2.0 PROPELLER NOISE

2.1 Overview

There are many applications in which propeller noise is a serious problem or a cause for concern. The commercial usage of propeller driven aircraft is limited by high levels of cabin noise. Ship propellers are a major cause of both shipboard noise, and radiation to the far field. Submarines need quiet propellers to be stealthy. On a larger scale, wind turbines can be very noisy if designed incorrectly. Helicopter rotors have many of the same characteristics as propellers, and there are both military and civil applications in which the reduction of helicopter noise is important. In all these examples the same source mechanisms are found, but the dominant processes depend on the application. In the following we will discuss the different mechanisms that cause noise from propellers and rotors, and then discuss their relevance to airboat noise. The discussion is based on the detailed reviews of propeller noise presented by Hubbard [1] and Blake [2].

2.1 Propeller Noise Signatures

Rotating blades emit two distinctly different types of acoustic signature. The first is referred to as tone or harmonic noise, and is caused by sources that repeat themselves exactly during each rotation of the propeller. The second is broadband noise which is a random, non-periodic, signal caused by turbulent flow over the blades. Figure 2.1 illustrates these signals and shows how they combine. In Figure 2.1 (a) the signature from a single blade is shown during the period of one revolution T_p. If the rotor has three blades then this signature is repeated at the blade passing frequency (BPF) and the sum (see Figure 2.1(b)) is a signature that repeats itself with a period of $T_p/3$. A typical broadband signal is shown in Figure 2.1(c) and this is seen to have a quite different character, with no associated periodicity, but an envelope that varies periodically. The sum of all the signal types is shown in Figure 2.1(d). Note how the sum tends to hide the details of the individual components shown in Figures 2.1 (a)-(c).

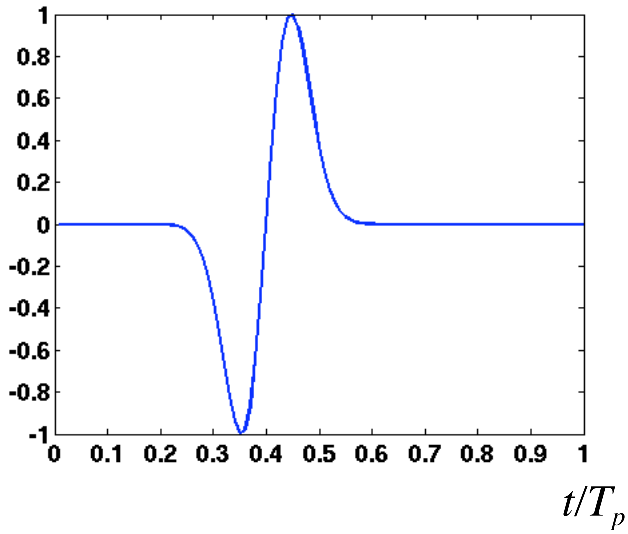

Figure 2.1(a) The time history of a pulse from a single blade

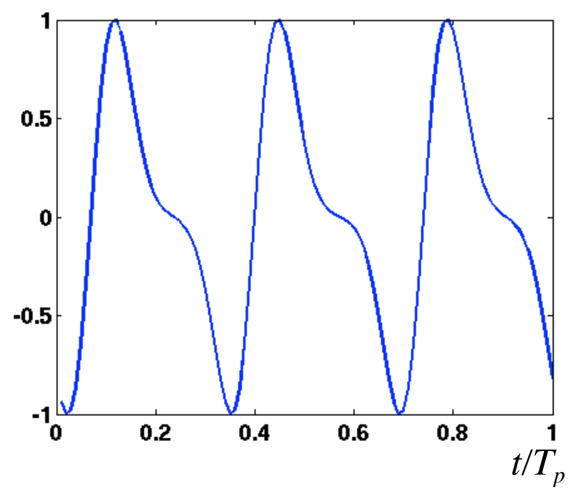

Figure 2.1 (b): The time history from a three bladed rotor

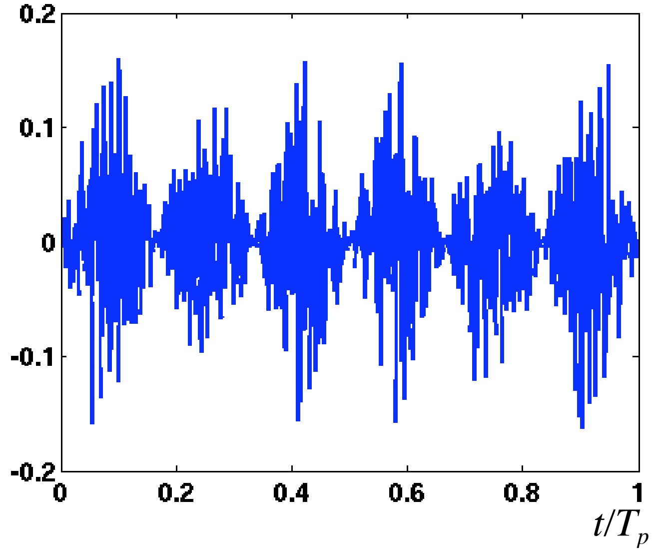

Figure 2.1 (c): The time history of broadband rotor noise

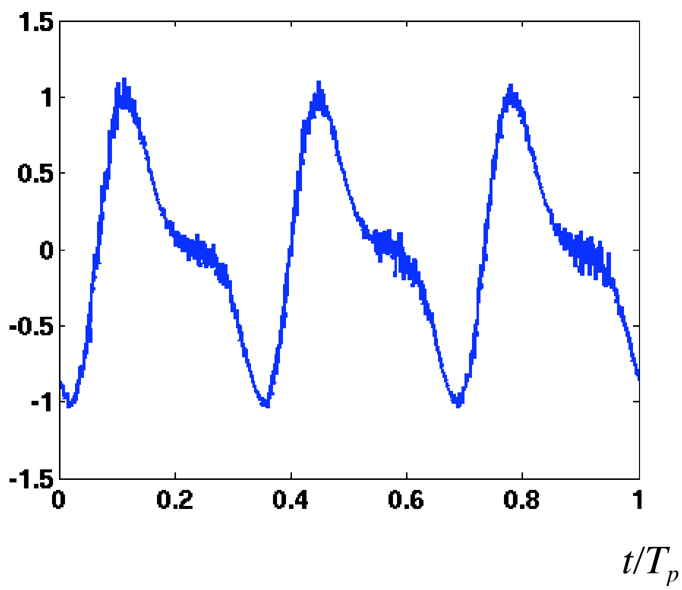

Figure 2.1 (d): The time history of rotor noise over one period

To determine the relative importance of tone noise and broadband noise we consider the narrow band frequency spectrum of the signal. Figure 2.2 shows a typical example of a rotor noise spectrum with a 3 Hz bandwidth for a three blade rotor at 600 rpm. The peaks define the tone noise and occur at the blade passing frequencies, which in this case are multiples of 30 Hz. At higher frequencies the broadband random noise dominates the spectrum.

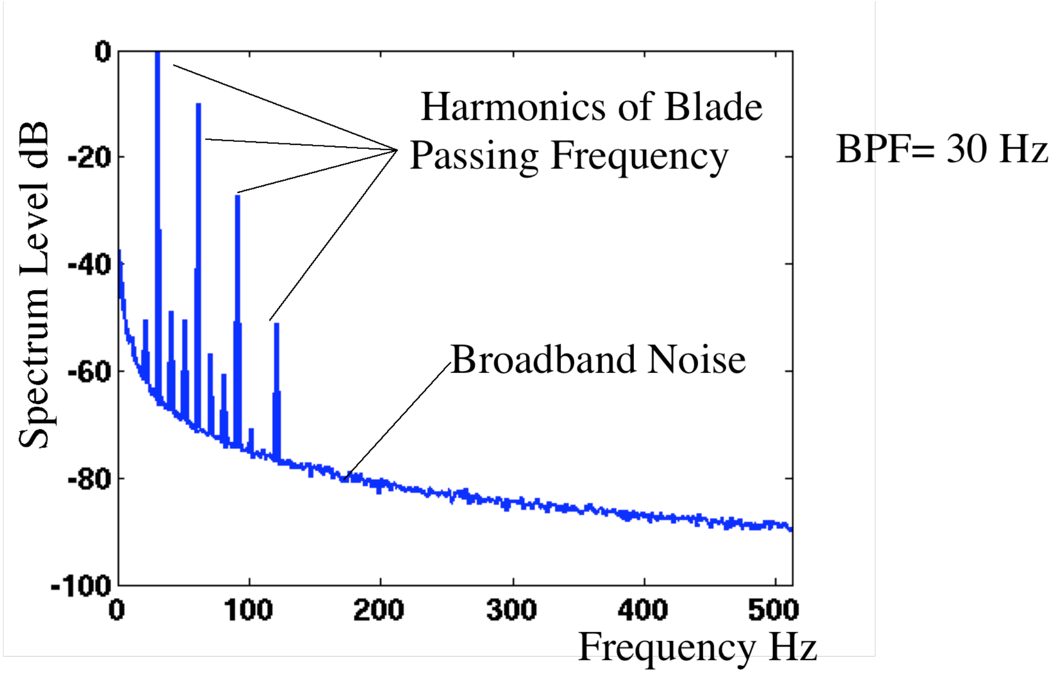

Figure 2.2: The spectrum of rotor noise showing harmonics at blade passing frequency and broadband noise

2.3 Sources of Tone Noise

The primary sources of tone noise depend on the rotor tip speed and the flow conditions in which the propeller is operating. At low speeds the dominant source of sound is caused by the unsteady pressure on the blade surface. There are many effects that can affect the blade loading. If the propeller is operating in a completely clean inflow, which is rarely the case, then the blade loading is steady in blade based co ordinates but the component of the force in the direction of the observer varies as the blade rotates. For example consider an observer close to the plane of the rotor as shown in Figure 2.3. From that position the observer "sees" a blade drag force that continuously changes direction and so its component in the direction of the observer varies with time and a sound wave is generated. The same is true, but to a lesser extent, for the lift (or equivalently the thrust force). The amount of variation of these steady forces that is “seen” by the observer is very directional because it is very dependent on the observer location.

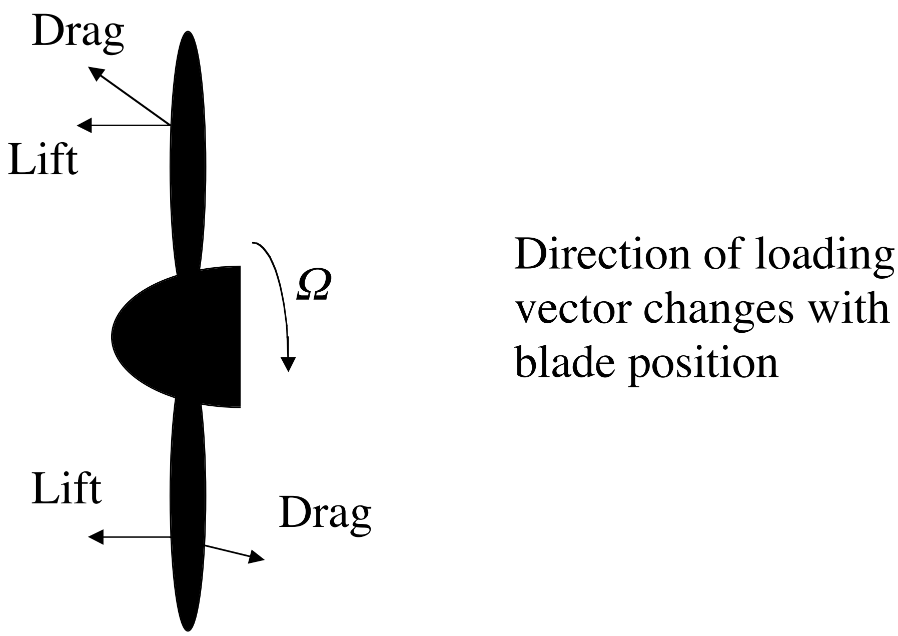

Figure 2.3: The lift and drag forces on a propeller

The sound caused by the time variation of the steady loading applies to all propellers but it is a relatively weak source of sound compared to the unsteady loading. Most propellers operate in a non-uniform distorted inflow and so the angle of attack of each blade varies continuously as the propeller rotates, see Figure 2.4. Smoothly varying changes of angle of attack are usually not very important, but when the blade encounters a velocity deficit in the flow then the angle of attack change is sudden and causes a rapid change in blade loading. It is the time variation of the loading that generates sound [1,2] and so a blade encountering a velocity deficit can be a very efficient source of sound. A classic example of this is a wind turbine which can be designed so that the blades operate either upwind or downwind of the tower (Figure 2.5). In the downwind design the tower causes a significant velocity deficit that the blade moves though, and as it does so, a strong acoustic pulse is generated (Figure 2.5(a)). In contrast if the wind turbine is designed so that the tower is downstream of the blades, then the blades never pass through the velocity deficit and they only encounter a small velocity perturbation as the pass the tower (Figure 2.5(b)). The upwind design of wind turbine is therefore significantly quieter than the downwind design. This principle applies to any propeller and, whereever possible, mounting of the rotor so that inflow distortions are minimized will reduce noise.

A special case of unsteady loading noise is caused by blade vortex interactions (BVI) in helicopter rotors (Figure 2.6). During forward flight the tip vortices of a helicopter can be ingested into the rotor and, given the right conditions, the helicopter blades can pass through the core of the vortex. This causes a local, very rapid, change in angle of attack and a sudden change in blade load. Blade vortex interactions emit a loud "thumping" sound, and are often the dominant cause for complaints about helicopter noise [1]. If the operational conditions are changed so that the wake is ingested in a different way then BVIs are eliminated, but unfortunately this is not always possible for some necessary maneuvers.

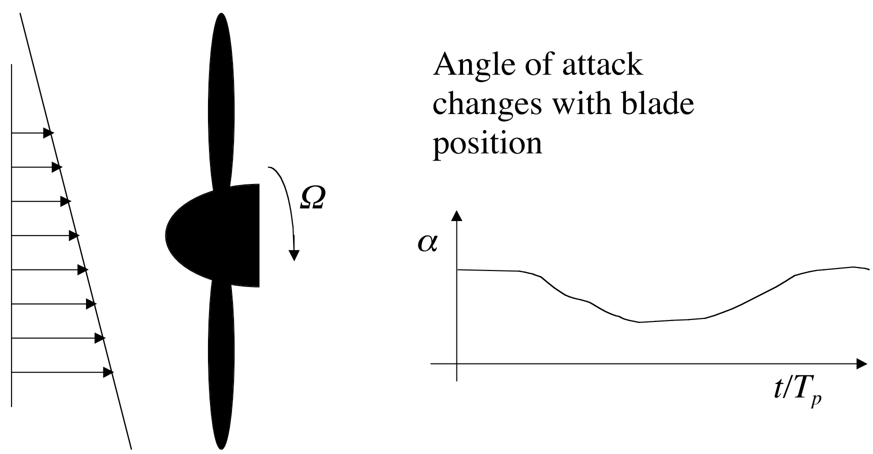

Figure 2.4: A propeller operating in a distorted inflow

In addition to unsteady loading noise there is a contribution from the blade motion that is referred to as thickness noise. This is only important at tip speeds with Mach numbers in excess of 0.7. However for high-speed helicopters and transonic propellers this source can be important. The mechanism for this source is the time varying displacement of fluid by the blade volume as it rotates. To the fixed observer the blade volume "appears" to change as it is "seen" from different perspectives during rotation, and this apparent variation in volume causes a sound wave in the far field. The simplest way to reduce thickness noise is to reduce the blade volume near the blade tip. If the blade thickness is halved in the tip region then the thickness noise is reduced by 6dB, which is not insignificant and can be an effective way to reduce the noise from high-speed rotors.

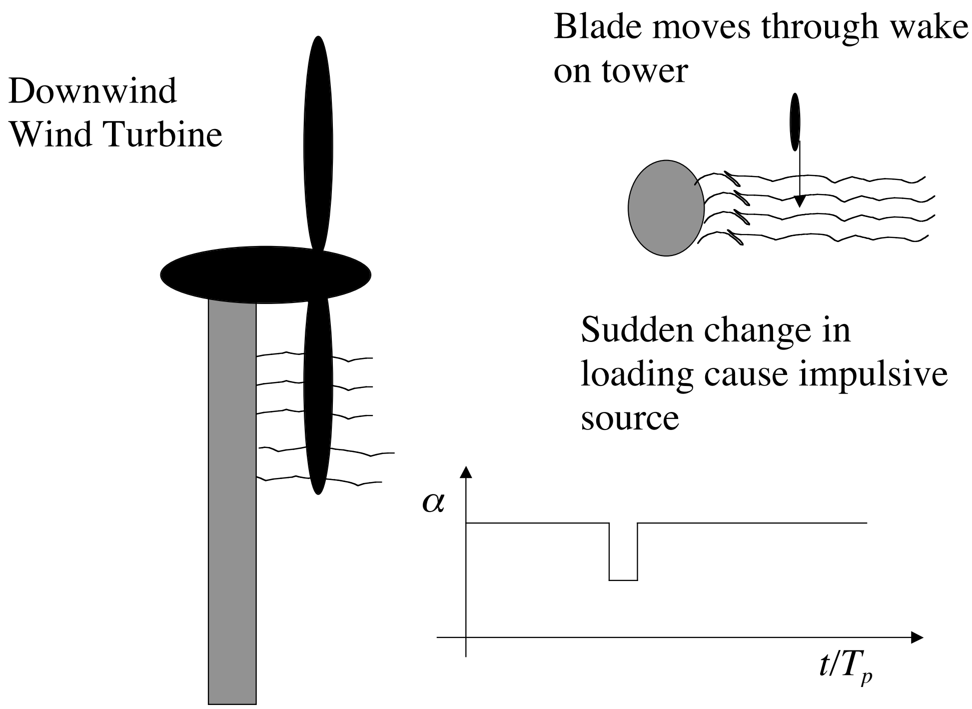

Figure 2.5 (a) Illustration of a downwind wind turbine

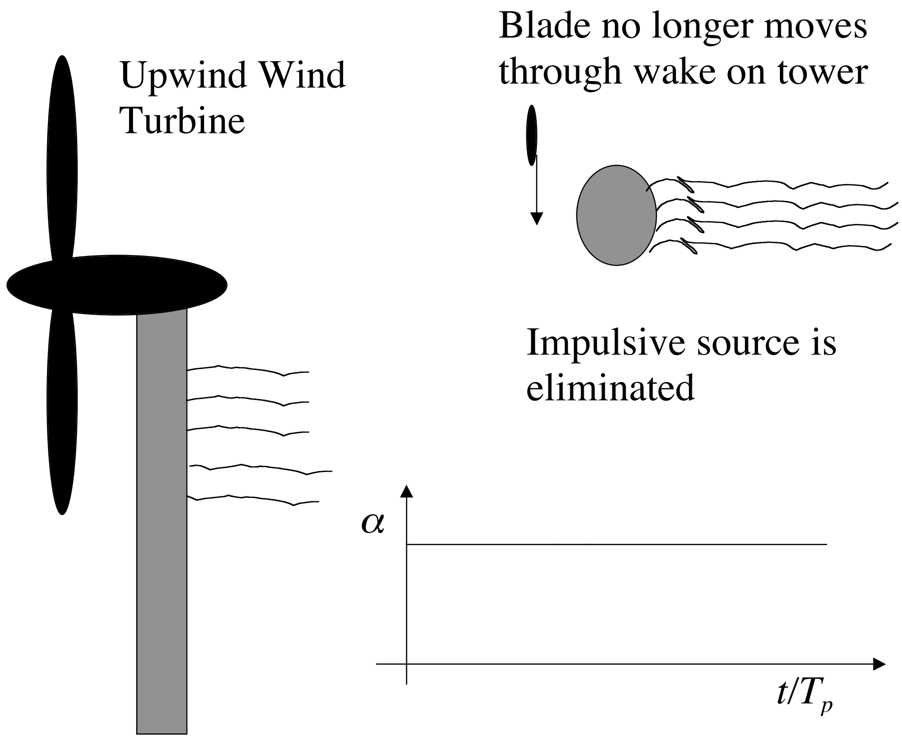

Figure 2.5 (a) Illustration of a upwind wind turbine

When the blade tip speed is transonic or supersonic then shock discontinuities can occur both on the blade surface and in the fluid surrounding the blade tips (Figure 2.7). From the observer's perspective, the shocks apparently change as the blade rotates and so they generate sound. This mechanism can be just as important as thickness noise in some rotor designs. In general the shocks are weaker if the blades are thinner, and so thinning of the blade tips is always advantageous for the reduction of transonic and supersonic rotor noise. Reference [1] gives several examples that show the importance of shock noise and demonstrates that it becomes important when the tip Mach number exceeds 0.85.

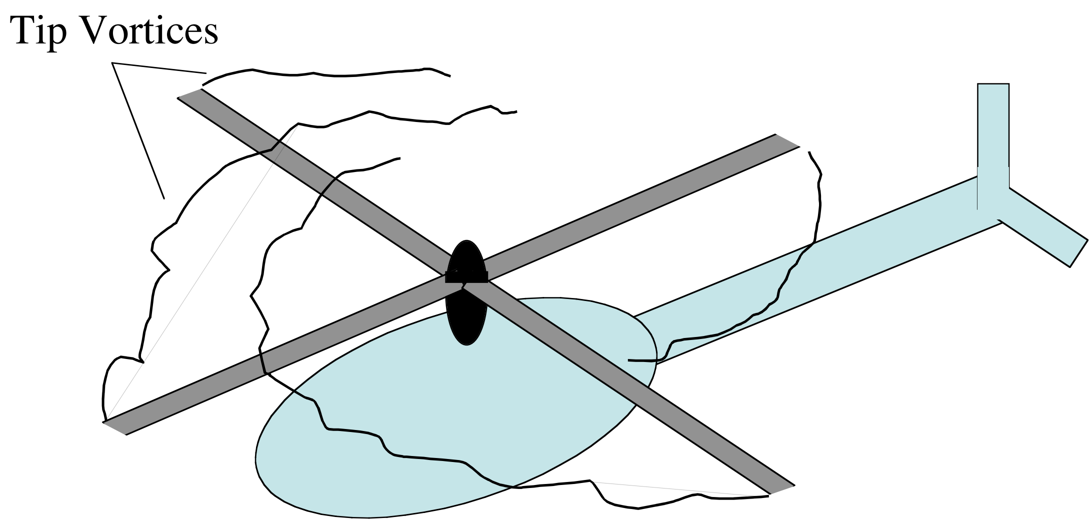

Figure 2.6: Illustration of Blade Vortex Interactions

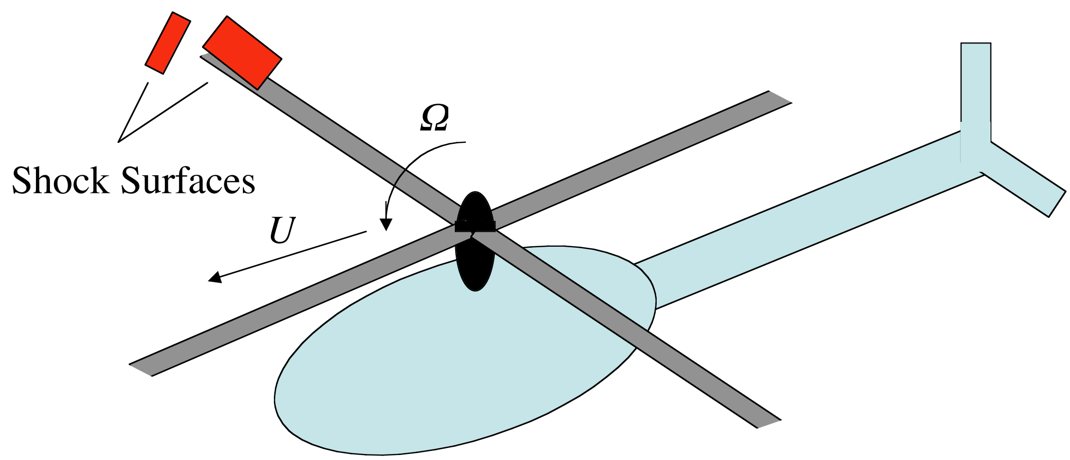

Figure 2.7: The shock surfaces which can produce quadrupole noise from rotating blades

2.4 Broadband Propeller Noise

Broadband rotor noise is always caused by random variations in blade loading resulting from the interaction of the blades with turbulence. The turbulence is often generated upstream of the propeller and ingested into the rotor, but it can also be self-generated in the blade boundary layer or at the blade tips. Inflow turbulence is important is on ships where the propellers operate in a very disturbed flow underneath the hull [2]. On helicopters, the trailing tip vortices that cause BVI noise can also cause high levels of turbulence that generate broadband noise and this is referred to as blade wake interaction noise (BWI) [1]. The turbulence in the blade boundary layer does not generate much sound by itself, but when it passes the blade trailing edge the local boundary conditions change rapidly, and significant sound generation can occur. This is called trailing edge noise (TE noise) [1,2] and is often considered as the most important mechanism of broadband noise generation in fans and propellers. Broadband noise from the turbulence at blade tips is not well understood at this time but may be important on low aspect ratio blades and should not be discounted as a possible noise source mechanism.

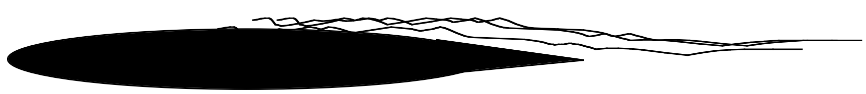

Figure 2.9 Trailing edge noise from the blade boundary layer interacting with the trailing edge of a blade.

2.5 Airboat Propeller Noise

In the above we have summarized all the important source mechanisms for propeller and rotor noise. It is clear from this discussion that there are a number of competing mechanisms that are all important. In any particular application or set of operational conditions there may be several equally significant mechanisms or one may completely dominate. There are however some important differences between airboat propellers and aircraft propellers or helicopter rotors. These are:

- Aircraft propellers and helicopter rotors have a variable pitch and run at design conditions, whereas airboat propellers operate at fixed pitch and use large variations in propeller rpm to control the craft.
- Aircraft propellers and helicopter rotors operate in a clean inflow, whereas airboat propellers operate downstream of a wire mesh cage, the engine and hub support structure.
- Aircraft propellers and helicopter rotors have blade thickness to chord ratios of 0.12, whereas airboat propellers are often thicker and have significant camber (or cupping).
- Aircraft propellers and helicopter rotors operate at forward speeds in excess of 70 mph, whereas airboat propellers operate at speeds from zero to ~50 mph.

In aircraft and helicopter applications the noise has been shown to scale directly with the blade tip Mach number. Hubbard [1] gives examples of how the amplitude of the pressure pulse generated by many different helicopter rotors can be collapsed onto a single curve as a function of blade tip Mach number. This type of data collapse can be expected when the inflow is clean and all the blades are of approximately the same thickness. It leads to the design requirement that the blade tip speed should be minimized for the required aerodynamic performance.

Hubbard[1] gives a section on the control of aircraft propeller noise in which it is noted that operating conditions can be modified to reduce noise, and the most significant reductions are obtained by reducing the tip speed. The other way to reduce noise is to reduce the disk loading which usually requires increasing the blade diameter, but this should not be done at the expense of increased tip speed. The objective is to minimize the blade tip speed for a given thrust and since thrust is proportional to (disk area x (tip speed)^2) this can be achieved by increasing the disk area and operating at a lower rpm. In general the overall noise in dB for conventional propellers operating at moderate flight speeds varies as 40 times the tip Mach number [3], and noise varies inversely with the disk area.

Blade design parameters that affect the noise are blade sweep, blade thickness, blade count, propeller diameter, blade shape and airfoil section. (Detailed formulae for the calculation of propeller noise can be found in Hubbard[1])

- Blade sweep: Increasing blade sweep reduces noise when the blade tip Mach number is high because it reduces shock associated noise. For airboat applications this is most probably not an issue because the tip Mach numbers rarely exceed 0.85. The sweep may also reduce the noise from the interaction of the blade with sudden velocity deficits if they occur along a radial line.
- Blade thickness: Thickness noise is important at high tip Mach numbers and reducing the blade volume at the tip is beneficial when the blade tip Mach number exceeds 0.7
- Blade Count: For a given thrust requirement increasing the blade count reduces the noise at the blade passage frequencies, but the blade passage frequency is increased. The noise reduction from increased blade numbers can therefore be offset by the dB(A) weighting scale which is more sensitive to higher frequencies. The high frequency broadband noise will also be proportional to blade number and so will increase with blade count.
- Blade shape and airfoil section: In general these parameters have a much larger effect on the aerodynamic performance of the propeller than they do on the noise. Hubbard suggests that modest improvements in the order of 3 dB can be achieved with varying amounts of aerodynamic performance loss.

Hubbard[1] also cautions that the above should only be considered in terms of the overall system performance. Noise reduction concepts are only useful if the aerodynamic performance of the propeller can be maintained, otherwise the propeller will be operated off design and the noise reductions will be mitigated.

One of the important differences between aircraft propellers and airboats is that the airboat propeller operates in a very disturbed airflow, and so high frequency broadband noise will be more important in airboat applications. Of particular importance is the wire mesh and engine cowling (or lack thereof). To minimize noise, obstructions to the flow should be at least one blade chord from the propeller disk. There is a lot of scope for improving the inflow into an airboat propeller and this will both improve performance and reduce noise, but the improvements can only be evaluated by detailed engineering design and testing. In general minimizing upstream disturbances will reduce noise.

In conclusion, all propeller noise sources are a function of blade tip speed and the most effective way to reduce propeller noise is to minimize the tip speed. Thin blade tips help to reduce the noise at high tip Mach numbers, but blade count, blade shape and section design have a much larger impact on the aerodynamic performance than they do on the noise.