine used for experimental work in this chapter 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 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 of Section 4.2 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 seconds, which is biologically unlikely with normal bat flight behaviour. Even assuming the pipistrelle-like bat was approaching the rotor from a maximum detectable distance of 15 m (based on the interpulse interval, after Holderied *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, as results indicated at least 45 pulses were required for mean shift convergence. This is highlighted in Figure 4.41 which depicts the relative reliability of blade motion interpretation according to distance of approach (and therefore number of possible echolocation pulses produced).

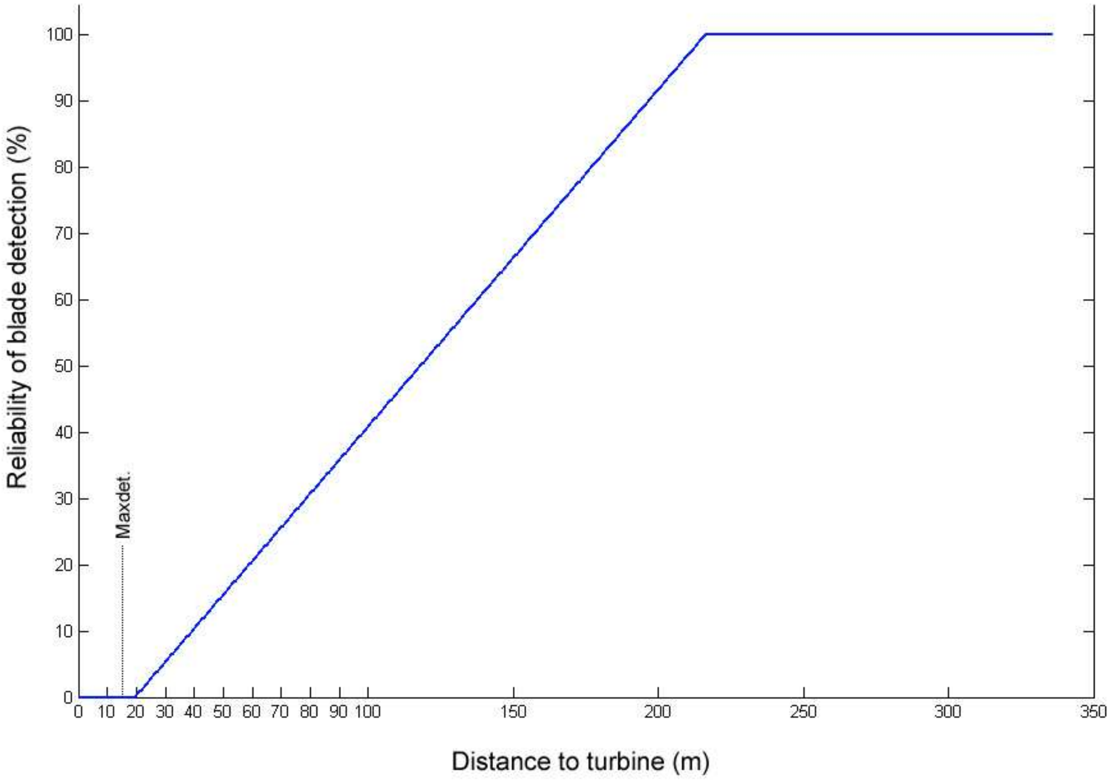

Figure 4.41- Demonstrating how the reliability of information presented to the bat may vary according to distance of approach (and hence number of echolocation pulses produced before the bat reaches the turbine). Calculated using the pulse length and interpulse interval of the common pipistrelle (*Pipistrellus pipistrellus*) assumed to be travelling at a constant 5 m s^{-1}. Dashed line labelled 'Maxdet.' indicates the maximum likely detectable distance of the turbine for this bat species. Based on a minimum of 45 pulses and a maximum of 400 pulses for accurately assessing the nature of blade Doppler shift sweeps.

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 & Schnitzler, 1986), are typically consistent with target movements and are also observed in fluttering insect echo returns (Sum & 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 & Perdeck, 1950) 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.

4.5 Ultrasound Emission from Turbines

It is not known whether operational wind turbine rotors produce significant levels of ultrasonic emission that could potentially interfere with echolocation during bat-turbine interactions. It might be speculated that ultrasonic noise in the vicinity of the rotor could potentially 'jam' the ultrasonic emissions of a bat. It has even been suggested that the noise itself is attractive to bats (Johnson & Kunz, 2004; BCT, 2006) or at least attracts the curiosity of bats (Arnett *et al*., 2005), although investigations by Ahlén (2004) to this effect have demonstrated negative results and this hypothesis remains largely unverified (Arnett *et al*., 2005). Given that an active turbine produces a lot of human-audible noise from the blades and nacelle, it seems feasible there could also be an ultrasonic component (Johnson & Kunz, 2004), although turbine noise is predominantly low frequency with almost all acoustic contribution at 65 dB SPL from frequencies below 2 kHz (Dooling, 2002). The rotational frequency and its harmonics can produce unwanted vibrations (Twidell, 2003), which could play a part in ultrasonic emission. Some studies have been unable to detect any ultrasonic noise produced by active turbines, although it is possible that the distance between the turbine blades and ground level was large enough to prevent detection by the equipment used at the time (Johnson & Kunz, 2004). To date, there have been very few investigations into the ultrasonic emissions of different makes of turbine. Schröder (1997) investigated the ultrasonic emissions of 47 turbines (19 types) in Germany, using a 'Pettersson D980' bat detector at ground level from the base up to 100 m away. The majority of turbines in Schröder's study were found to produce ultrasound, typically between 20-50 kHz, which correlates well with frequencies used by European bat species for echolocation (although the sound intensity, and the relationship with bat mortality, were not investigated). A similar study by Szewczak & Arnett (2006) examined ultrasonic emission components of 7 types of turbine at wind plants around the US, as measured by a 'Pettersson D240x' at ground level. In contrast with Schröder's findings, Szewczak & Arnett found most turbines contributed little, if any, ultrasound above ambient noise. There appears to be no 'standard' type of ultrasound emission between different makes of turbine, with some structures emitting no ultrasound while others emit significant levels of ultrasonic sound. Although the turbines in Schröder’s study ranged from 10-92 m, there did not appear to be a correlation between ultrasonic emission and turbine size, and the source of the ultrasonic noise remains unknown. According to Twidell (2003), high frequency noise is generated from the blade tips, while low frequency noise may be generated from the blades passing the tower and perturbing the wind. The internal machinery is also reportedly a generic source of noise, and while Szewczak & Arnett (2006) found the electronic machinery of some turbine models to generate ultrasonic noise, in most cases this was not detectable more than 10 m from the nacelle. Some turbines have a digital anemometer on top of the turbine rotor housing, and these have been found (in some cases) to emit ultrasound themselves in the region of 38 kHz (Arnett *et al*., 2005), well within the frequency range found to be used by bat species observed in the areas of the study. Arnett and colleagues disabled some of these anemometers and found that there was no effect on the bat mortality rate. The conclusion was reached that these emissions were too readily attenuated to have any effect on the bats present; however the intensity of the emissions from these devices was not measured. It was noted that other sources of ultrasonic emissions on the turbines needed further investigation. Some blades are known to ‘whistle’ due to slight defects in the blade (Dooling, 2002), which Dooling hypothesised may help birds (and possibly bats) to avoid these blades (another theory which remains untested). Dooling also proposed adding these ‘whistles’ intentionally to turbines, which was claimed to make no measurable contribution to overall human-audible turbine noise level. The impact of ultrasonic emissions on bats is thought to be limited, particularly during the summer and during migration (Rodrigues *et al*., 2006), however this theory remains untested and the way bats react to turbine ultrasound (or indeed ultrasonic noise in general) remains unknown (Bach & Rahmel, 2004; Bach, 2001). Some observations suggest that serotines actually avoid locations where ultrasonic emissions occur, but other bats (such as pipistrelles) do not (Bach, 2001). It is possible that serotines are able to use ultrasound produced by turbines as an ‘acoustic landmark’ and use this for orientation or avoidance (after Jensen *et al*., 2005). Clearly this is an area in need of further investigation, but is largely outside the scope of the current thesis.

4.5.1 Microturbine Sound Field Measurement

In order to examine for ultrasonic sound emission from the six-blade microturbine used in experimental work, the sound field profile of the operational rotor was measured. As in previous experiments, the rotor was driven using a fan at the equivalent wind speed of 4.1 m s^{-1} and allowed to rotate freely while data were recorded using the GRAS 40BF calibrated microphone (frequency range 2 Hz-100 kHz) and USB-6251 DAQ card (the fan was turned off during data collection). The microphone was positioned opposite the rotor, 0.6 m from the centre of the turbine hub, and the rotor angled in 10° increments around the central pivot point (directly beneath the hub), starting at the 0° position with the hub's centre facing the microphone. A control measurement was also taken inside the anechoic chamber whilst the turbine rotor was stationary. Data were saved direct to a PC in .wav file format.

A one second segment of each recorded data file was analysed in MATLAB and a DFT trace completed over the frequency range of interest, between 45-55 kHz, using a FFT algorithm. Although noise measurements are typically taken at a single specified frequency, given the broad frequency range covered by common British bat species, including the common pipistrelle, it seemed logical to assess a wider frequency band. The mean peak amplitude of the selected frequency range was obtained for each data file and this value converted into dB re 20 µPa. These values were then plotted onto a polar sound map, which is shown in Figure 4.51.

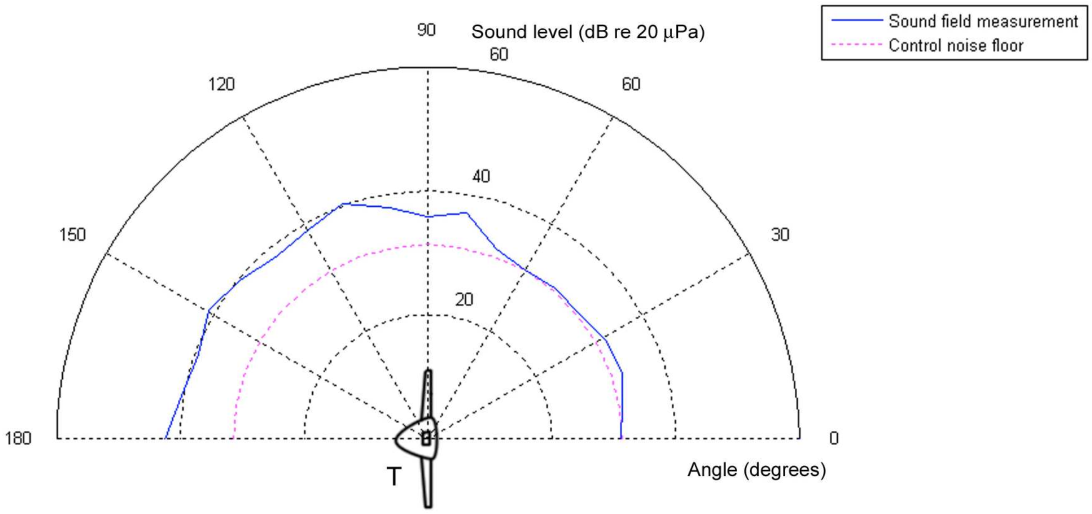

Figure 4.51- Polar sound map of microturbine sound field in the ultrasonic region between 45-55 kHz, as measured by calibrated ultrasonic microphone at a distance of 0.6 m. Solid line indicates the noise measurement, dotted line the control noise floor level for the microphone, while 'T' denotes the location of the microturbine.

As the operational turbine rotor did not contribute appreciable ultrasonic noise above the undistorted noise floor level of the microphone, it was concluded that the operational rotor did not contribute a high level of ultrasonic noise to the environment in the range of 45-55 kHz. In addition, sonograms of the ultrasonic frequency band recorded (20-100 kHz) revealed no other ultrasonic contribution in this range. Experimental work by Griffin *et al*. (1960) concluded that sounds produced by small insects of 25-30 dB re 20 μPa at 15 cm were unlikely to be detectable by a bat over 50 cm away, so it seems unlikely that the similar noise level produced by this turbine could be acting as an acoustic lure or masking echolocation. Although this particular microturbine model has been previously linked to bat deaths, it seems unlikely that ultrasound emission played any critical role.

4.5.2 Unusual Turbine Fault Emission

As noted by Dooling (2002), minor blade structural discrepancies/faults can cause operational rotors to 'whistle', either in the human-audible or ultrasonic range. An interesting example of this was recorded using the calibrated microphone from the 20 kW turbine at the Oadby site, as demonstrated in Figure 4.52.

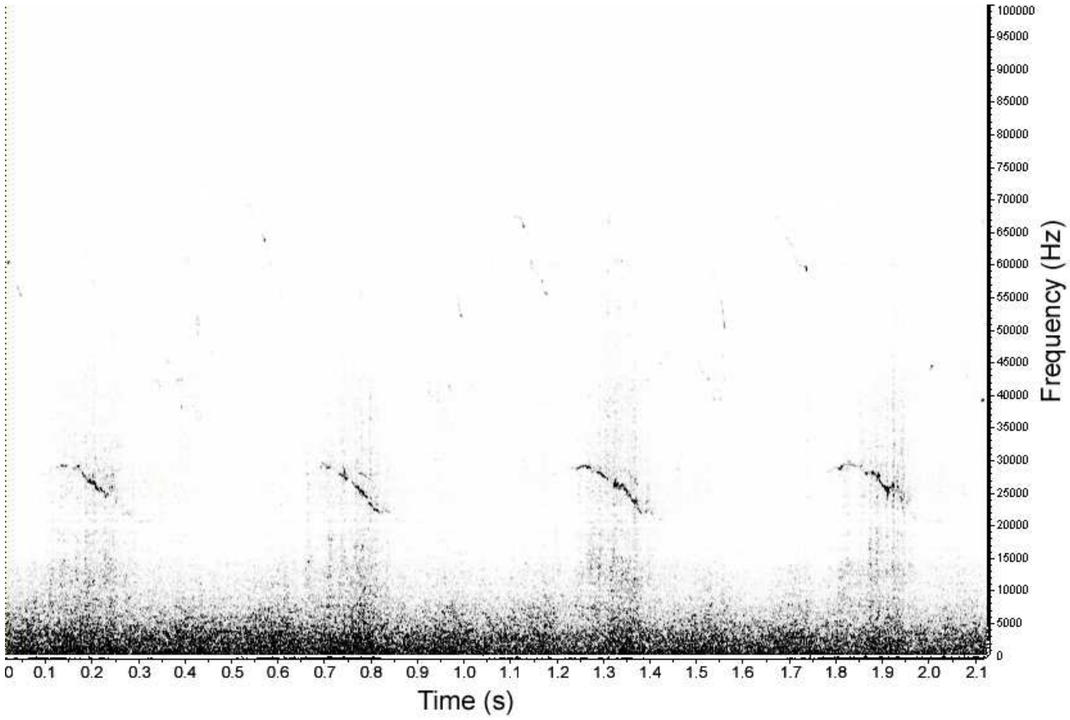

Figure 4.52- Acoustic emission spectral FFT profile from the Oadby 20 kW turbine, recorded at 200 kS s^{-1} at the turbine base, one metre above ground level (hub height 13 m). Hanning window, FFT length 1024 bands, 75 % overlap, 40 % linear energy scaling.

Ultrasonic FM sweeps were produced by the turbine, between around 22-30 kHz and lasting about 140 ms. By analysing video footage of the moving blades (25 frames s^{-1}), these FM sweeps were confirmed to correlate with the passage of one of the turbine's three blades. The owners of the turbine reported that there was one damaged/defective blade that had previously been repaired, but not replaced. Figure 4.53 highlights the overall amplitude difference between sound emission from the turbine and a control background noise measurement taken in the same location while the turbine was not operational, over the frequency range of the emitted sweep (22-30 kHz).

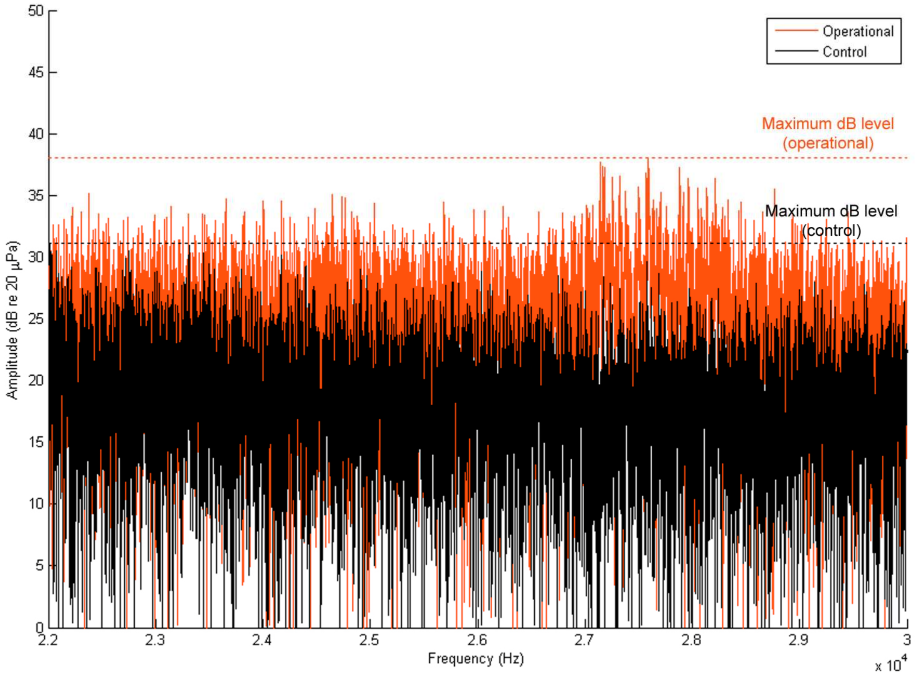

Figure 4.53- DFT trace of the recorded amplitude data comparing a control measurement to that taken during turbine operation, between 22 to 30 kHz (DFT calculated using MATLAB's FFT algorithm, sampled at 200 kS s^{-1}, FFT length 262144 bands). Red and black dotted lines indicate maximum dB levels for the operational and control recordings, respectively. Data taken from 600 ms samples of original recordings (one complete blade sweep cycle).

Although the predominant ultrasound emissions between 22-30 kHz may be below the detectable range of some of the more common bat species, the serotine, Leisler's and noctule bats all echolocate at the lower end of the ultrasonic spectrum, within this range, and may therefore be able to detect this particular turbine's acoustic emission. While the peak amplitude of the emission over this range was over 5 dB re 20 µPa louder than the ambient background noise, the peak was less than 40 dB re 20 µPa in total as measured directly underneath the blades (12 m to hub), and degraded such that it was not discernible above background noise over 20 m away from the source. This can be compared with the relative sound levels produced by the operational turbine within the human audible range (up to 20 kHz), with a peak of 96 dB re 20 µPa in the <1 kHz zone, as measured at the turbine's base (Figure 4.54).

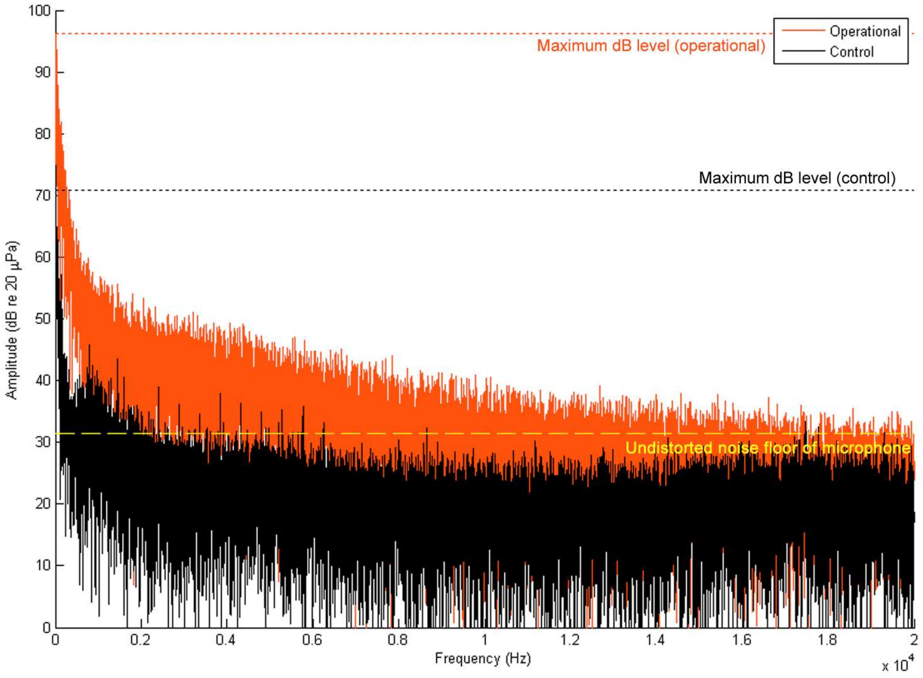

Figure 4.54- DFT trace of the recorded amplitude data comparing a control measurement to that taken during turbine operation, between 4 Hz to 20 kHz (DFT calculated using MATLAB's FFT algorithm, sampled at 200 kS s^{-1}, FFT length 262144 bands). Dashed line at 31 dB re 20 μPa represents the undistorted noise floor level of the measurement microphone; red and black dotted lines indicate maximum dB levels for the operational and control recordings, respectively. Data taken from 600 ms samples of original recordings (one complete blade sweep cycle).

It is therefore conceivable that some bats could detect the ultrasonic emissions from this particular turbine which are caused by a blade fault. However, bats in the locality of the turbine may not be able to detect such emissions unless they were in the immediate vicinity, for example within a radius of 10 m, due to the low amplitude of the ultrasound emission and high attenuation.

4.6 Conclusions

In conclusion, in the laboratory study 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 insonation and blade position. Frequencies were shifted by up to 6.9 % by turbine rotor blades operating under experimentally simulated low wind speed conditions ($<6\ \mathrm{m\ s^{-1}}$). Computer simulations using a Monte Carlo method 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. Finally, the operational microturbine rotor was found not to produce significant levels of ultrasound within the region detectable by most bat species, however it was found to be possible that structural blade faults can cause ultrasonic emissions which have the potential to be detectable by some bat species in the vicinity.

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Red microturbine, Loughborough, C.V. Long (2010)

5

Insect Attraction to Wind Turbines

Because it is not exclusively bat species that are involved in wind turbine interaction it is possible to look for common features between the aerial animals that are affected. Many reports, such as that of Erickson *et al* (2002), have found that the vast majority of turbine bird-strike victims are insectivorous passerines (a broad classification of ‘perching’ birds), comprising over 80 % of all avian collisions. This data, coupled with that of insectivorous bat species, highlight the possibility that insect activity around turbine structures may be acting as a lure for insect predators. Whilst it is still unclear why bats frequent wind turbine installations, recent research has shown that bats appear to actively investigate turbine rotors (Horn *et al.*, 2008). Some species may be assessing them as potential roost sites (Cryan, 2008), however there is also some evidence of foraging behaviour around turbines (Horn *et al.*, 2008; Ahlén, 2004). Bats tend to be concentrated in areas of high insect density (Nicholls & Racey, 2007) and are much more likely to begin hunting when large numbers of insects are congregating (Griffin *et al*., 1960). Reports into bat-turbine interactions frequently state the importance of investigation into the possibility of insect attraction to turbines (e.g. Johnson & Kunz (2004); Ahlén (2004); Nicholls & Racey (2007); Rodrigues *et al.* (2006)), particularly since the recent loss of feeding habitats may be pressuring bats to feed in alternative areas (Wickramasinghe *et al.*, 2003). Turbine colour may play an important part in insect attraction (Ahlén, 2004), although to date this has not been closely investigated. Turbines are mostly painted white (Johnson & Kunz, 2004) or shades thereof; the reasoning behind painting turbines in light colours appears to be connected with making turbines "visually unobtrusive" against the skyline, to make them "blend well into the landscape", or to make them easier to locate for meteorological purposes (Danish Wind Industry Association, 2003). In the case of offshore turbines, light colours minimize visibility from shore (Department of Trade and Industry (DTI), 2005). Offshore turbines are also required to be painted yellow from the level of 'highest astronomical tide' up to 15 m (DTI, 2005) to ensure they are visible to ships. Turbines are typically coloured by paint mixed to RAL colour specifications; RAL is an established firm that is known internationally and has been producing colour standards for over 70 years. The two most common turbine paint shades are 'Pure White' (RAL 9010) or 'Light Grey' (RAL 7035) (e.g. Vestas Wind Systems, 2006). Turbine colour is usually dependent on local building regulations and occasionally turbines are painted in other shades, for example 'Squirrel Grey' (RAL 7000) (Bracknell Forest Borough Council, 2007), a colour which was chosen as it was deemed to "blend in better with a rural landscape and the UK skyline", and was "less visually obtrusive" than green, brown or black (Bracknell Forest Borough Council, 2007). The effect of this on bird and bat mortality was not considered. To date, there has been one notable study to investigate effects of turbine colour, by Young *et al*. (2000), with regard to painting turbines with ultraviolet (UV) reflective paint as a visual warning for birds. The results indicated an increase in the number of avian fatalities around UV painted turbines (68 % at UV turbines; 15 % at non-UV turbines). It could be speculated that the UV paint would increase the attraction of insects to the turbine, and thus the attraction of insectivorous birds; this theory is supported by the fact that members of the fly genus *Drosophila* are consistently attracted to UV reflecting objects, a trait frequently exploited by web-making spiders (Craig & Bernard, 1990). In this chapter the insect attraction to specific turbine colours is investigated in an attempt to determine whether this is one variable that needs to be addressed for future wildlife-turbine mitigation. Indeed, if changing the turbine colour alone could largely mitigate the problem, this would provide a cost-effective and minimally disruptive design solution to the issue. So, whilst this thesis has already identified acoustic reasons why bats may not be able to accurately interpret moving blades, the current chapter addresses the question of why bats may be initially drawn to turbine structures.

5.1 Methodology

5.1.1 Study Area

The location for experimental work was a meadow at the base of a 13 metre, 3-blade turbine (light grey), approximately 5 m from the base. This turbine was situated in an area of public parkland, at GPS coordinates 52°35’16.70” N, 1°05’06.28” W in Oadby, Leicestershire, UK. Deciduous woodland and hedgerow (see Figure 5.11) surrounded the meadow on all sides; there was an abundance of local bird and bat activity (although no known documented mortality incidents) in the vicinity.

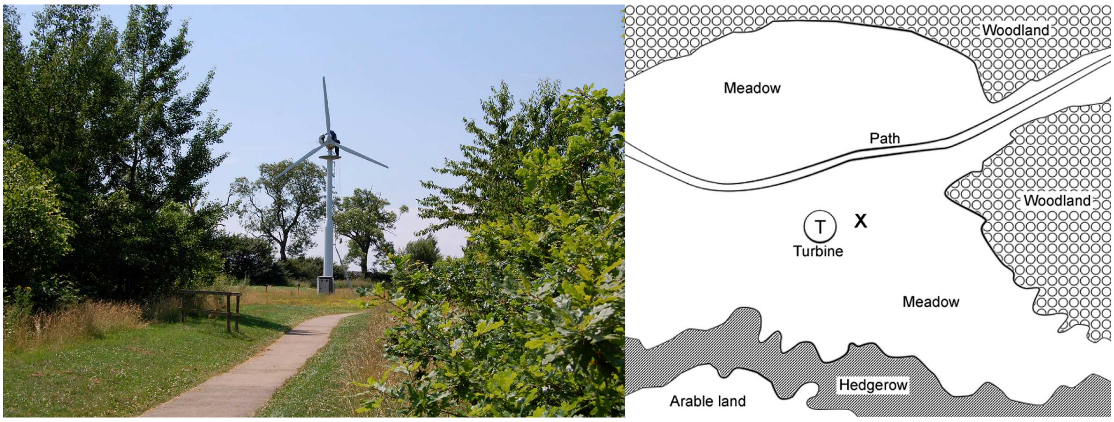


Figure 5.11- Demonstrating the local habitat of the study site; a photograph of the site (left) taken in July at midday, and an aerial plan diagram of the immediate area (right), where ‘X’ denotes the precise location of measurements.

5.1.2 Data Collection

A selection of ten reference colour cards from the RAL colour range were used, each measuring 215 mm by 303 mm and impregnated on one side with the specified RAL colour by the manufacturer (RAL gemeinnützige GmbH, Germany). The colours chosen were as follows; RAL 9010 “Pure White” (white), RAL 7035 “Light Grey” (light grey), RAL 7000 “Squirrel Grey” (dark grey), RAL 5015 “Sky Blue” (blue), RAL 3020 “Traffic Red” (red), RAL 4001 “Red Lilac” (purple), RAL 1023 “Traffic Yellow” (yellow), RAL 8025 “Pale Brown” (brown), RAL 6026 “Opal Green” (green) and RAL 9005 “Jet Black” (black). Colours were selected in such a way as to produce a varied spectrum of samples, in addition to the common turbine colours (white and light grey), a less common turbine colour (dark grey), and black. Some of the other additional colours were chosen for various reasons; several flower visiting insects express an innate colour preference (Lunau and Maier, 1995) with many insects being attracted to yellow colours (560-590 nm) (Prokopy and Owens, 1983), including Diptera (flies) and Lepidoptera (butterflies and moths) (Kevan, 1983). Blue flowers (400-500 nm) have been observed to be particularly attractive to Hymenoptera (bees) (Kevan, 1983), while pink and red flowers (650-700 nm) are frequently visited by Lepidoptera (Kevan, 1983). In order to protect colour cards and to prevent discolouration by moisture contamination and other debris, each card was laminated inside a transparent plastic pocket. An empty laminated pocket was included as a transparent control. To assess the relative “attractiveness” of each colour card to insects, cards were laid out, face up, in two rows of 6 and 5 cards, respectively, approximately 2 cm apart. Each card was then observed, in turn, for a set period of time, during which the number of flying insects present on or within approximately 10 cm from the card’s surface was recorded. After 5 seconds, the next card along the grid was observed, and so on in an anti-clockwise pattern, over a total of 10 minutes. By assessing cards in this manner, it is quite possible to re-count the same insect on the same card several times; this is not problematic as it effectively weights the count to account for a greater attraction to any one colour card. After this 10 minute period, the cards were gathered, carefully cleaned, shuffled and randomly re-distributed throughout the grid in order to avoid potential bias caused by the proximity of any one colour to another. This was repeated 3-5 times in succession and the insect species present noted at the end. For sunset observations only, a low power torch (300 lux peak luminous emittance at 300 mm) was used to illuminate the card under observation in order to facilitate insect identification. While certain nocturnal insect species, such as moths, are known to be attracted to light sources, the torch was used consistently for observations and turned off between readings in order to minimise any bias caused by its use. Each set of measurements were taken between the months of June to October, corresponding with the months of peak bat activity, over a three year period. In year 1, readings were taken at midday only, in year 2, readings were taken 1 hour after sunset only, and in year 3, readings were taken both at midday and 1 hour after sunset on the same day. Before each measurement, the time and weather conditions were noted and temperature, relative humidity and wind speed readings taken from an HHF81 digital 4-in-1 meter (OMEGA engineering, Inc., CT, USA). In addition, the wavelength spectral reflectance peaks (within a range of 900-300 nm) of all cards used in the experiment were measured using a UV/VIS Lambda Bio 40 Spectrometer (Perkin-Elmer, Inc., MA, US).

5.1.3 Statistical Analysis

Data were analysed using the GLM ANCOVA module of Statistica 5.1 (StatSoft, Inc., OK, USA). ‘Insect count per 10 minute period’ was selected as the dependent variable in all cases, while either ‘colour’, ‘month’, ‘time of day’, ‘year’, ‘weather conditions’, ‘temperature’, ‘relative humidity’ or ‘wind speed’ were chosen as independent variables. Since these factors also varied in conjunction with the independent variables, in all cases the relevant variables from ‘colour’, ‘month’, ‘time of day’, ‘year’, ‘weather conditions’, ‘temperature’, ‘relative humidity’ and ‘wind speed’ were selected as covariates. In order to assess the importance of spectral peak percentage reflection, peak UV reflection and peak infrared (IR) reflection, these were selected as independent variables with ‘insect count per 10 minute period’ as dependent variable and ‘colour’, ‘month’, ‘year’, ‘weather conditions’, ‘temperature’, ‘relative humidity’ and ‘wind speed’ selected as covariates. Because UV and IR measurements taken represented reflection in peak light conditions, this analysis was applied only to midday measurements with weather conditions of ‘sunny’ and ‘sunny spells’.

5.2 Results

A total of 2012 insect observations were made over the three-year course of the study, from 59 10-minute sessions. Note that the vast majority of insects counted had landed on the surface of the colour cards.

5.2.1 Effects of Colour on Insect Attraction

Colour was found to have an overall significant effect on insect count ($p < 0.0005$; $F_{[10,631]} = 3.25$); Figure 5.21 demonstrates the total mean insect count for each colour tested. Of these, the colour yellow was the most attractive overall ($p < 0.00005$; $F_{[2,631]} = 11.09$), however the turbine colours white and light grey were significantly more attractive than all other colours (excluding yellow) tested ($p < 0.05$; $F_{[2,631]} = 4.34$). Purple attracted significantly fewer insects overall ($p < 0.05$; $F_{[2,631]} = 4.63$) than any of the other colours tested.

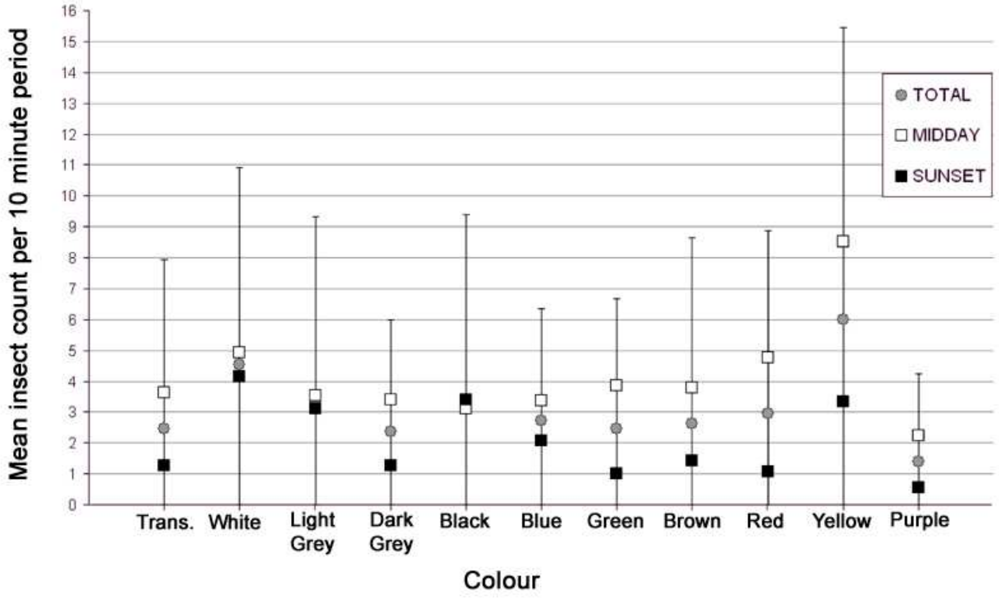


Figure 5.21- Mean insect count per 10 minute period for each colour tested. Grey circles indicate total means with ± standard deviation whiskers; white and black boxes indicate means for midday and sunset +1 hr counts, respectively.

5.2.2 Effects of Spectral Reflectance on Insect Count

Spectral reflectance peaks were found to vary between each colour card tested, both in the visible, UV and IR spectrum (Figure 5.22). Overall, peak spectral reflectance had a significant effect on insect count per 10 minute period ($p<0.005$; $F_{[9,225]} = 3.0$) for midday (sunny and sunny spells) measurements. Both peak UV reflectance and peak IR reflectance significantly influenced insect count ($p<0.005$; $F_{[9,225]} = 3.0$; $p<0.05$; $F_{[8,226]} = 2.82$) with higher spectral reflectance in these ranges attracting more insects. The card colours yellow and white gave the highest IR reflectance peak, while the transparent ‘control’ card, interestingly, gave the highest UV peak (see Figure 5.22).

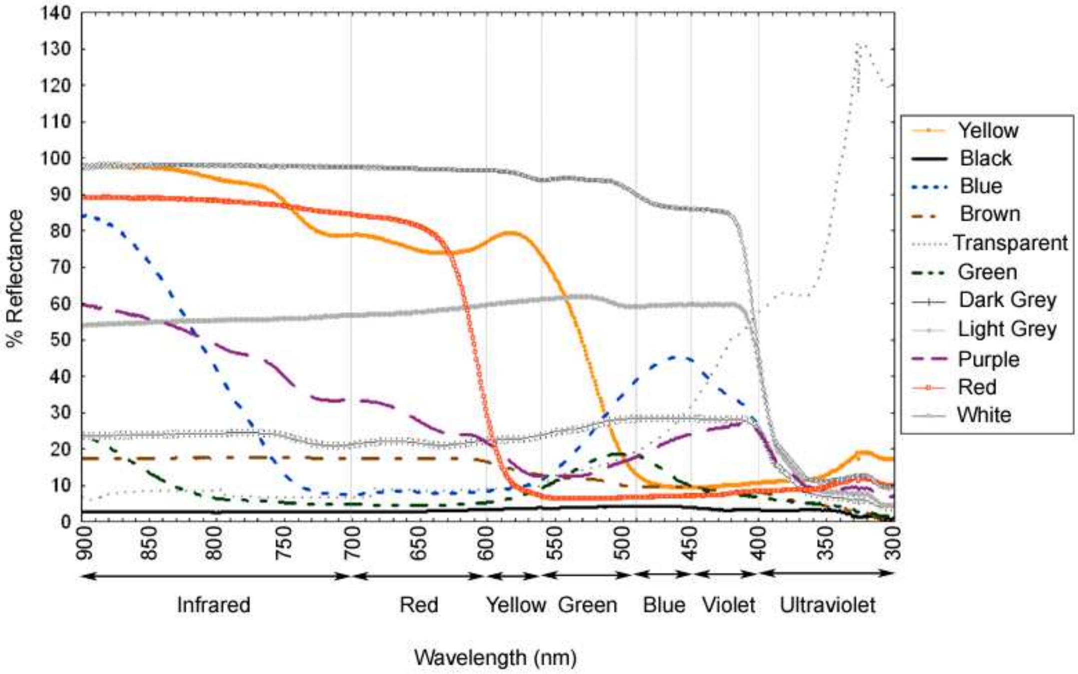


Figure 5.22- Spectral reflectance data for each experimental card, demonstrating peaks in reflectance for wavelengths between 900 (infrared) to 300 (ultraviolet) nm. Note that the reflectance peak for the transparent card is above 100 % due to fluorescence in the UV range.

5.2.3 Seasonal, Annual and Meteorological Effects on Insect Count

Time of day was found to significantly influence insect numbers; total insect counts were significantly lower after sunset than at midday ($p <0.00005$; $F_{[1,640]} = 18.44$), although this phenomenon did vary according to colour (see

Figure 5.21). Insect counts varied significantly according to month ($p < 0.00005$; $F_{[4,637]} = 10.76$) over the course of the data collection period. The month of July had the highest total mean count and October the lowest, as shown in Figure 5.23.

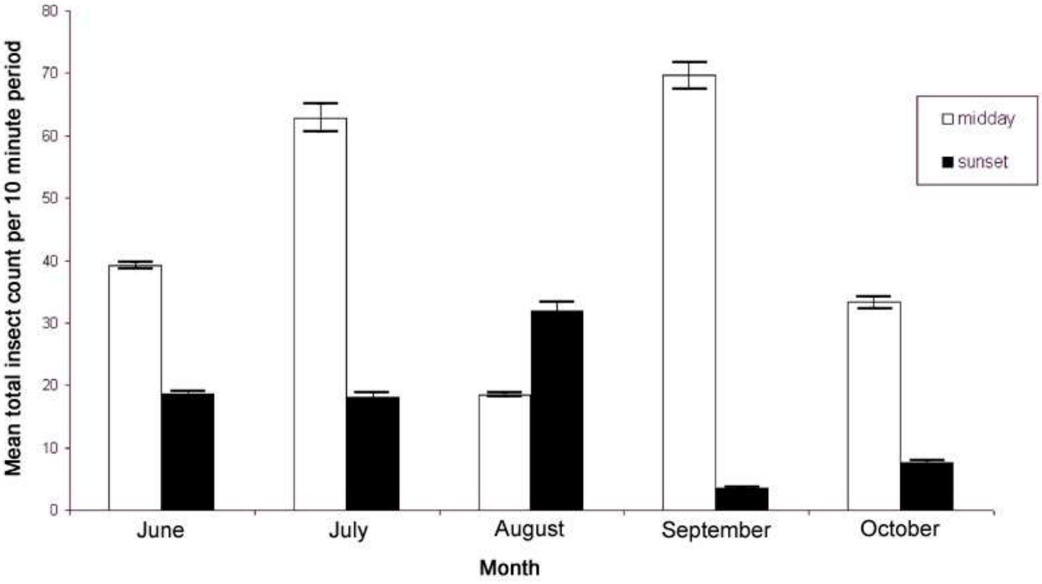
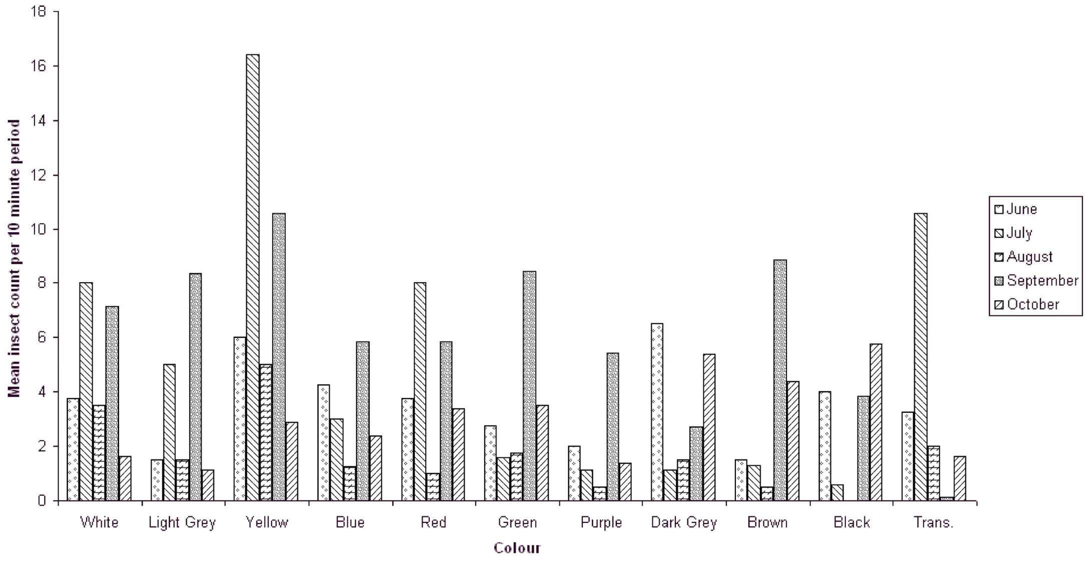
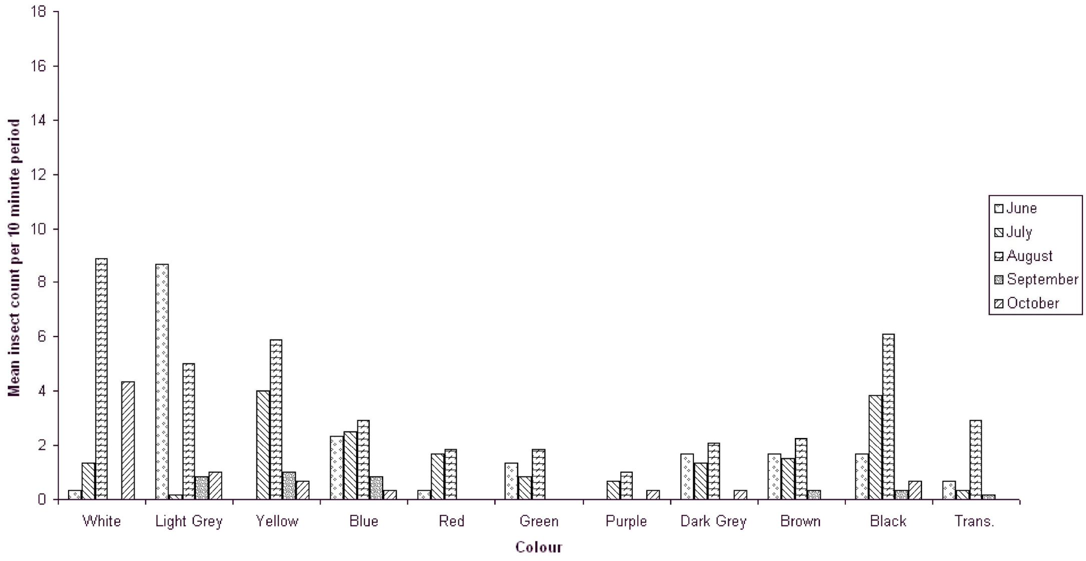


Figure 5.23- Mean total insect count per 10 minute period according to month of observation, at both midday and 1 hour after sunset.

Relative insect attraction to each colour was found to be inconsistent between months or times of day, as demonstrated in Figure 5.24. Table 5.21 describes the insect orders observed each month during the data collection period.



A: MIDDAY



B: SUNSET

Figure 5.24- Variation in mean insect count for each colour per 10 minute period according to month, for both midday (a) and 1 hour after sunset (b) observations.

Weather conditions had an overall significant effect on insect count ($p < 0.005$; $F_{[4,637]} = 3.82$) with fewer insects observed in 'clear' and 'cloudy' weather than other conditions ('overcast', 'sunny spells', 'sunny'). Figure 5.25 demonstrates the effect of wind speed, temperature and relative humidity on total mean insect counts per 10 minute period; temperature significantly influenced insect count ($p < 0.00005$; $F_{[10,631]} = 8.31$) with the highest activity observed at 15 and 16^{o}C. Relative humidity also significantly influenced insect activity ($p < 0.05$; $F_{[3,638]} = 2.93$) with lowest activity at 60-69 % RH, as did wind speed (p <0.00005; $F_{[5,636]} = 9.75$) with speeds of 2.5-4.4 m s^{-1} showing the highest counts.

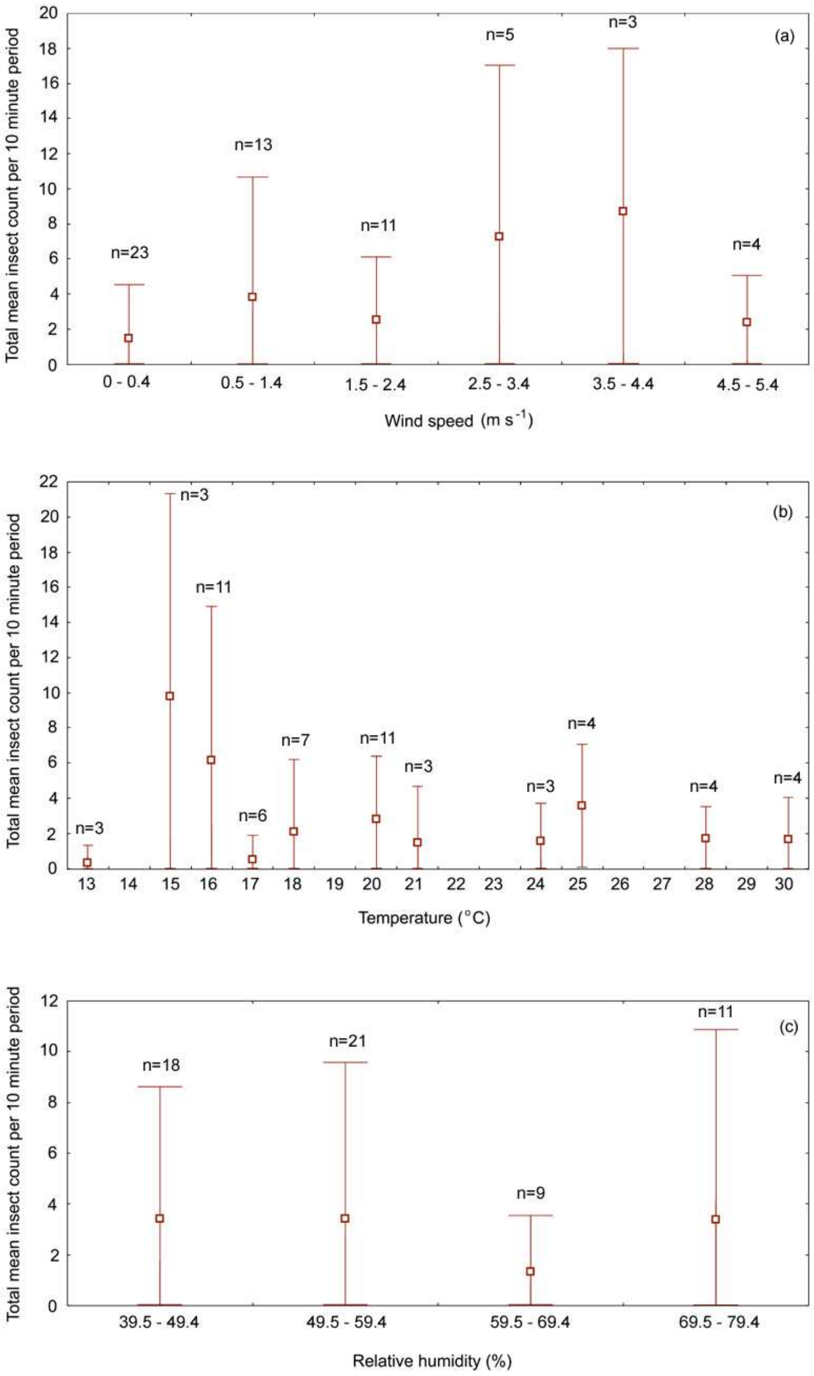


Figure 5.25- Effect of environmental conditions on total mean insect count per 10 minute period, including wind speed (a), temperature (b) and relative humidity (c). Boxes indicate means with ± standard deviation whiskers. In all cases ‘n’ represents the number of 10 minute sessions performed at that range.

Month	Insect species (MIDDAY)	Insect species (SUNSET)
June	Small Diptera (body size <5 mm), large Diptera (body size =>5 mm), Hemiptera, Orthoptera.	Orthoptera, Hemiptera, Coleoptera.
July	Small Diptera (<5 mm), large Diptera (=>5 mm), Thysanoptera, Coleoptera, Lepidoptera, Hymenoptera, Hemiptera, Orthoptera.	Small Diptera (<5 mm), Hemiptera.
August	Small Diptera (<5 mm), large Diptera (=>5 mm), Thysanoptera, Lepidoptera, Hymenoptera, Hemiptera.	Small Diptera (<5 mm), large Diptera (=>5 mm), Coleoptera, Lepidoptera, Thysanoptera, Hemiptera, Tipulidae.
September	Small Diptera (<5 mm), large Diptera (=>5 mm), Tipulidae, Thysanoptera, Hemiptera, Hymenoptera, Coleoptera.	Small Diptera (<5 mm), large Diptera (=>5 mm), Hemiptera, Thysanoptera, Coleoptera, Tipulidae.
October	Small Diptera (<5 mm), large Diptera (=>5 mm), Hemiptera.	Small Diptera (<5 mm), large Diptera (=>5 mm), Hemiptera, Coleoptera.

Table 5.21- Insect species observed over the data collection period.

5.3 Discussion and Conclusions

The finding that the common turbine colours white and light grey were amongst the most attractive colours to insects, independent of time of day, is significant. Insects attracted to a turbine mast and rotor present a foraging opportunity to local insectivores, and thus this is likely to greatly increase the time spent in the vicinity of the turbine, which in turn increases the risk of fatal interaction with operational rotors. Furthermore, it is conceivable that flying insects attracted to white turbine structures could then become trapped in the rotor wake vortices (Arnett *et al*., 2005; Johnson & Kunz, 2004). It is not entirely clear why these light white and near-white colours are attractive to insects; Prokopy & Owens (1983) noted that foliar reflectance occurs around 350-650 nm, which accompanied by a lower saturation via an increase in UV and blue reflectance results in a ‘whitish’ appearance. It could therefore be that insects mistake the white colour of the turbine for foliage and are drawn to it for foraging, mating or resting opportunities. White flowers have also been found to be highly visually attractive to a wide range of insects (Kevan, 1983). It is therefore essential to stress the importance of considering alternative turbine colours for future installations, particularly in areas known to be high in insectivore activity. Whilst white and light grey are by far the most common choices for turbine colour, dark grey is also known to be used; dark grey appeared to be slightly less attractive overall than light grey (Figure 5.21), although this trend was not significant ($F_{[2,631]} = 1.73$).

Several other colours had marked effects on overall relative insect attraction. The fact that one colour demonstrated the lowest overall insect count (purple) indicates there are also likely to be other suitable candidates for turbine colour that are not highly attractive to insects independent of season, and these need to be further investigated for mitigation purposes. Whilst the colour yellow may be expected to be highly attractive to insects (given the link between the yellow colour of many pollen types at the centre of flowers where nectar is located, and the spectral peak at which green leaves reflect most light (Prokopy & Boller, 1971)), the high insect counts for the colour black were somewhat surprising. It may be speculated that the heat-absorbing properties of this colour acted as a ‘thermal lure’ for some insects observed. Black attracted more insects in the colder months of September and October during midday observations (Figure 5.24), and was also the only colour to attract more insects, on average, after sunset than at midday (Figure 5.21). Many insects are influenced by thermal gradients; tabanid flies, for example, have an exceptionally strong attraction to heat (Thorsteinson, 1958), and so it is important to consider the thermal properties of the turbine structure in addition to colour. Both Ahlén (2004) and Horn *et al*. (2008) have used thermal imaging cameras on operational turbines to investigate this effect, finding the top portion of the tower, the blades and nacelle to appear warmer than the surrounding air. Insects may be attracted to the warmer air around the nacelle, particularly in autumn (Dürr & Bach, 2004), which requires further investigation in conjunction with colour effects.

The transparent ‘control’ was found not to differ significantly in attractiveness as compared to all other colours ($F_{[2,631]} = 1.69$), which may have been due to the reflection of UV light from the card during midday readings. The results of the spectral reflectance tests (Figure 5.22) confirm that this card reflected strongly in the UV region under peak light conditions, even fluorescing above 100 % reflectance. This theory is supported by the higher midday insect counts for June and July (Figure 5.24), months more likely to experience weather conditions of ‘sunny’ or ‘sunny spells’ in the dataset and UV index is highest. Whilst peak spectral reflectance of all cards was found to influence insect attraction in strong light conditions, it seems unlikely that overall spectral reflectance influences insect attraction in lower light levels. This is supported by the fact that the colour black, which had the lowest mean spectral peak (Figure 5.22), did not attract the fewest insects overall, and that the colour red, which had a spectral trace similar to that of yellow, did not attract the same insect numbers.

It is interesting to note that the UV reflectance of the colour cards was markedly reduced as compared to the transparent laminate, despite all cards being laminated inside identical plastic pockets. This suggested that the coloured paints have UV absorbing properties, although the extent to which UV is absorbed did vary between colours. Because paint colours reflecting more UV light attracted significantly more insects under strong light conditions (even when the transparent card was not included in analysis ($p<0.05$; $F_{[8,210]} = 2.39$)), it may be important to select paint colours which do not have strong UV reflectance peaks for turbine installations. Similarly, the fact that paint colours with strong IR reflectance attracted significantly more insects (the turbine paint colour white had an IR peak identical with that of yellow; Figure 5.22) indicates IR reflective properties may need to be taken into consideration in addition to visible colour spectrum alone. As the least attractive colour, purple, had an UV reflectance of 10 % and an IR reflectance of 60 %, this could provide a useful comparison for turbine paint colour selection in relation to insect attraction under strong light conditions.

Seasonal variation in the relative attraction of insects to specific colours (as shown in Figure 5.24) could be affected by the seasonality of the different insect species observed (see Table 5.21). For example, while small and large Diptera, common prey items for insectivorous wildlife, were present throughout all monthly midday counts and most sunset counts, species belonging to the order Tipulidae were present only in August and September. The variation in attraction of different colours between different insect species was not a factor that was considered in this study, but may account for some degree of seasonal variation. Monthly variation is also likely to be linked with changes in temperature, weather conditions and relative humidity which all have significant interplay with insect activity levels (e.g. Willmer, 1983; McCall & Primack, 1992), which the data in this chapter support. It is particularly interesting to note the relationship between total insect count and wind speed, with low 3-4 m s^{-1} speeds showing the highest activity levels. Previous studies have identified that bat mortality in particular is highest on low wind speed nights (less than 6 m s^{-1}) (Arnett *et al*.; Horn *et al*., 2008) which could well be correlated with improved foraging opportunities at these lower wind speeds.

This study represents a preliminary investigation into the attraction of insects to turbine paint colours and it should be noted that further work is required in this area before firm conclusions can be drawn. It may be beneficial to repeat these simple experiments with replicate colour cards at a variety of other locations, both with and without turbines, to build up a greater picture of how insect activity may vary with habitat/location. In addition it would be of interest to measure insect colour attraction/activity at height, and to test paint colours on existing turbines.

In conclusion, the results indicate that the common turbine colours ‘Pure White’ (RAL 9010) and ‘Light Grey’ (RAL 7035) may be having a significant influence on the attraction of insects to wind turbine installations, which could in turn be providing foraging opportunities for both diurnal and nocturnal insectivores. Because some colours were demonstrated to be less attractive to insects than others it may therefore be possible to contribute to reducing insect attraction to wind turbines by altering paint colours, both in the visible spectrum and in the UV and IR spectrum. However, it should be made clear that modifying turbine colour alone may not be enough to mitigate the problem of wildlife-turbine interaction and that further research into other aspects such as thermal generation is needed.

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6

Site Survey Practice and Mitigation

The work detailed in this thesis investigating bat-wind turbine interaction has produced fruitful results, some of which may be adapted into possible methods of mitigating the problem. These include both passive methods, such as those modifying the turbine structure itself, and also more active methods such as acoustic deterrents. This chapter also details methods for assessing bat site-use at proposed and existing turbine locations that may be useful for future monitoring/planning work. It is hoped that implementing some or all of these suggestions would at the very least help to reduce the incidence of bat fatalities at various types of horizontal-axis wind turbine installations in the future, ultimately beneficial for both the wind industry and bat populations alike.

6.1 Proposed Modifications to Turbine Design

Based on the results of the ‘rotor rating’ equation application detailed in Chapter 3, it has been shown that it is possible to alter some of the physical properties of the turbine rotor in order to make it more ‘detectable’ to an approaching bat (by increasing the likelihood of pulse reflection from moving blades). It is therefore possible to either select a particular turbine rotor with the best ‘detectability rating’, or to design an optimally detectable rotor by taking into account the best options for each particular feature. As discussed in Chapter 3, the features of the rotor considered by the rotor rating equation include the diameter of the rotor, the number of blades, the width of the blades (both at the tips and toward the hub) and the relative speed at which the rotor turns. The diameter of the rotor intended to be installed depends largely on the required generation capacity and suitability of the site, so therefore it is the remaining features that can be adjusted to obtain the most ‘bat friendly’ rotor. Such features found to provide optimal detectability ratings included a larger number of blades in the rotor (rotors with three blades or fewer generally had lower ratings), wide blades both at the hub and at the tips (narrow blades result in a lower ratio of solid surface for potential pulse interception as compared to gaps between blades) and rotors that rotated faster at each given wind speed. It is therefore suggested that the selection of multi-bladed, fast turning rotors with wide blades could improve rotor detection by an approaching bat and may contribute to mitigation of bat-turbine mortality, although this has yet to be tested in the field. Since the design stage of a new turbine requires many equations to be considered (such as those relating to optimum blade width, rotational speed, etc.), it may be useful to implement the bat detectability equation as described in this thesis alongside them to produce an optimal compromise. However, it should be noted that such modifications to rotor design may be impractical, particularly when taking into consideration that such rotor elements are often optimised for power production. It may therefore not always be feasible to implement these suggestions to optimise bat detection of the rotor without compromising the turbine’s efficiency or cost.

The results of Chapter 4 indicated that operational rotors may be particularly difficult to detect by bats that approach turbines toward the blade tips, rather than toward the blade faces. Because blade tips are so acoustically ‘quiet’ in terms of pulse reflection due to sound scattering, small surface area and high movement speed, it may be beneficial to adapt the design of the tips to maximise the potential for incident ultrasound pulse reflection. Design features to be considered could include the ‘winglet’ design of some aeroplane wing tips (Figure 6.11 A and B), and in the case of microturbines the more widespread use of a fixed circular brace around blade tips as already employed by some models (Figure 6.11 C).

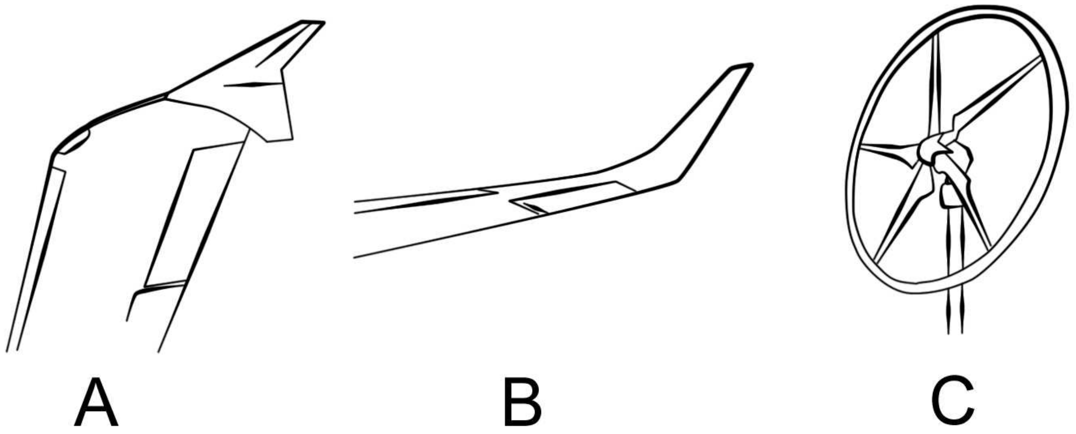


Figure 6.11- Design features that may help maximise blade tip acoustic detectability. These include aeroplane-utilised ‘winglets’ (A and B) and the fixed circular bracket of some microturbines (C).

An additional feature which is considered to be critically important in mitigation efforts is the implementation of operational cut-in wind speeds for all turbine installations, particularly with reference to microturbines which do not currently employ such features and are allowed to rotate freely even when wind speeds are not sufficient for power generation. As identified in Chapter 3, the detectability rating of a rotor can be significantly improved by the use of such low-wind speed operational cut-ins, which is especially important since rotors turning at low wind speeds (less than 6 m s^{-1}) are known to be particularly problematic to bats in terms of mortality levels (Baerwald *et al.*; Arnett *et al.*, 2009). Therefore by applying an operational cut-in to a turbine rotor at wind speeds less than 6 m s^{-1} or until a wind speed is reached where the detectability rating is nearing 100 %, an approaching bat has a much greater chance of detecting the moving blades and is at a much lower risk from the stationary blades. The results of Chapter 4 also supported the findings by other authors that minimum operational cut-in wind speeds are beneficial, since the Doppler shifting produced by some turbines in low wind speed conditions may prevent detection by some FM bat species. Therefore, by increasing the minimum wind speed required for rotor release, the minimum Doppler shift produced by the rotor will be greater (and hence more likely to be perceptible to an approaching bat).

One further turbine design feature which may be considered for mitigation efforts is the colour of the tower and rotor itself. As shown in Chapter 5, turbine paint colour may be of significant importance in attracting insects to the immediate vicinity, and thus attracting aerial insectivores such as bats. Because the two common turbine colours (white and light grey) were found to attract significantly more insects than some of the other colours tested, independent of time of day, selecting a less insect-attractive colour for turbine installations could further contribute to mitigation of the problem, both for bats and insectivorous birds.

6.2 Acoustic Deterrents

Previous tried and tested methods of deterring bats acoustically from specific areas have generally involved the emission of broadband ultrasonic noise. This has so far proved unsuccessful (Griffin, 1974; Nicholls & Racey, 2007), and although broadband ultrasound can have some effect on bats, ultrasonic rodent deterrents have been shown not to work (Westaway, 2007). This could, however, be due to the habituation of bats in the area to the sound, as happens with acoustic deterrent devices for birds (Dooling, 2002). A study by Nicholls & Racey (2007) investigated the use of radio frequency (RF) radiation as a deterrent for Scottish bat species. RF occupies the electromagnetic spectrum between 3 kHz-300 GHz, and reportedly short-term exposure to this can result in localised tissue heating in animal subjects (but see Lotz (1985); Paredi *et al*. (2001); Oysu *et al*. (2003)). The study took place around several radar stations, and although it was found that bat activity was significantly reduced in areas with a high EMF strength, this varied with radar type (and so location), and also insect density at each site was not recorded. Although this study was interesting, there is no clear evidence that bats are sensitive to RF energy, although it would be a significant finding if this were proven. Methods to deter bats from certain areas to date have therefore proved largely unsuccessful, and alternative methods need to be investigated.

Perhaps it would be useful to look to a more natural solution to the problem. Some arctiid and ctenuchid moth species have the ability to produce ultrasonic ‘clicks’ in the region of 30-90 kHz (Sales & Pye, 1974) by buckling the microtymbal membrane (Fenton & Roeder, 1974). Originally, it was hypothesised that these moths emit an ultrasonic bat ‘jamming’ signal by matching the power spectra and frequency-time structure of the bat’s emitted echolocation pulse, causing the bat to interpret the received sound as an echo reflected from a large obstacle such as a wall and take evasive manoeuvres (Spangler, 1988). However, it is now thought that the ultrasound produced by these moths serves as an acoustic warning of distastefulness to bats; an ‘aposematic’ mechanism (Sales & Pye, 1974; Surlykke & Miller, 1985;

Spangler, 1988; Hristov & Conner, 2005). Other species may utilise a form of Batesian mimicry by replicating these sounds. It could in theory be possible to replicate these sounds and employ them as an acoustic deterrent, as it is hypothesised bats are less likely to forage in areas with an apparent high density of distasteful prey.

6.2.1 Aposematic Signal Replication

Surlykke & Miller (1985) reported that arctiid moth clicks are between 60-300 µs in length and are often paired due to the microtymbal membrane buckling (in and out again). The delay between clicks is 2-25 ms and there is a pair interval of 10-180 ms. The maximum sound intensity is 85-94 dB peSPL re 20 µPa 5 cm from the source. These clicks are generally broadband between 40-80 kHz. Previous studies replicating arctiid clicks have used centre frequencies of 32 or 51 kHz with a bandwidth of 20-50 kHz or 20-100+ kHz, of duration 25-50 µs (Tougaard *et al.*, 1998). Figures 6.21 and 6.22 show example waveforms and a sonogram recorded from several arctiid species.

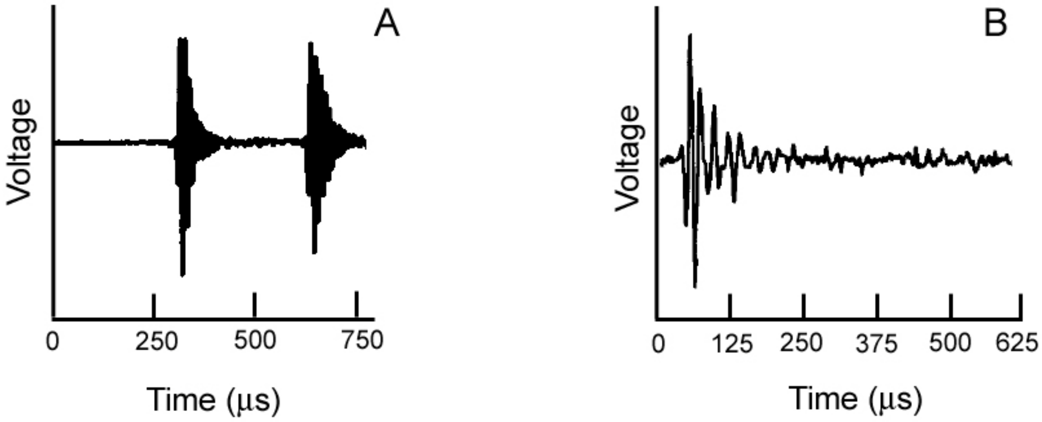


Figure 6.21- Waveforms of aposematic clicks from two moth species; the ruby tiger moth (*Phragmatobia fuligninosa*), A (adapted from Miller (1991)), and the garden tiger moth (*Arctia caja*), B (adapted from Surlykke & Miller (1985)).

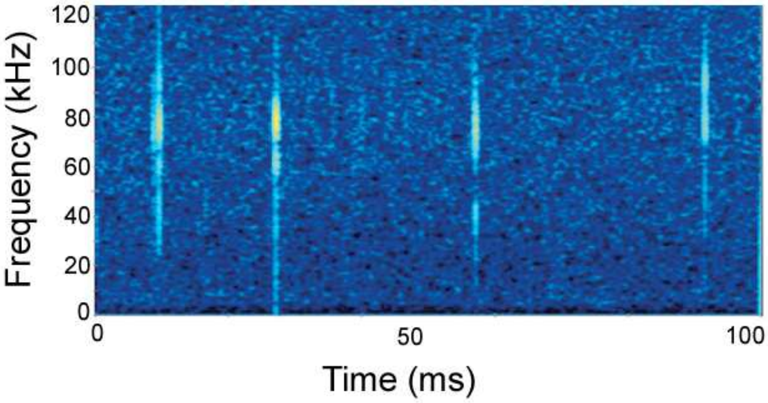


Figure 6.22- Sonogram of aposematic clicks from the yellow-collared scape moth (*Cisseps fulvicollis*). Adapted from Ratcliffe & Nydam (2008); sonogram information not provided.

In order to generate artificial arctiid aposematic clicks, the above information was used to simulate a sequence of clicks in MATLAB. After Tougaard *et al*. (1998) a short CF sine of 50 kHz was created, 100 µs in duration modelled on the garden tiger click. This was done in an identical manner to that used to create artificial CF bat pulses in Chapter 4, including changes in amplitude over time. The time delay between clicks was set at 10 ms, with a pair interval of 150 ms. Figure 6.23 shows the waveform of a single generated click.

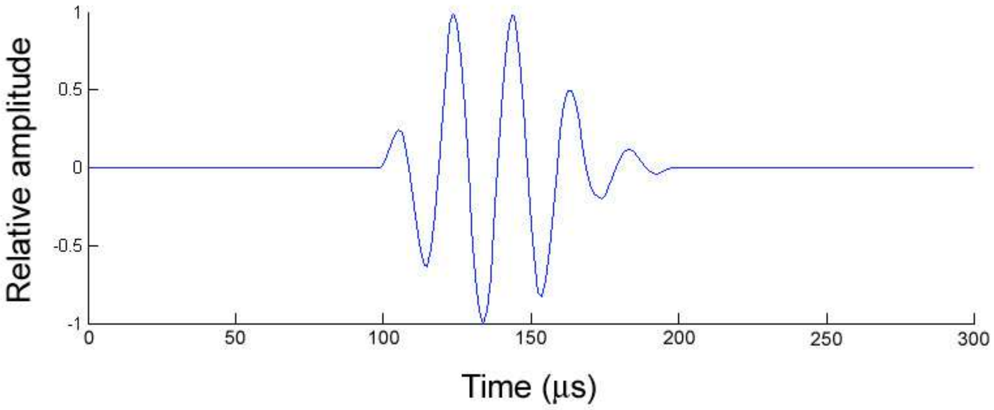


Figure 6.23- Simulated arctiid aposematic click waveform, generated in MATLAB at 800 kS s^{-1}.

For testing purposes, these clicks were outputted via the USB-6251 DAQ card and ultrasonic tweeter used in previous experimental work. The calibrated microphone was used to record a train of emitted pulses, as shown in Figure 6.24.

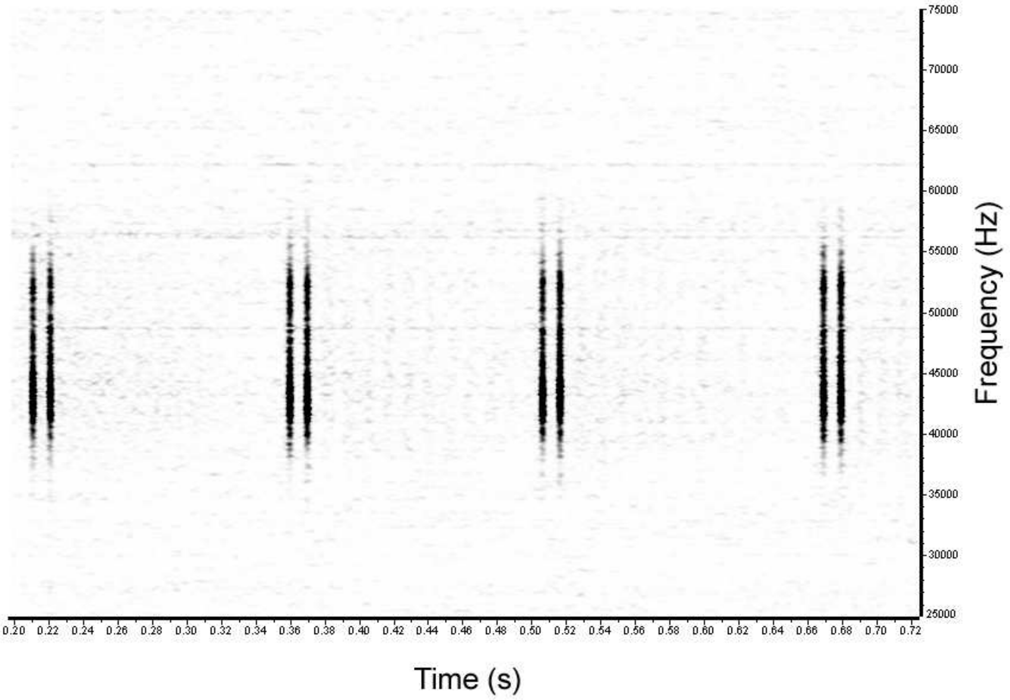


Figure 6.24- Sonogram of simulated aposematic moth clicks generated via the ultrasonic tweeter at 800 kS s^{-1}, recorded with the calibrated microphone at 200 kS s^{-1}. Hanning window, 75 % overlap, FFT length 1024 bands, 120 % linear energy scaling.

Clicks had a sound intensity of 22 dB peSPL re 20 µPa as measured 15 cm from source and so require further amplification for any future experimental work.

6.2.2 Limitations

Unfortunately, it has not been possible to test these signals in the field to assess their effectiveness, due to the strict UK licensing laws regarding any potentially disturbing field work with British bats. This is understandable, and it may instead be possible to test the signal on captive bats. However, this may ultimately prove problematic to turbine owners wishing to install such devices on turbine structures, and rigorous testing would be required to ensure there were no far-reaching or long-term effects on bat populations in the proposed area of use.

Furthermore, it should be considered that the effectiveness of these aposematic acoustic signals is a learned response (Hristov & Conner, 2005), rather than being innate to the bat (i.e. known from birth). The extent to which a bat would know to avoid the source of this sound would ultimately depend on its previous experience with that particular moth species. This means it would have to have previously encountered and consumed the moths possessing the distasteful chemical in order to negatively associate the experience with the sound (just as in operant conditioning). For this reason, the correct aposematic signal needs to be selected based on the likelihood of that moth species to be in the locality of the turbine. However, naïve bats are known to be initially startled on the first encounter with these novel sounds (Miller, 1991). It should also be noted that not all bat species prey on moths (some smaller bat species may be unable to deal with larger insects), so this acoustic ‘trick’ may only work for certain bat species, which requires further investigation.

6.3 Local Site Considerations

An important part of the mitigation process is selecting an appropriate site for wind turbine installation, in such a way that it poses minimal risk to local fauna. Pre-construction habitat surveys are a critical part of any such planning, since mitigation is most effective where problems are avoided pre-emptively, rather than attempting to mitigate problems post-construction as an afterthought. A good example of the dangers of lack of pre-construction bat activity assessment may be taken from the Mountaineer Wind Energy Farm in West Virginia, USA, consisting of fourty four 116 m wind turbines located along a densely forested ridge-top. Post-construction survey revealed the site to be particularly problematic to local bat species, with an average of 48 bats killed per turbine over the 8 month period of assessment (in addition to the 4 bird deaths per turbine over the same period) (Kerns & Kerlinger, 2003). The dense forest habitat would be an important site for bat roosting and foraging, so the impact of the wind plant on the local bat population could have been greatly reduced by selecting an alternative location for turbine installation had the site been surveyed prior to construction.

Because bat activity is seasonally variable, it is necessary to select the appropriate time of year for activity surveys at potential construction sites. Many British bat species either migrate or enter hibernation in the winter months, so surveys in the UK are best conducted throughout summer months when activity is at a peak. Published data from bat-turbine studies confirm that bat activity around turbines is at its height between July-August (Johnson *et al*., 2004), and have also found bat activity (particularly around turbines) not to be evenly distributed through the night, with most activity within 2 hours of sunset (Arnett *et al*., 2005; Arnett *et al*. 2006). It is therefore appropriate to conduct assessments at these times in order to create a relevant picture of local bat site use. Also to be considered are the proximity of the proposed turbine site to features used by bats such as hedgerows, woodlands and lakes, and the foraging strategies and echolocation types of bat species in the area. For example, it is known that bat species employing aerial hawking feeding strategies may be particularly at risk of turbine interaction (e.g. Betts, 2006), and based on the results in Chapter 4 it is predicted that FM bats may be at a particular disadvantage in terms of detecting turbine blade movement. Work by Bach & Rahmel (2004) has shown that turbines can disrupt bat flight path behaviour along hedgerows less than 10 m away, and existing mitigation guidelines advise turbines should be situated at least 50-100 m from the nearest woodland (Dürr & Bach, 2004). Rahmel *et al*. (2004) Suggest a study radius of at least 1000 m for large scale turbine constructions.

In order to carry out site surveys it is necessary to be able to detect the bat species present for identification purposes. An efficient method of doing this is by the use of a hand-held bat detector and recording device which allows the surveyor to log bat activity along a particular transect route around the site. Because most bat species echolocate above the human hearing range, many bat detectors work by manipulating the input frequency and reducing it to the human hearing range, commonly in one of three formats; heterodyne, time expansion and frequency division detectors. Heterodyne detectors work on the principle of outputting the frequency difference between two waveforms, one being the frequency used by the bat, f_{bat}, the other an internally generated sine wave of a low frequency, f_{gen}, that can be tuned accordingly.

$$\sin(2\pi f_{bat}t)\cdot\sin(2\pi f_{gen}t)=\frac{1}{2}\cos\left[2\pi\left(f_{bat}-f_{gen}\right)t\right]-\frac{1}{2}\cos\left[2\pi\left(f_{bat}+f_{gen}\right)t\right] \quad (6.31)$$

The resulting output is two separate frequencies; the sum of the two input frequencies (which is discarded) and the difference of the two. Figure 6.31 provides a graphical example of the process:

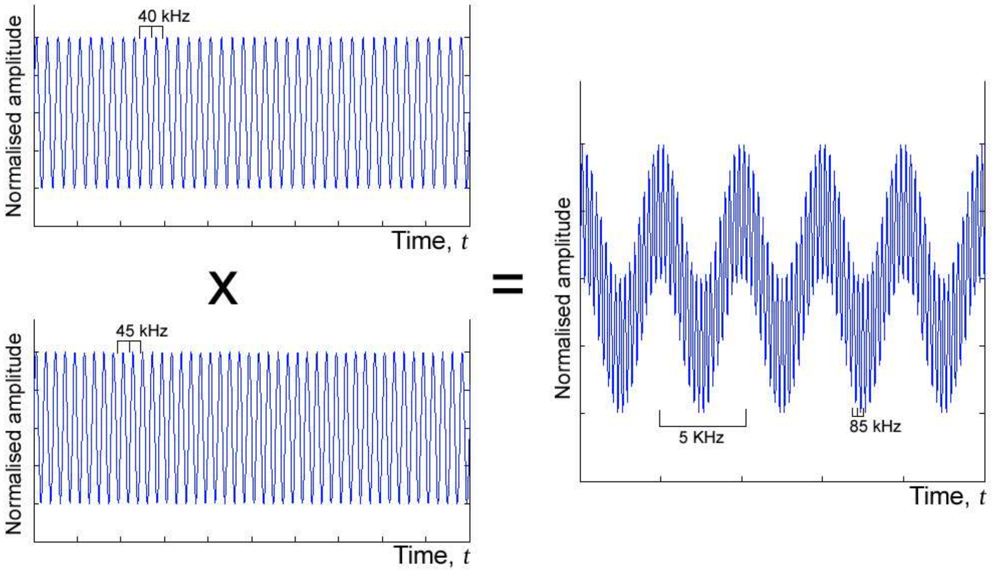


Figure 6.31- Demonstrating the heterodyne principle. Multiplying a 40 kHz sine wave with a 45 kHz sine wave produces two frequencies, one at the sum of the two inputs (85 kHz) and one at the difference (5 kHz), which is used in bat detectors as the output.

Frequency division bat detectors use a different principle to reduce the frequency of the output sound, f_{out}, by converting the waveform into a square wave and then reducing the frequency of the square wave, usually through an internal peak counter. It is based on the following simple equation:

$$f_{out} = \frac{f_{bat}}{n} \tag{6.32}$$

Where n is usually 10 (i.e. the wave frequency is reduced by a factor of 10). This method is depicted in Figure 6.32.

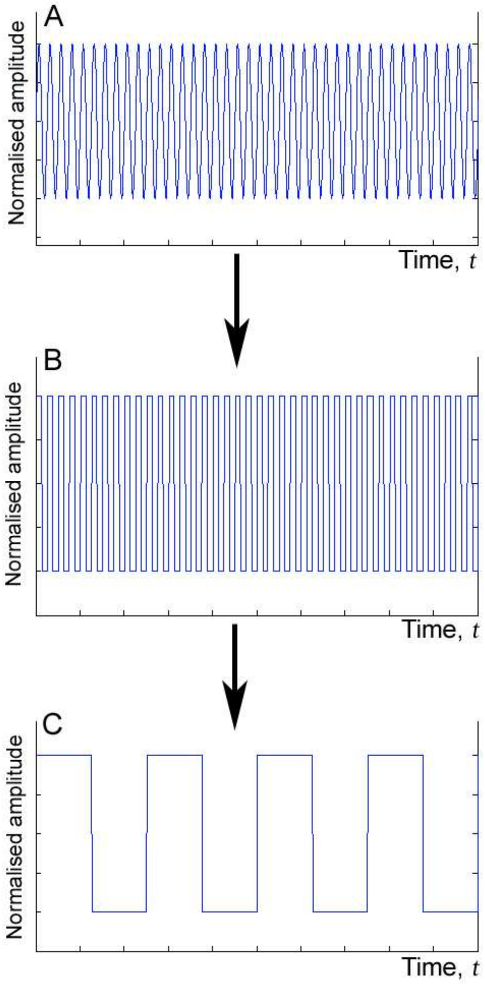


Figure 6.32- Demonstrating the principle of frequency division. The incoming 40 kHz bat waveform, A, is converted into a square wave, B, and reduced in frequency by a factor of 10, C. This results in a 4 kHz waveform which is output by the bat detector.

Time expansion bat detectors employ a third principle, based on the slowing down of the incoming sound wave. Incoming sounds are recorded by the unit at a high sample rate and then played back at a lower sample rate, effectively stretching out the waveform in time (Figure 6.33).

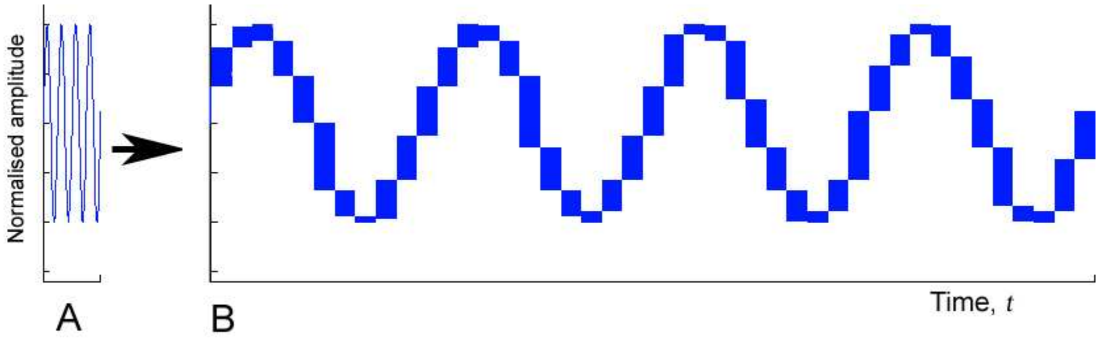
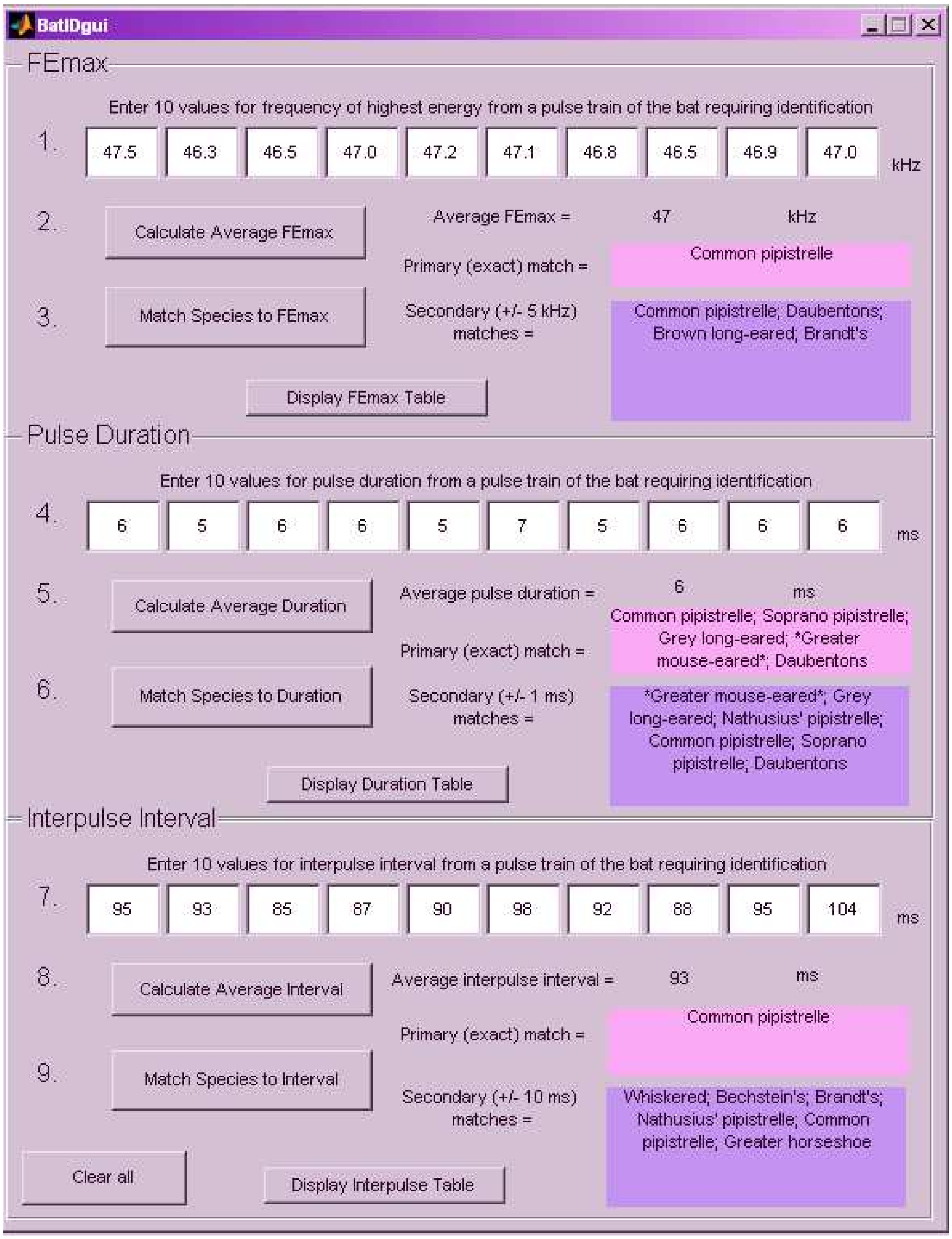


Figure 6.33- Demonstrating time expansion. A short segment of the original frequency waveform (A) is recorded and then replayed at a lower sample rate, resulting in a waveform of longer duration and lower frequency (B).

Whichever method the surveyor uses to assess bat activity at the site, it is not normally possible to determine the bat species present in the area right away. For this reason it is necessary to record the data collected on the transect for further analysis later. Post collection analysis typically entails inspecting the sonograms of any bat calls recorded and identifying the species based on comparing various call parameters with known species values. This can be time consuming and subjective, and so in order to facilitate the process, the following Graphical User Interface (GUI) was developed and coded in MATLAB.

6.3.1 Bat ID GUI

The program, named ‘Bat ID’, was designed to allow the user to input several variables from the recorded bat pulses and to then automatically find a match from known, internally stored published parameters. The variables normally used to identify bat species are the pulse duration (‘duration’), the frequency of highest energy/intensity (‘FEmax’) and the interpulse interval (‘interval’), all of which were included as inputs in the GUI. The program functions by averaging a sequence of ten input variables to obtain a mean value for each parameter (FEmax (in kHz), duration (in ms) and interval (in ms), respectively), and then matches this average to the internally stored known values. The result is a display of any exact matches, and also a separate display box for ‘secondary’ matches within a certain range. These are displayed for each parameter and the user can then correlate any matches common between all three result boxes, giving preference to the result common to the ‘exact’ match. To assist matching, tables giving the range of known values for each British bat species are available by clicking the relevant buttons on the GUI. All internally stored values were obtained from the data referenced in Table 2.32 (Chapter 2). Figure 6.34 overleaf shows a screencapture of the GUI in operation.



Enter 10 values for frequency of highest energy from a pulse train of the bat requiring identification

1. 47.5 | 46.3 | 46.5 | 47.0 | 47.2 | 47.1 | 46.8 | 46.5 | 46.9 | 47.0 kHz

Average FEmax = 47 kHz

Primary (exact) match = Common pipistrelle

Secondary (+/- 5 kHz) matches = Common pipistrelle; Daubentons; Brown long-eared; Brandt's

Enter 10 values for pulse duration from a pulse train of the bat requiring identification

4. 6 | 5 | 6 | 6 | 5 | 7 | 5 | 6 | 6 | 6 ms

Average pulse duration = 6 ms

Primary (exact) match = Common pipistrelle; Soprano pipistrelle; Grey long-eared; *Greater mouse-eared*; Daubentons

Secondary (+/- 1 ms) matches = *Greater mouse-eared*; Grey long-eared; Nathusius' pipistrelle; Common pipistrelle; Soprano pipistrelle; Daubentons

Enter 10 values for interpulse interval from a pulse train of the bat requiring identification

7. 95 | 93 | 85 | 87 | 90 | 98 | 92 | 88 | 95 | 104 ms

Average interpulse interval = 93 ms

Primary (exact) match = Common pipistrelle

Secondary (+/- 10 ms) matches = Whiskered; Bechstein's; Brandt's; Nathusius' pipistrelle; Common pipistrelle; Greater horseshoe

Figure 6.34- Screencapture of the Bat ID interface in operation. In this example the values entered have produced an exact match common between all three result boxes, the common pipistrelle.

6.3.1.1 GUI Advantages and Limitations

Using the Bat ID GUI to identify recorded bat species removes some of the subjectivity associated with the task and increases the ease and speed of analysis in what can be a time-consuming task. However, the system is not yet able to extract the relevant parameters directly from the recorded files, this needs to be done manually by using waveform and FFT data using software such as MATLAB or Adobe Audition. In addition to this, echolocation pulse durations and interpulse intervals are known to vary quite widely depending on what the bat was doing at the time of recording and its surroundings, as bats adapt their echolocation strategies accordingly (Schnitzler & Henson, 1980; Waters & Jones, 1995; Schnitzler & Kalko, 2001). The ‘secondary’ match results box allows for small variations in parameters to a certain extent, but can make precise identifications difficult.

6.3.2 Site Survey Technique

As identified above, bat site-use surveys at proposed turbine installation sites are best conducted throughout the summer months (although it may be beneficial to conduct a year-round assessment), from sunset to sunset +2 hours. It is advised that at least one survey be conducted per month over consecutive months in order to generate a more reliable picture of how bats may be using the site (or not) on a seasonal basis. The surveyor should create an appropriate transect route along which to conduct the survey, to include as many of the likely bat-utilised features within the immediate vicinity of the proposed turbine location, within a minimum radius of 10 m (after Bach & Rahmel (2004)). Such features should include hedgerows, forest edges and water features including streams, ponds and lakes (natural and man-made), as bats frequently use these for both foraging and navigation (e.g. Vaughan *et al.* (1997)). During transects, recorded data should be taken of the ultrasound activity along the route for post-analysis; this can be done with the use of a hand-held bat detector as described above. The route around the immediate turbine location should be walked at least twice in order to maximise the activity data for that area. In addition, it is recommended that any observed bat flight paths be noted on a map of the area; this may be useful in determining potential foraging hot-spots and commuting corridors around the site, although it can be somewhat subjective (this will be further discussed in the following section).

Post-data collection, recorded bat echolocation data may be analysed with the aid of the Bat ID program to assist species identification. As with all recorded data, it is important to be aware of the limitations of the recording/monitoring equipment used, for example if a frequency division bat detector was used, this can result in reduced temporal/frequency resolution as compared to, for example, a time-expansion detector. The diversity of bat species in the area, the total number of bat passes recorded and how frequently bat data was collected in the vicinity of the proposed turbine location can all be used to assess the likely impact the turbine may have on the existing local bat population.

An example of a bat site-use assessment can be found in the appendix.

6.4 Bat Flight Path Tracking

Current methods of assessing bat activity within specific areas are time-consuming and fairly subjective, especially where identifying bat flight paths is concerned. It is particularly difficult to track the movement of a fast-moving (around 5 m s^{-1}), small (in the region of 30 cm) bat which is frequently done by human eye in low light level conditions (coupled with acoustic information from the bat detector). While it is important to assess the flight behaviour of bats at a proposed turbine site pre-construction as discussed in the previous section, it would also be extremely useful to monitor the exact flight behaviour of bats in the immediate vicinity of an existing turbine structure. While some previous studies have been able to monitor bat flight activity around turbines, to an extent, by using thermal imaging video cameras (e.g. Arnett *et al.*, 2005), the two-dimensional nature of this kind of monitoring has its limitations. Tracking the four-dimensional flight path of a bat in a given area would yield detailed information from which could be extracted the type of behaviour of bats within that area (for example a commuting route, feeding activity, investigatory behaviour of a specific structure) and the site’s frequency of use over an extended period of time.

It is proposed that such a tracking system would utilise the bat’s own acoustic emissions in order to localise the source of the sound at the point of emission. The concept behind the theory that follows was initially based on some MATLAB code, written by Sutoyo (2008), to locate earthquake epicentres in 2 Dimensions. This code was then extensively modified by the author to work in 4D for the purpose of tracking bats acoustically. The mathematical formulation of this code was derived by the author; further details may be found in Tarantola & Valette (1982). Because the most common British bats, FM bats, produce very short, high-intensity pulses of sound at a fairly rapid rate, it is theoretically possible to localise the position of a bat every time it produces an echolocation pulse, and by tracking these pulses in time to extract the flight path and direction. In order to localise an acoustic point source, an array of receivers would be required, capable of ultrasonic pulse detection within the area of interest. To locate the source in two dimensions, at least three receivers are needed, arranged around the source on the same plane as shown in Figure 6.41. The proximity of the source to any one of the receivers will affect the time taken for the emitted sound to travel to the receiver; the difference in time of arrival of the pulse at all three receivers can then be used to determine the location of the source, known as ‘multilateration’.

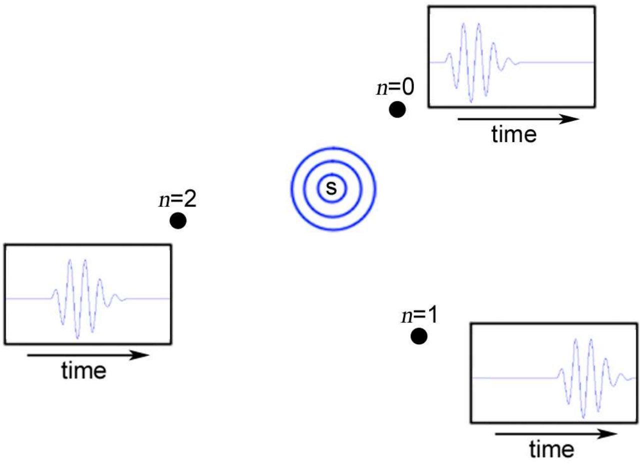


Figure 6.41- Example receiver (n=x) locations for the multilateration of an acoustic point source (s) in 2D. Boxes show waveforms indicating the arrival times of the source pulse at each receiver.

In order to track in 3D, more receivers may be added arranged around the source in three dimensions, for example the arrangement in Figure 6.42.

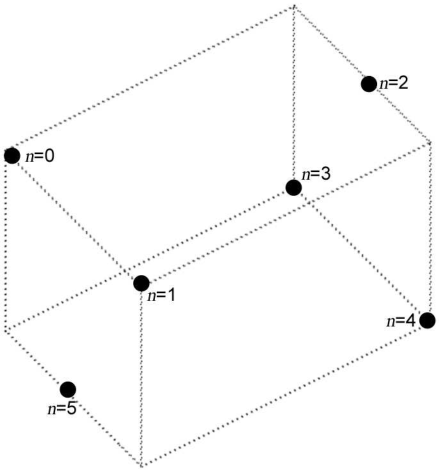


Figure 6.42- Example receiver locations for the multilateration of an acoustic point source in 3D, using six receivers.

Because the exact time of pulse emission at the source is unknown, the receiver nearest to the source (i.e. the first receiver to detect the pulse, or 'primary' receiver, n_0) is used to obtain the initial start time, or t=0 point. Once n_0 has been identified, the difference in time of arrival relative to the primary receiver can be calculated for each additional receiver, n, to obtain a series of relative arrival times, Δt_n:

$$\Delta t_n = t_n - t_{n_0} \tag{6.41}$$

Where t_{n0} is the arrival time at the primary receiver and t_n the arrival time at receiver n. In order to perform the multilateration of the source, a Least Squares (LS) method can be employed, based on an initial guess at the source location (G). This method allows for small errors in time of arrival/source location that may occur in the field due to slight discrepancies in receiver position, for example. The location of the initial guess may be anywhere within the receiver array and has its own Cartesian coordinates (X_G, Y_G, Z_G). Firstly, the distance of the guess position from the n_0 receiver (R_n) is obtained by trilateration of the difference in coordinate locations as follows:

$$R_n = \sqrt{\left(x_{n_0} - X_G\right)^2 + \left(y_{n_0} - Y_G\right)^2 + \left(z_{n_0} - Z_G\right)^2} \tag{6.42}$$

Where x_{n0}, y_{n0} and z_{n0} represent the Cartesian coordinates of the primary receiver. The time taken for the pulse to travel from the guess position to receiver n_0 (termed T_n) is then calculated:

$$T_n = \frac{R_n}{v} \tag{6.43}$$

Where v is the speed of sound in air (≈ 330 m s^{-1}). The distance of the guess location from all other receivers can now be calculated using Equation 6.42, by substituting the coordinates for n_0 with each receiver coordinate (x_n, y_n, z_n). Similarly, guess distance travel times relative to each receiver can be obtained using Equation 6.43. Next, the difference in time of arrival, t_{ndif}, based on the receiver arrival time (Δt_n; Equation 6.41), guessed pulse emission time (T_G) and primary receiver-guess arrival time (T_n; Equation 6.43) is calculated as follows for all receivers:

$$t_{ndif} = \left(\Delta t_n - T_G\right) - T_n \tag{6.44}$$

As the LS solution relies not only on times of arrival but also on independent X, Y and Z coordinates, the theoretical times of arrival for each guess coordinate relative to each receiver coordinate (X_{Gtndif}, Y_{Gtndif}, Z_{Gtndif}) are deduced as follows:

$$\begin{aligned} X_{Gtndif} &= \left(\frac{[x_n - X_G]}{R_n v}\right) \\ Y_{Gtndif} &= \left(\frac{[y_n - Y_G]}{R_n v}\right) \\ Z_{Gtndif} &= \left(\frac{[z_n - Z_G]}{R_n v}\right) \end{aligned} \tag{6.45}$$

We now can build matrices of t_{ndif} values (Equation 6.44), $\underline{\mathbf{t}}_{\mathbf{DIF}}$, and coordinate values (Equation 6.45), $\underline{\underline{\mathbf{G}}}$, for each receiver as follows:

$$\underset{\underline{\mathbf{t}}_{\mathbf{DIF}}}{\begin{pmatrix} t_{n_0 dif} \\ \vdots \\ \vdots \\ t_{ndif} \end{pmatrix}} = \underset{\underline{\underline{\mathbf{G}}}}{\begin{pmatrix} 1 & \frac{x_{n_0} - X_G}{R_{n_0} v} & \frac{y_{n_0} - Y_G}{R_{n_0} v} & \frac{z_{n_0} - Z_G}{R_{n_0} v} \\ \vdots & \vdots & \vdots & \vdots \\ \vdots & \vdots & \vdots & \vdots \\ 1 & \frac{x_n - X_G}{R_n v} & \frac{y_n - Y_G}{R_n v} & \frac{z_n - Z_G}{R_n v} \end{pmatrix}} \underset{\Delta\underline{\mathbf{M}}}{\begin{pmatrix} \Delta T \\ \Delta X \\ \Delta Y \\ \Delta Z \end{pmatrix}} \tag{6.46}$$

Since we want to know $\Delta\underline{\mathbf{M}}$, the LS solution can be calculated. This process can be effectively performed in MATLAB by the use of the *inv* function, a predefined function based on LAPACK routines (Anderson *et al*., 1999), which inverts the matrices $\underline{\mathbf{t}}_{\mathbf{DIF}}$ and $\underline{\underline{\mathbf{G}}}$ as follows:

$$\Delta\underline{\mathbf{M}} = \left[\underline{\underline{\mathbf{G}}}^{\mathbf{T}}\underline{\underline{\mathbf{G}}}\right]^{-1}\underline{\underline{\mathbf{G}}}^{\mathbf{T}}\underline{\mathbf{t}}_{\mathbf{DIF}} \tag{6.47}$$

This results in a LS solution of probable source location, producing a difference in the guessed time of emission ($\varDelta T$) and a difference in guessed X, Y and Z coordinates ($\varDelta X$, $\varDelta Y$, $\varDelta Z$). These are then used to update the original guess time of emission and coordinates, and the process is repeated for the updated guess variables until the LS solution is zero (i.e. the source has been localised). The solution can typically be obtained within 10 iterations.

6.4.1 Example Path Tracking in Simulation

It is possible to simulate how such a flight path tracking system would work by implementing the multilateration Equations and LS solution in the previous section. Example receiver inputs can be ‘created’ by taking an example bat pulse (real or simulated, such as that detailed in Chapter 4) and artificially altering the start time delay. It is useful to be able to automatically extract pulse arrival times from the data input of each receiver, which would facilitate integration of hardware developed for multilateration with the Equations in the previous section. This may be implemented by applying a band-pass filter to the input signal, which would allow only those frequencies of interest to be detected by the system (e.g. in the region of 40-60 kHz for a common pipistrelle, *Pipistrellus pipistrellus*). A pulse envelope detector can then be created by performing a full-wave rectify, which effectively removes the negative amplitude portion of the waveform, leaving only the positive portion but doubling the frequency. This can be done effectively by square-rooting and then squaring the waveform (see Figure 6.43). To complete the envelope detector, the waveform is again filtered with a low-pass filter, leaving only the outer envelope of the pulse of interest. This process is detailed in Figure 6.43.

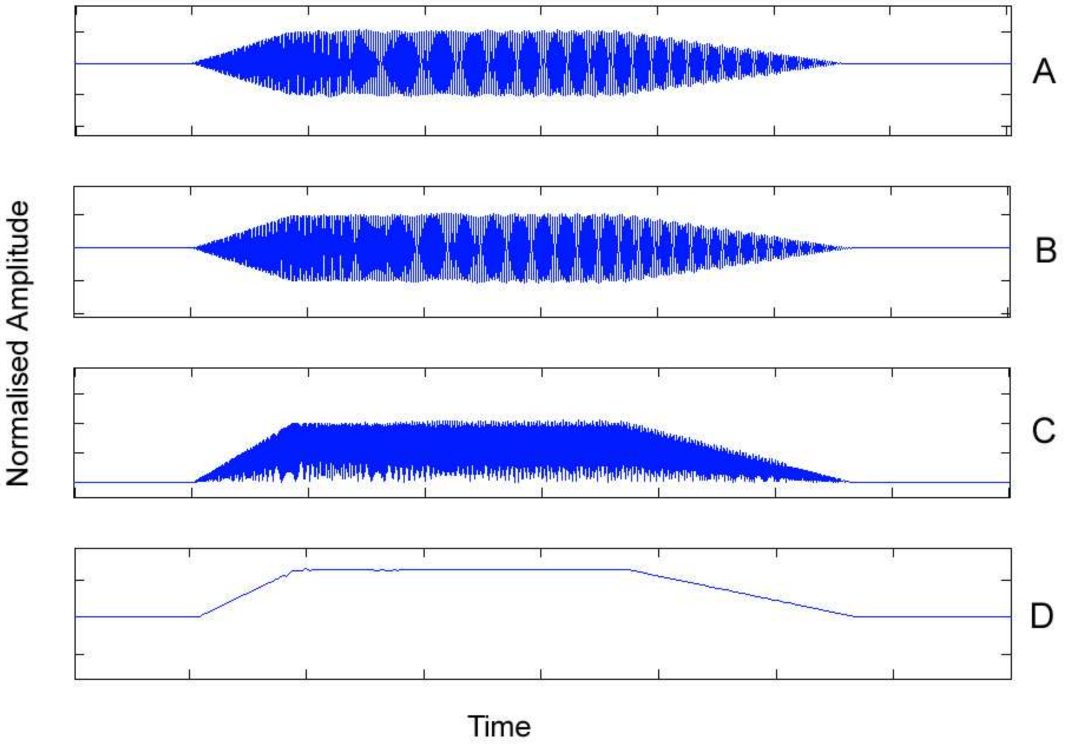


Figure 6.43- Example envelope detector. The bat pulse is recorded, A (in this case a simulated *P. pipistrellus* pulse), and then filtered with a Butterworth band-pass filter (order 8; 40-100 kHz), B. A full-wave rectify is performed, C, and the signal filtered with a Butterworth

low-pass filter (order 8; 0-15 kHz), D. This leaves the envelope of the pulse and removes all the high-frequency information.

The resulting pulse envelope can be used to determine the start time of each pulse by setting an amplitude ‘threshold’, above which the pulse is confirmed to have been detected.

Once the start times for each receiver signal have been extracted, the multilateration equations and LS solution can be employed. For simulation purposes, coding was performed in MATLAB for two consecutive source locations, designed to represent an echolocating bat moving through the receiver array. The resulting solution was output to a 3D graph, shown in Figure 6.44.

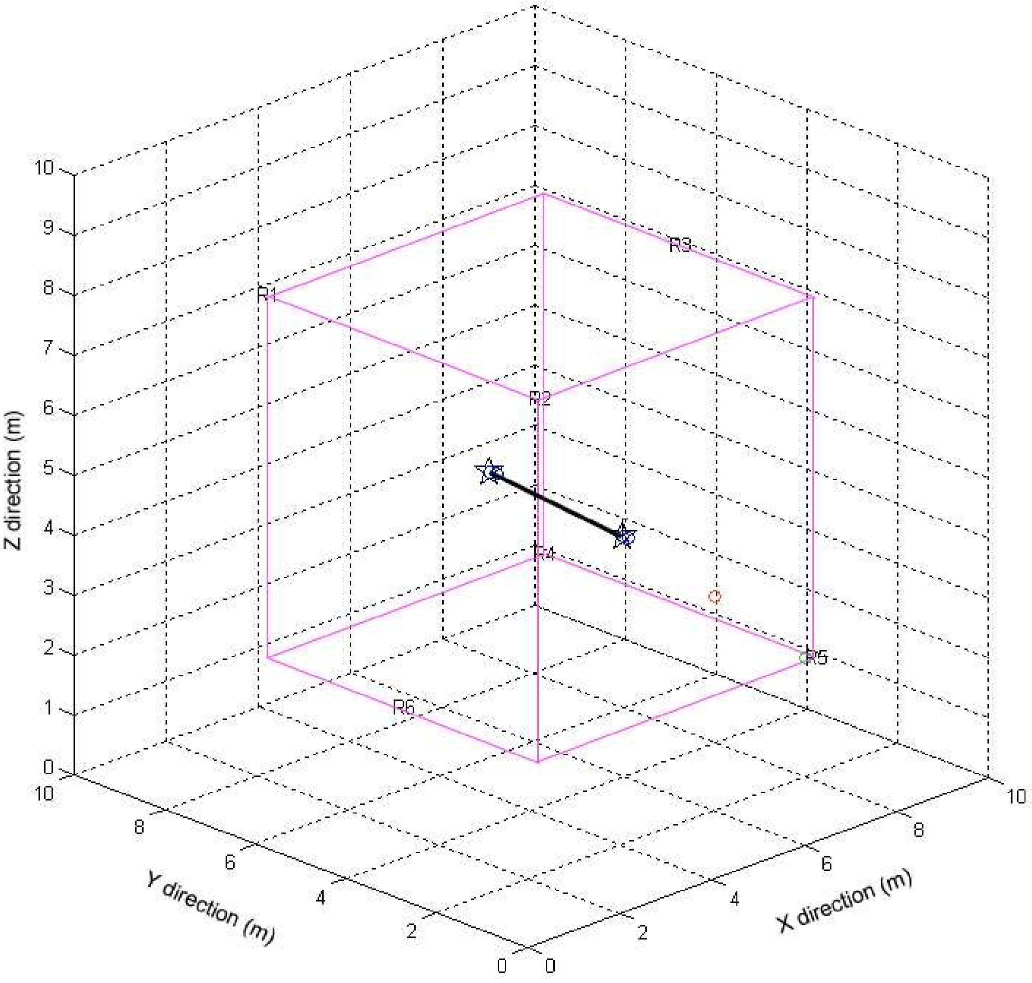


Figure 6.44- Demonstrating 4D bat flight path tracking in simulation using a multilateration technique with Least Squares solution. Magenta box represents detection area with receiver positions indicated. Red circle shows initial guess location, blue circles each iterative LS

solution and black stars the final source localisation for each of two pulses. Black line connecting stars represents shortest distance between points/most likely flight path.

The principles behind this multilateration theory can therefore be applied to a system which would allow the tracking of a bat's flight path in four dimensions through a receiver array placed at a specific location (for example around a turbine or at a potential turbine site). In theory, the height of the receiver placement would need to correlate with the typical flight heights of bat species likely to be in the area. Research by Collins & Jones (2009) demonstrated that it is useful to raise bat detection devices up to 30 m in height in order to detect some of the more high-flying UK species, such as noctules (*Nyctalus noctula*), which may not always be detected from ground level. The number of receivers required in the array would depend on both the area covered by the array (i.e. the spacing between receivers) and the detection range and beam angle of the receivers used.

Overall, the application of such a system would significantly reduce the subjectivity associated with assessing bat site use and could allow the interpretation of bat behaviour within the receiver array, with particular emphasis on monitoring bat flight paths around wind turbines.

6.5 Summary

To summarise, this chapter provided suggestions for modifying turbine design to help reduce fatal bat-turbine interactions. This encompassed proposed modifications to rotor design to maximise their detectability under operation from the point of view of an approaching bat. Such features included a greater number of blades, wider blades, faster rotation speeds and the more widespread implementation of operational rotor cut-ins above low wind speeds, which appear to be particularly problematic to bats. Further consideration regarding turbine colour and insect attraction was also encouraged. The use of acoustic aposematic signals as audible bat deterrents was explored and designed, for possible future deployment on existing wind turbine structures. Details of bat site-use survey protocol were provided with regard to assessing bat activity at sites for future turbine installations, including example assessments and information of a program developed to aid the acoustic identification of bat species based on recorded data collected during such surveys. Finally, a method for tracking bat flight paths by the use of an acoustic multilateration technique was proposed, designed and successfully simulated, which included an envelope detector for identifying bat echolocation pulses within a receiver array.

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Turbine at Sunset, Mablethorpe, C.V. Long (2010)

7

Conclusions and Further Work

The aim of the work in this thesis was to investigate, understand and attempt to mitigate the phenomenon of bat interaction with wind turbine installations, with the intention of reducing the problem both for the wind industry and for bat species. This final chapter concisely summarises the conclusions drawn from the research undertaken, highlighting the areas for potential mitigation. Additionally, some suggestions for future research directions in this area are provided.

7.1 Conclusions of This Thesis

Because comparatively little is fully understood about the intricate nature of bat echolocation systems, the majority of the research done in this thesis involved investigating how a bat might be acoustically interacting with a wind turbine, with particular reference to the main ‘danger zone’, the rotor swept region. It was shown that it is possible to theoretically predict the time-space interplay between a bat’s outgoing echolocation pulses and the moving turbine blades, resulting in the formulation of an equation to predict the ‘detectability’ of an operational turbine rotor to any particular approaching bat species. Furthermore, certain physical features of the turbine rotor were identified as having an impact on rotor detectability and these may be adjusted to maximise the potential detection from the point of view of a bat. The application of such a ‘rotor rating’ system may be of use to those considering turbine design at the planning stage, particularly as it can be tailored to meet the requirements of local bat species.

Experimental work revealed that operational microturbine blades produced characteristic Doppler shift ‘sweep patterns’ which change according to blade position and angle of insonation/approach. It was speculated that the Doppler shift returns from such turbine blades operating under low wind speed conditions ($<6 \text{ m s}^{-1}$) may not be perceptible by some FM bat species, which are not able to identify small changes in frequency due to the more wide-band nature of their echolocation pulses. Monte Carlo simulation of the short, bat-like sampling of these Doppler sweep patterns revealed that up to several hundred echoes may be required by an approaching CF or FM bat species (assuming the shift was perceptible) to allow accurate assessment of blade movement, something that may not be possible given the short approach time-window of the bat. Additionally, echoes reflected from moving blades had markedly less sound energy than those reflected from stationary blades and specular surfaces, suggesting that complex acoustic scattering occurs in the rotor region. This suggests that maximising the acoustical reflective properties of turbine blades is of potential importance for mitigation.

An investigation into why bats may be initially attracted to turbines suggested that ultrasonic turbine emissions may not play a significant role in luring bats into the rotor vicinity (although in this thesis only two models were assessed), consistent with the findings of other studies assessing the emission levels of ultrasound from turbines. However, it was identified that the colour of the turbine itself may be an important factor in attracting insects. The common turbine colours ‘white’ and ‘light grey’ were both found to attract significantly more insects than most of the other colours tested, independent of time of day, seasonal and meteorological effects. This may have implications for insectivore attraction to turbine installations.

Finally, suggestions for mitigation opportunities based on these findings were presented, alongside methods for local bat survey and pre-construction site-use assessments, complete with designs for tools to aid such data collection and analysis. Of the mitigation possibilities outlined, the use of minimum wind speed operational cut-ins for all types of horizontal axis turbine was identified as being perhaps one of the most important/effective options for future implementation, particularly for microturbines which do not typically utilise this feature.

7.2 Future Work

The issue of bat-turbine interaction is a complex one and there may be no single, simple ‘cure-all’ to the problem. However, over the course of this work several other potential study areas have arisen which could provide further useful insight into the phenomenon.

7.2.1 Vertical Axis Turbines

Although much less commonly used than horizontal axis wind turbines, vertical axis turbines are on the increase (an example can be found in Figure 2.23 in Chapter 2). To date there has been no documented evidence of bat or bird mortality at vertical axis installations, although this could simply be due to the relatively low incidence of their use. However, due to the positioning of the blades, equations developed in this thesis such as the ‘rotor detectability rating’ equation of Chapter 3 cannot be applied to vertical axis turbines. It is also not known if the moving blades would produce similar Doppler shift patterns or the same degree of pulse scattering as horizontal axis models, so it would be extremely useful to assess this in future study.

7.2.2 Aposematic Signal Testing

It would be useful to be able to test the effectiveness of the simulated acoustic aposematic signal detailed in Section 6.2 of Chapter 6. Ideally, this would involve obtaining a license to collect data from wild bats in the field, however it may also be possible to test such a device on captive insectivorous bats in a flight chamber. This would be a very interesting possibility for future mitigation efforts.

7.2.3 Bat Flight Path Tracking Experimental Rig

An additional area to expand into would be to create a prototype experimental rig for use with the automated bat flight path tracking system designed and tested in Section 6.4 of Chapter 6. This would require the system to be integrated with a receiver array and data acquisition hardware for testing purposes. Such a system would be particularly useful for tracking bat flight path behaviour around existing wind installations in order to more closely assess the interactions with the rotor region under various wind speed conditions, and could replace the need to rely on carcass collection (thus removing searcher bias).

7.2.4 Bat ID GUI Development

It may be useful to adapt the bat species identification program detailed in Section 6.3 to become more automated and save the surveyor even more time post data collection, for example by automatically reading recorded data files and extracting relevant echolocation pulse parameters. Future versions of the GUI may also be designed to include an additional section to allow comparison of the pulse shape produced by the spectrogram which is sometimes used to aid analysis (for example to distinguish between CF and FM bats or pure FM and FM-short-CF bats). Pulse shapes would, however, vary somewhat depending on the type of system used to record the data and also the settings used to generate the FFT at the user end.

Appendix

A.1 Example Bat Site-Use Assessment

The author was asked to conduct a bat site-use assessment for a proposed 15 m Iskra wind turbine installation south-east of Holywell park, Loughborough (GPS coordinates 52°45’24” N, 1°14’40” W). The site was located in a suburban, open area of land adjacent to fields and bordering a car park at the north edge (see Figure A.1).

Figure A.1- Aerial view of the proposed turbine site.

The north and east edges of the site land were bordered by dense hedgerow, while the southern edge was bordered by newly planted hedgerow shrubs such as hazel and hawthorn. The site was over 100 m from the nearest mature woodland.

Two surveys were conducted, one on the 16th June, 2008, the other on the 15th July, 2008, both between 15 minutes – 1 hour 15 minutes after sunset in order to correspond with bat emergence and peak foraging times. Bat echolocation activity was recorded using a Batbox Duet (Batbox Ltd., West Sussex, UK) handheld frequency division bat detector, connected to a Sharp MDMS702H2 (Sharp Corporation, Osaka, Japan) MiniDisc recorder. The HHF81 digital 4-in-1 meter was used to take temperature, light level, wind speed and relative humidity readings. A survey transect route was planned and is detailed in Figures A.2 and A.3. Over the course of each survey, the direction of flight of any bats observed was recorded on the maps.

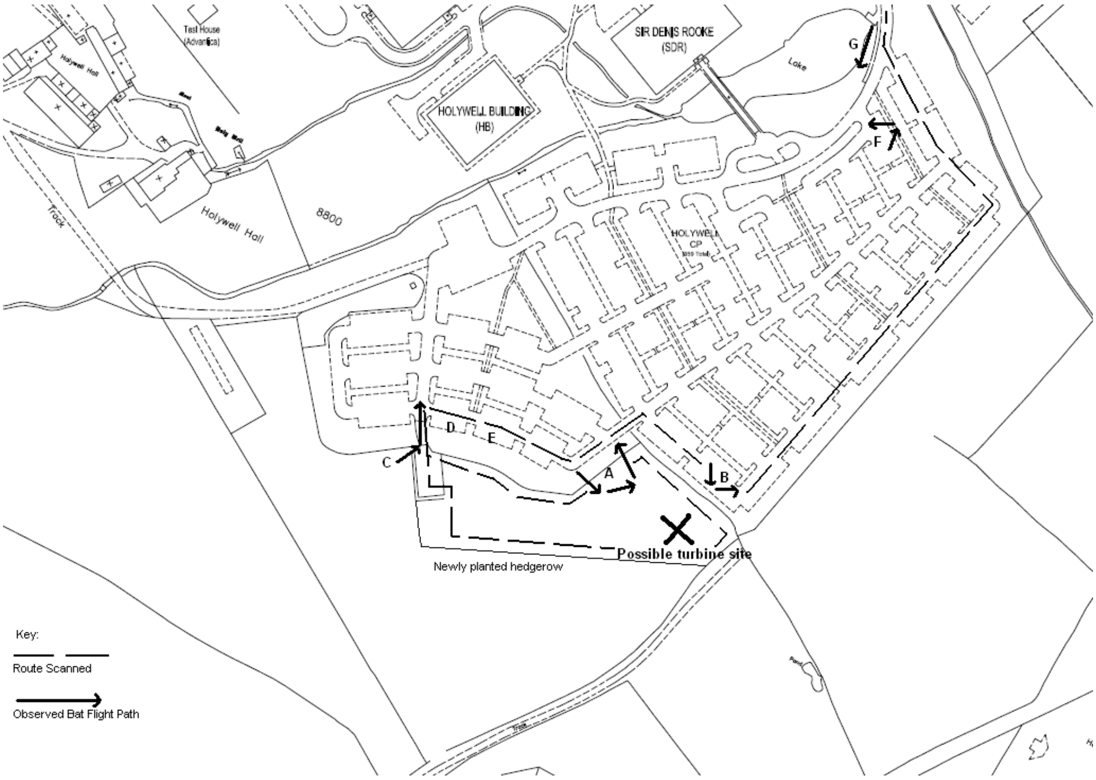


Figure A.2- Survey transect route for the June site use assessment. Dashed line indicates route; arrows indicate observed bat flight paths. ‘X’ denotes the potential turbine location.

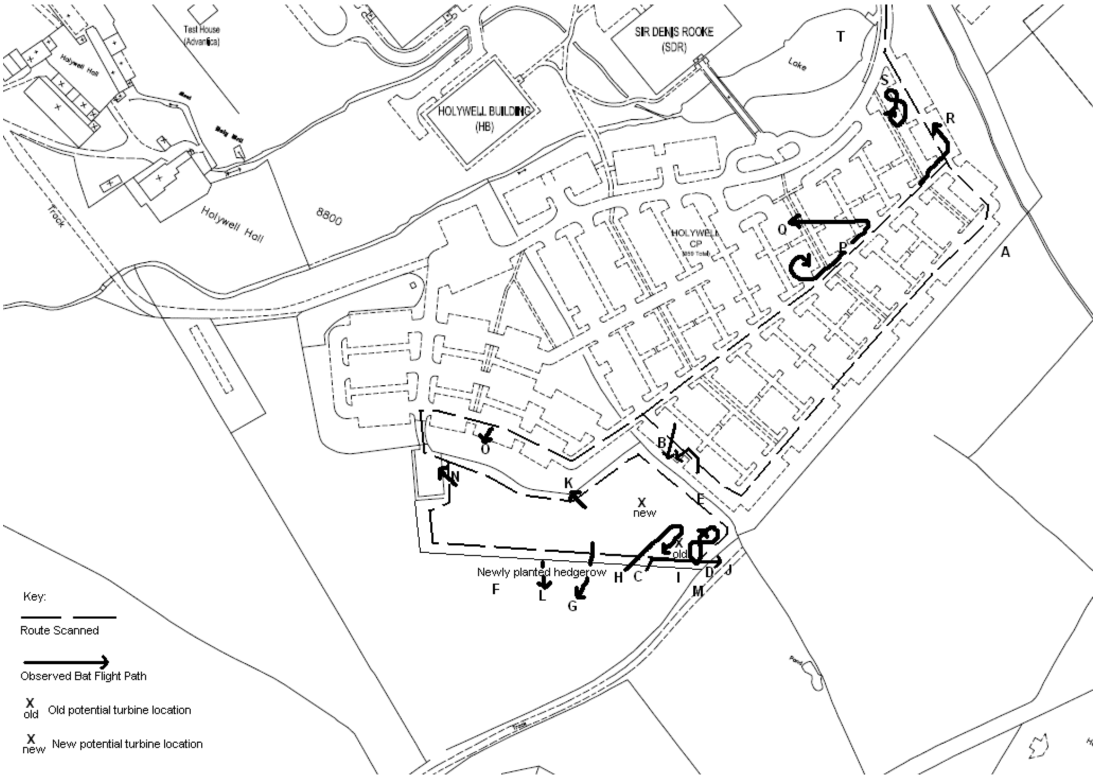


Figure A.3- Survey transect route for the July site use assessment. Dashed line indicates route; arrows indicate observed bat flight paths. ‘X’ denotes the potential turbine location.

In both cases, the transect around the car park was scanned twice and the transect around the proposed site was scanned three times. Post data collection, the recorded audio data were saved on to a PC in .wav format, then analysed using Adobe Audition 1.0 to obtain echolocation pulse parameters. These data were input into the Bat ID GUI and used for species identification.

Bat activity was recorded along most of the transect, with the exception of the south-west area of the proposed site. Tables A.1 and A.2 provide the results of the bat species identified from recordings along the transect with the use of the Bat ID GUI.

Location on map (Figure A.2)	**Species/details**
Proposed site transect	
A	Here a bat was observed feeding around the hedgerow, flying out a short way over the site and then back into the hedgerow. This species was identified as Natterer's bat (*Myotis nattereri*).
B	Here a bat was observed on a flight path just behind the hedgerow bordering the site. This species was not identified due to lack of sufficient recorded samples.
C	This flight path route was observed to be used by several bats, at least one of which was identified as a common pipistrelle (*Pipistrellus pipistrellus*).
D	This bat was recorded but not observed, presumably flying within/behind the hedgerow. The species could not be exactly identified (closest match Nathusius' pipistrelle (*Pipistrellus nathusii*)).
E	Again the bat was detected but not observed. This species could not be exactly identified (closest match serotine (*Eptesicus serotinus*)).
Car park transect	
F	Here several bats were observed feeding and heading towards the small lake. The species was identified as the common pipistrelle.
G	Significant bat activity was observed and recorded around the small lake within Holywell park. Although only the north-eastern tip was scanned, species identified included common pipistrelles, soprano pipistrelles (*Pipistrellus pygmaeus*) and serotines.

Table A.1- Bat species identified in the June site use assessment.

Location on map (Figure A.3)	**Species/details**
Proposed site transect	
B	Here a bat was observed feeding in the direction of the hedgerow, and another was observed on a flight path toward the hedgerow. One species was identified as a soprano pipistrelle the other species could not be exactly identified (closest match Natterer's bat).
C	This bat was observed on a flight path adjacent to the newly planted hedgerow, just inside the proposed site land. This species could not be exactly identified (closest match Daubenton's bat (*Myotis daubentonii*)).

Continued overleaf…

…continued

Location on map (Figure 6.37)	**Species/details**
D	Here a bat was recorded behind or within the hedgerow but not directly observed. This species could not be exactly identified (nearest match Daubenton's bat).
E	This bat was recorded behind or within the hedgerow but not directly observed. This species was identified as a noctule (*Nyctalus noctula*).
F	This bat was recorded over the open field to the south of the proposed site, although was not directly observed. This species could not be exactly identified (closest match Natterer's bat).
G	Here a bat was observed on a flight path from the site into the field to the South. This species was identified as Daubenton's bat.
H	This bat was observed foraging in a loop path directly over the proposed site (in the immediate vicinity of the old proposed turbine location), at a height of between ~5-10 m. The species could not be exactly identified (closest match Daubenton's bat).
I	Here several bats were observed repeatedly flying in a loop whilst foraging over the proposed site approximately 2 m from the Eastern hedgerow. The species could not be exactly identified (closest match Daubenton's bat).
J	Here a bat was recorded behind or within the hedgerow but was not directly observed. This species could not be exactly identified (closest match common pipistrelle).
K	This bat was observed on a flight path into the northern hedgerow from the site. This species could not be exactly identified (closest match Daubenton's bat).
L	This bat was observed on a flight path from the site into the field to the south. The species could not be exactly identified (closest match Daubenton's bat).
M	Here a bat was recorded behind or within the hedgerow, although not directly observed. The species could not be exactly identified (closest match Daubenton's bat).
N	This bat was observed on a flight path from the site over the Northern hedgerow. The species was identified as a common pipistrelle.
O	This bat was observed on a flight path into the hedgerow in the direction of the site. The species could not be exactly identified (closest match serotine).

Continued overleaf…

…continued

Location on map (Figure 6.37)	**Species/details**
Car park transect	
A	Here a bat was recorded behind or within the hedgerow, although not directly observed. The species was identified as a common pipistrelle.
P	Here several bats were observed on flight paths along the line of trees outlining the car park thoroughfare, then in foraging loops slightly to the West of the thoroughfare. Both species could not be exactly identified (closest match common pipistrelle and Daubenton's bat).
Q	Here a bat was observed on a flight path from the thoroughfare out over the Western car park. The species could not be exactly identified (closest match Daubenton's bat).
R	These bats were observed on a flight path from the thoroughfare in the car park to the Northern hedge. The species were identified as the common pipistrelle and Nathusius' pipistrelle.
S	Here several bats were observed foraging in loops over the car park just East of the ornamental lake. One species was identified as Daubenton's bat. The other two species could not be exactly identified (closest match Daubenton's bat and the common pipistrelle).
T	Directly over the ornamental lake extensive bat activity was observed and recorded. Several species were present foraging over the water; These were identified as Daubenton's bat, the common pipistrelle, the soprano pipistrelle and Natterer's bat. Two other species could not be exactly identified (closest match Natterer's bat and the barbastelle (*Barbastella barbastellus*)).

Table A.2- Bat species identified in the July site use assessment.

For both surveys, weather conditions were ideal for bat activity (low humidity, low wind speed and warm, associated with high insect activity). Bats were predominantly observed feeding and commuting along the hedgerows bordering the proposed site, although some bats did fly short distances inside the site, including directly over the old proposed turbine location (July survey). The species recorded were predominantly aerial hawking species (pipistrelles, serotines, Natterer's bats) and as such were those most likely to be involved in wind turbine interaction (Betts, 2006). While the south-west area of the proposed site had the least bat activity, the newly planted hedgerow on the south site border could increase bat activity around this area as it matures. Bach (2001) reports that small turbines positioned close to forage sites are likely to have significant impact on common pipistrelles and Nathusius' pipistrelles, and have some effect on the local activity of serotines. While the impact on the more common species such as soprano and common pipistrelles in the area is likely to be small, species such as Nathusius' pipistrelle and the serotine are fairly uncommon in the UK midlands region (Bristol University Bat Research Group, 2005), and therefore at much greater risk of impact at the population level through interactions with turbines. Although the lake area on the car park transect was 200 m from the proposed turbine site, the fact that this was clearly an important foraging site for several bat species could be a significant factor in local bat activity. In addition, the possible detection of a barbastelle at this location (rare in the UK but known to roost in Leicestershire) could be significant in terms of habitat preservation. The conclusion of these surveys was that the proposed turbine site was rich in bat activity, including species that may be vulnerable to wind turbine mortality at the local population level. As the site was bordered on all sides by hedgerow within 35 m of the proposed turbine locations, with bat activity observed within the site, it was advised that an alternative location be considered for future pre-construction assessment.

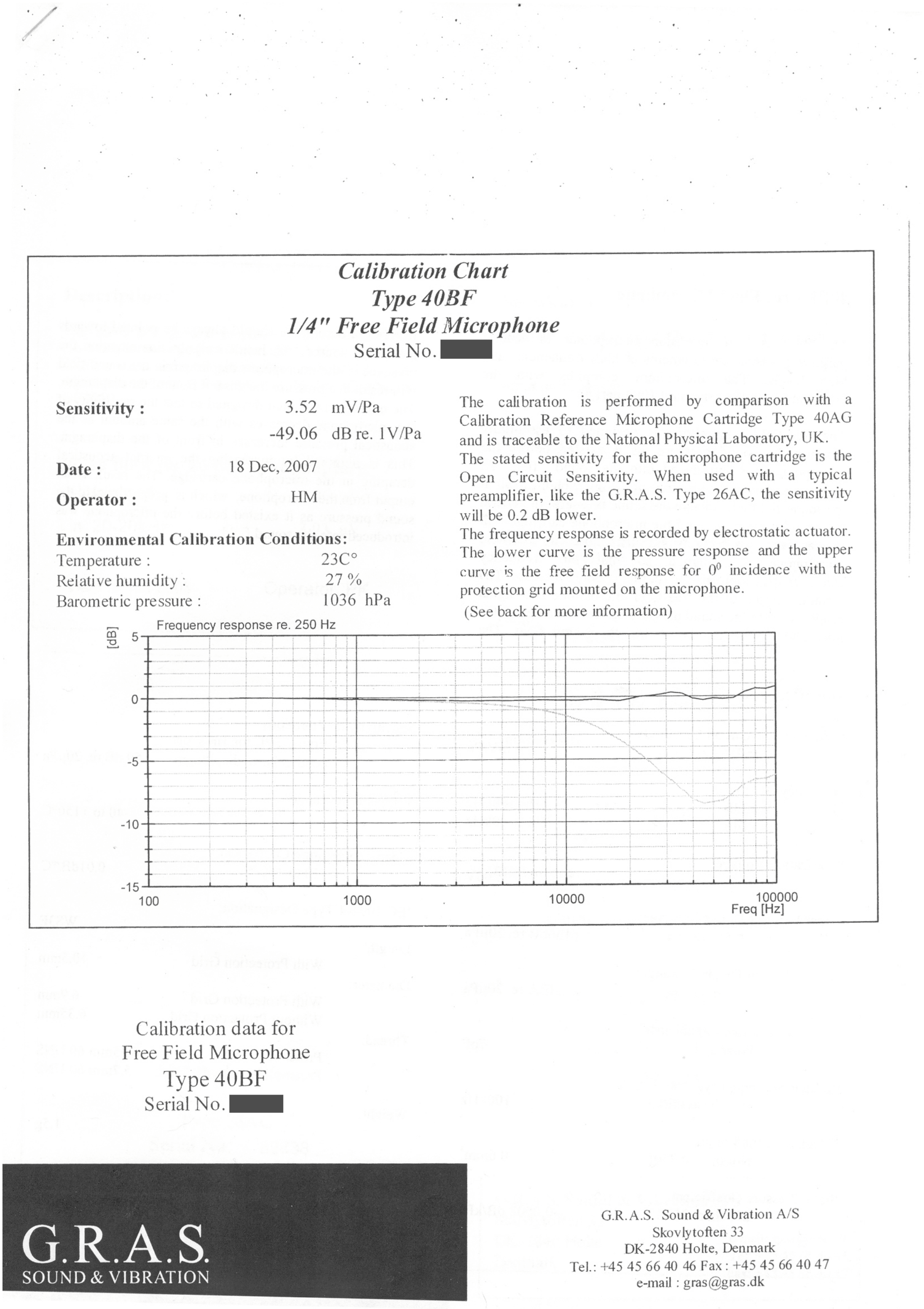
A.2 References

Bach, L. (2001) '[Bats and the use of wind energy- real problems or only fancies?]' *Vogelkdl. Ber. Niedersachs*., **33**: 119-124.

Betts, S. (2006) 'Are British bats at risk from wind farms?' *British Wildlife*, **17**: 339-345.

Bristol University Bat Research Group (2005) *British Bat Guide* [www document]. <http://www.bio.bris.ac.uk/research/bats/britishbats/> (Accessed 17 June, 2008).

A.3 GRAS Microphone Specification Sheet



Calibration Chart
Type 40BF
1/4" Free Field Microphone
Serial No. [redacted]

Sensitivity :	3.52	mV/Pa
	-49.06	dB re. 1V/Pa
Date :	18 Dec, 2007	
Operator :	HM	

Environmental Calibration Conditions:

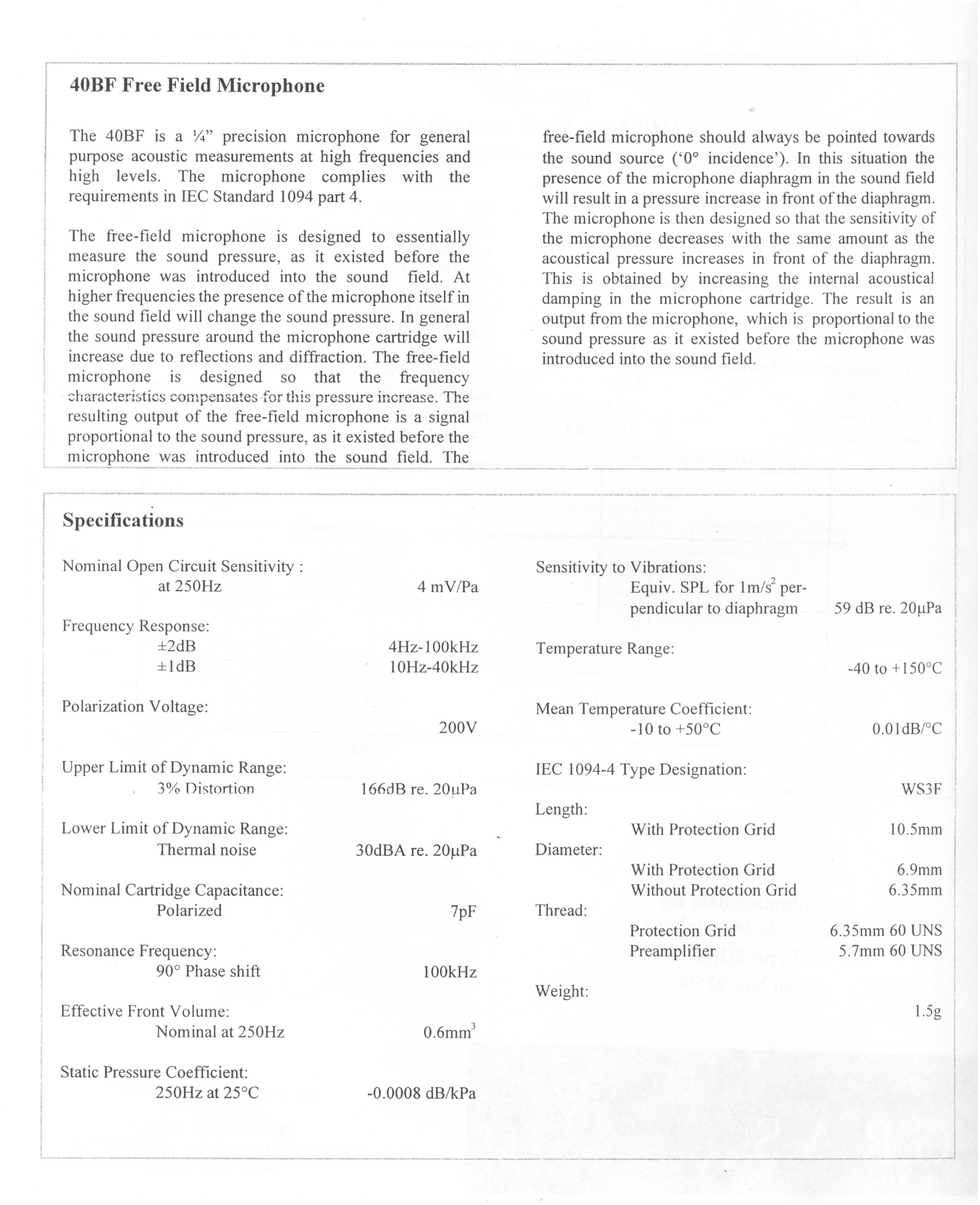
Temperature :	23C°
Relative humidity :	27 %
Barometric pressure :	1036 hPa

The calibration is performed by comparison with a Calibration Reference Microphone Cartridge Type 40AG and is traceable to the National Physical Laboratory, UK.
The stated sensitivity for the microphone cartridge is the Open Circuit Sensitivity. When used with a typical preamplifier, like the G.R.A.S. Type 26AC, the sensitivity will be 0.2 dB lower.
The frequency response is recorded by electrostatic actuator. The lower curve is the pressure response and the upper curve is the free field response for 0^0 incidence with the protection grid mounted on the microphone.
(See back for more information)

Calibration data for
Free Field Microphone
Type 40BF
Serial No. [redacted]

G.R.A.S.
SOUND & VIBRATION

G.R.A.S. Sound & Vibration A/S
Skovlytoften 33
DK-2840 Holte, Denmark
Tel.: +45 45 66 40 46 Fax : +45 45 66 40 47
e-mail : gras@gras.dk



40BF Free Field Microphone

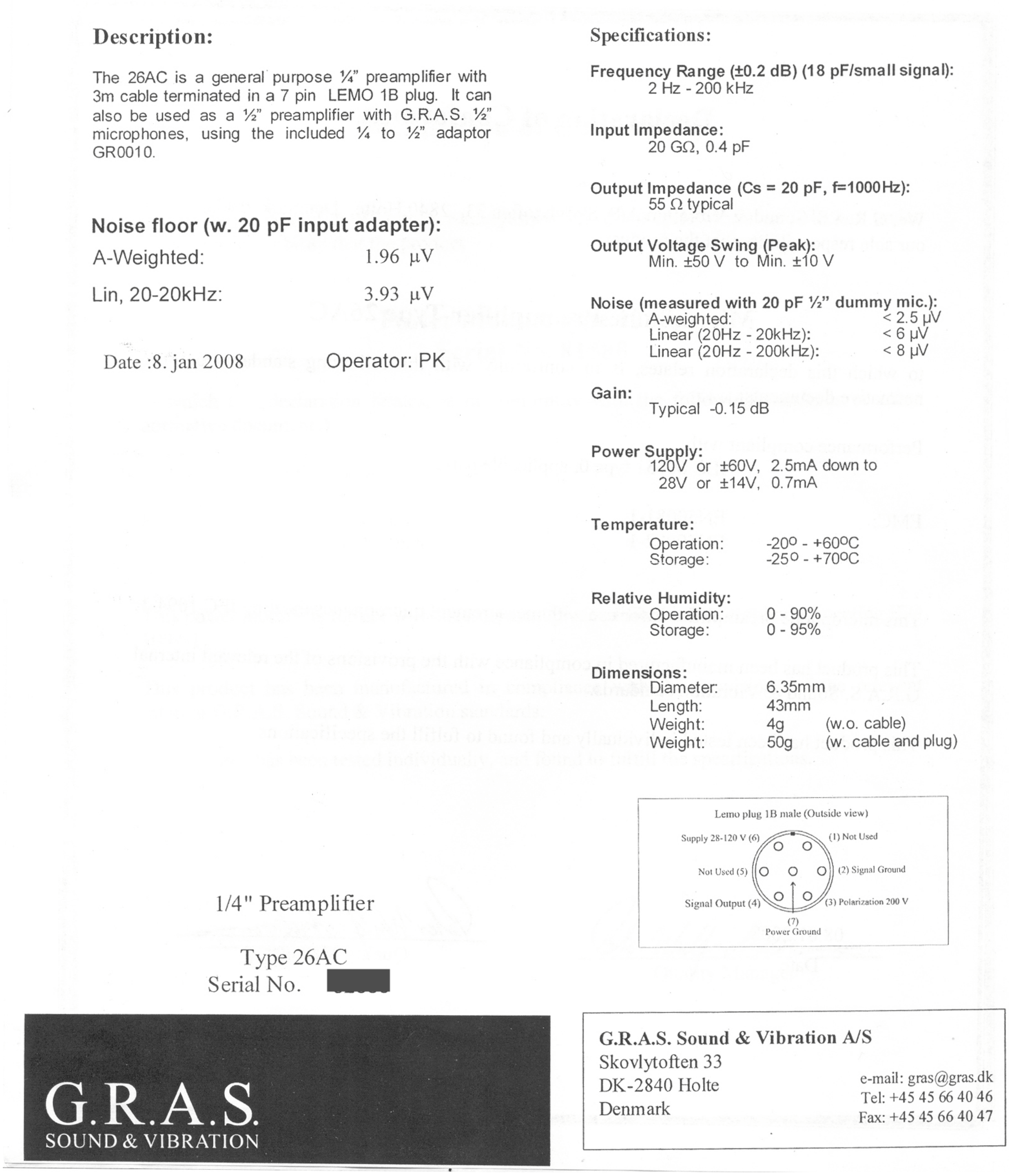
The 40BF is a ¼” precision microphone for general purpose acoustic measurements at high frequencies and high levels. The microphone complies with the requirements in IEC Standard 1094 part 4.

The free-field microphone is designed to essentially measure the sound pressure, as it existed before the microphone was introduced into the sound field. At higher frequencies the presence of the microphone itself in the sound field will change the sound pressure. In general the sound pressure around the microphone cartridge will increase due to reflections and diffraction. The free-field microphone is designed so that the frequency characteristics compensates for this pressure increase. The resulting output of the free-field microphone is a signal proportional to the sound pressure, as it existed before the microphone was introduced into the sound field. The free-field microphone should always be pointed towards the sound source (‘0° incidence’). In this situation the presence of the microphone diaphragm in the sound field will result in a pressure increase in front of the diaphragm. The microphone is then designed so that the sensitivity of the microphone decreases with the same amount as the acoustical pressure increases in front of the diaphragm. This is obtained by increasing the internal acoustical damping in the microphone cartridge. The result is an output from the microphone, which is proportional to the sound pressure as it existed before the microphone was introduced into the sound field.

Specifications

Nominal Open Circuit Sensitivity :		
	at 250Hz	4 mV/Pa
Frequency Response:		
	±2dB	4Hz-100kHz
	±1dB	10Hz-40kHz
Polarization Voltage:		200V
Upper Limit of Dynamic Range:		
	3% Distortion	166dB re. 20μPa
Lower Limit of Dynamic Range:		
	Thermal noise	30dBA re. 20μPa
Nominal Cartridge Capacitance:		
	Polarized	7pF
Resonance Frequency:		
	90° Phase shift	100kHz
Effective Front Volume:		
	Nominal at 250Hz	0.6mm^3
Static Pressure Coefficient:		
	250Hz at 25°C	-0.0008 dB/kPa

Sensitivity to Vibrations:		
	Equiv. SPL for 1m/s^2 perpendicular to diaphragm	59 dB re. 20μPa
Temperature Range:		-40 to +150°C
Mean Temperature Coefficient:		
	-10 to +50°C	0.01dB/°C
IEC 1094-4 Type Designation:		WS3F
Length:		
	With Protection Grid	10.5mm
Diameter:		
	With Protection Grid	6.9mm
	Without Protection Grid	6.35mm
Thread:		
	Protection Grid	6.35mm 60 UNS
	Preamplifier	5.7mm 60 UNS
Weight:		1.5g



Description:

The 26AC is a general purpose ¼" preamplifier with 3m cable terminated in a 7 pin LEMO 1B plug. It can also be used as a ½" preamplifier with G.R.A.S. ½" microphones, using the included ¼ to ½" adaptor GR0010.

Noise floor (w. 20 pF input adapter):

A-Weighted:	1.96 μV
Lin, 20-20kHz:	3.93 μV

Date :8. jan 2008 Operator: PK

Specifications:

Frequency Range (±0.2 dB) (18 pF/small signal):
2 Hz - 200 kHz

Input Impedance:
20 GΩ, 0.4 pF

Output Impedance (Cs = 20 pF, f=1000Hz):
55 Ω typical

Output Voltage Swing (Peak):
Min. ±50 V to Min. ±10 V

Noise (measured with 20 pF ½" dummy mic.):

A-weighted:	< 2.5 μV
Linear (20Hz - 20kHz):	< 6 μV
Linear (20Hz - 200kHz):	< 8 μV

Gain:
Typical -0.15 dB

Power Supply:
120V or ±60V, 2.5mA down to
28V or ±14V, 0.7mA

Temperature:

Operation:	-20° - +60°C
Storage:	-25° - +70°C

Relative Humidity:

Operation:	0 - 90%
Storage:	0 - 95%

Dimensions:

Diameter:	6.35mm	
Length:	43mm	
Weight:	4g	(w.o. cable)
Weight:	50g	(w. cable and plug)

Lemo plug 1B male (Outside view)

Supply 28-120 V (6)
(1) Not Used
Not Used (5)
(2) Signal Ground
Signal Output (4)
(3) Polarization 200 V
(7)
Power Ground

1/4" Preamplifier

Type 26AC
Serial No. [redacted]

G.R.A.S.
SOUND & VIBRATION

G.R.A.S. Sound & Vibration A/S
Skovlytoften 33
DK-2840 Holte
Denmark

e-mail: gras@gras.dk
Tel: +45 45 66 40 46
Fax: +45 45 66 40 47