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PROGRESS TOWARDS QUIETER CIVIL HELICOPTERS

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Abstract

A review of recent developments in helicopter noise reduction is presented. The paper includes a discussion of the present state of understanding of helicopter noise radiation mechanisms, and a review of actual noise reductions achieved by the manufacturers over the past decade. An analysis of progress achieved in meeting certification targets is given, together with an evaluation of the impact on design. Future trends in helicopter noise reduction based on current noise research programmes are discussed, and suggestions advanced for possible additional areas of study.

Introduction

Helicopter noise is widely recognised as one of the key features which prevent wider civil use of the helicopter. Indeed it may prohibit broad areas of civil use of helicopters in populated areas. For military helicopters noise radiation also has undesirable consequences, since it provides forewarning of the approach of the aircraft. However the principal focus of the present paper will be on noise from the civil rotorcraft.

Noise is undesirable. But it also acts as a focus for other concerns about helicopter usage. To quote a US Firechief "we never get complaints about noise when a helicopter is being used for rescue". To some extent the helicopter is the victim of its ability to land in confined areas. This means that any noise which it does produce can impinge directly on a local population. Nevertheless, this provides even greater incentive to reduce the noise output of the helicopter, so that it can fully exploit its key advantage as a transport vehicle, vertical take-off and landing.

Helicopter noise has been recognised as a problem for many years. Earlier work has been reviewed by Lowson (1973), George (1978), and more recently by JanakiRam (1990). There have been many initiatives to reduce it. Several of these have been industry wide. The earliest was the US "Fly Neighborly" program Cox (1971), see also Cox (1984). This grew from the recognition that a considerable reduction in radiated noise from the helicopter could be accomplished by careful choice of operating procedures. The sensitivity of the helicopter noise to operational aspects remains, and will be discussed later in this paper.

A more recent initiative was the NASA-AHS National Rotorcraft Noise Reduction Program, summarised by Childress(1991). This developed as a joint activity of US manufacturers following attempts by ICAO to set noise certification limits which would have excluded 80% of the helicopter fleet then operational. This work progressed through most of the 1980's, and has produced some valuable results. Reports have also been given by Sternfeld(1988), JanakiRam(1988), Shenoy(1989) and Martin(1989). The most recent substantial activity is the EC Helinoise programme which brings together researchers throughout Europe, from manufacturers, Universities, and Research Institutes in a combined theoretical and experimental programme. This work is still in progress, but initial results have been reported by Kloppel (1991).

The purpose of the present paper is to review the accomplishments to date, to analyse what is currently understood about helicopter noise radiation mechanisms, and to examine prospects for further developments.

The Objectives

Certification rules for helicopters are now in place. Development of any certification procedure is always a difficult compromise, and the present rules require that the helicopter meet levels at microphone locations of the order of 150m from the helicopter under three conditions: Take-off, Flyover, and Approach. The levels are a function of weight and are shown in Fig 1, which also gives data points for existing helicopters. It is not proposed to go into the rules in detail here. Details are given in the relevant ICAO documentation, or in papers such as Pike (1990). A brief review of the principal features of subjective response is given in the next section.

These rules provide the initial target for the manufacturer. In fact the real target is considerably more severe, even for certification requirements alone, since the manufacturer must design his aircraft to guarantee meeting the targets. Failure to meet the targets would prevent certification of the helicopter, and bring into question the whole of the investment in development. Thus any manufacturer must aim to provide near certainty of meeting the requirements. As will be seen subsequently, the state of the art of prediction of helicopter noise is far from perfect. This lack of knowledge forces design to a target level

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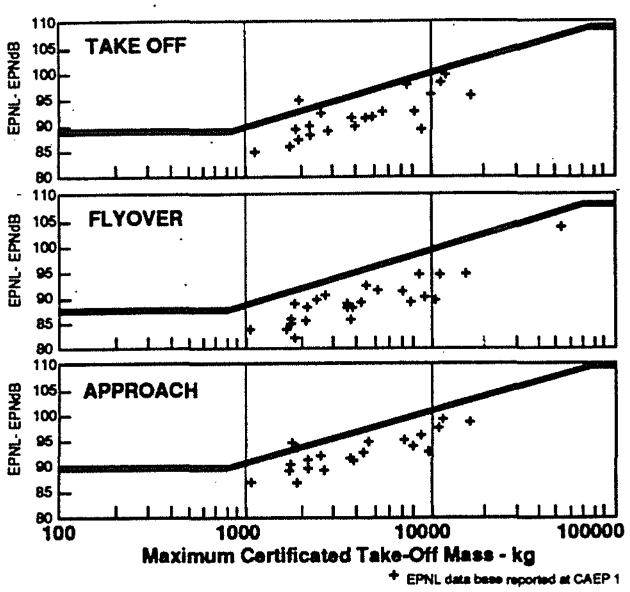

Figure 1 ICAO Helicopter Certification Requirements

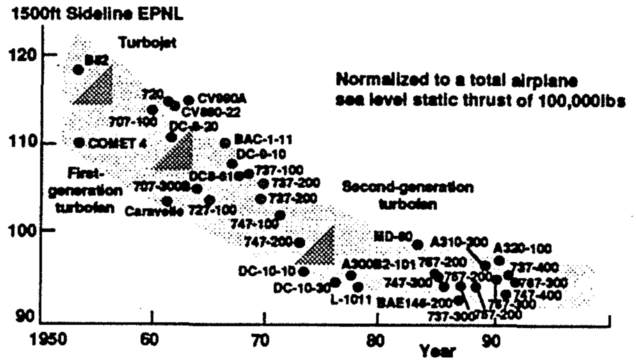

Figure 2 Noise Reduction by Civil Jet Aircraft

considerably below the certification requirements. On average therefore, new helicopters can be expected to be noticeably below the certification level.

There is a second target which is in the minds of the helicopter designer and user. This is the recognition that civil jet aircraft have demonstrated considerable noise reduction over the years. The rate of progress by such aircraft is shown in Fig 2. It can be argued that much of this benefit for fixed wing aircraft has been fortuitous, since the trend towards higher by-pass ratio necessary for better fuel economy coincides with reduced mean jet exhaust velocity and thus reduced noise output. Unfortunately, there is no equivalent relationship in the case of the helicopter. Further, some of the noise reduction solutions available to the jet engine, such as acoustic mufflers, are not feasible for helicopter rotor noise. Despite these issues it must be asked to what extent the helicopter industry can demonstrate a capability paralleling that of fixed wing aircraft.

A third target for the designer is to satisfy the local requirements which many communities have placed on heliport usage. Such local requirements often have a different form, and are frequently more stringent than the certification rules. Local requirements may place additional operating restrictions on noisier helicopters. They might also offer the opportunity to reduce noise by operating technique. The consequence is that noise radiated by a helicopter in any phase of flight, eg manoeuvre, not covered by certification, may nevertheless be an important target for control.

First Principles

Noise from a helicopter is only a major issue because of the incredible sensitivity of the human ear. A typical medium size helicopter utilises around 1MW of power for flight, but only produces around 100W of power in the form of noise. The acoustic radiation processes are already very inefficient. Since the human ear is able to distinguish sound levels which correspond to an estimated impact of a single molecule on the eardrum, these rather small levels of energy become of considerable subjective significance.

It is important also to recognise that the physical processes of noise radiation are essentially parallel to other aero-mechanical phenomena. Reduction of acoustic power radiated by a helicopter is, in principle, no easier (or harder) than reducing the power used in other ways. The difficulties spring principally from the nature of human response. The logarithmic decibel (dB) scale is used to mimic human response to noise, and on this scale a halving of noise output corresponds to a reduction of 3dB. Experiments demonstrate that this level of change is only just distinguishable by a single individual in a laboratory. On the other hand, tests also demonstrate that, for a whole community, such levels of change lead to measurable reductions in the proportion of those annoyed.

For helicopter noise the frequency response of the human ear plays a crucial role. The ear responds most strongly to frequencies in the 1000 - 4000 Hz range. A helicopter produces most of its sound output at much lower frequencies than this. For example, a typical blade passing frequency may be around 20Hz, which is below the normal range of hearing. Over most of the low frequency range the sensitivity of the ear increases as the square of the frequency, so that increasing the frequency of the sound, for example by increase of rotor speed, has a direct effect on the audibility of the sound produced. In the case of rotor speed an increase will also increase the absolute level of the sound radiated, and thus provide a double disadvantage. PNdB or dBA scales are calculation methods which attempt to mimic the frequency response of the ear so that an estimate of annoyance can be made. Further details can be found in standard texts on acoustics, eg Kinsler and Frey (1967), Kryter (1970).

A final vital issue for helicopter noise is the fact that many of the more critical noise conditions correspond to the production of strongly impulsive

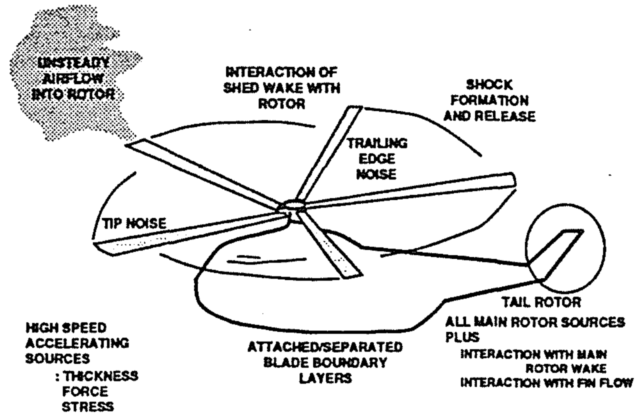

Figure 3 Basic Mechanisms of Rotor Noise Generation

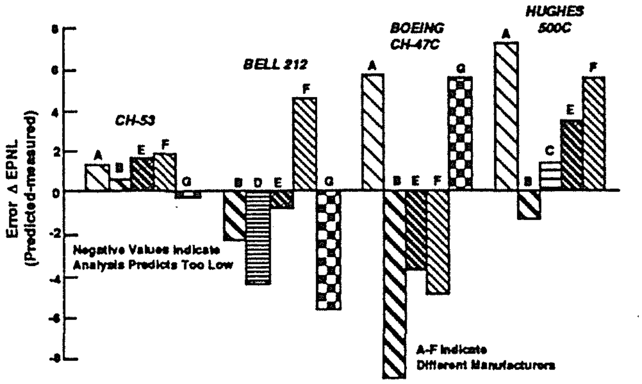

Figure 4 Helicopter Noise Prediction Capability

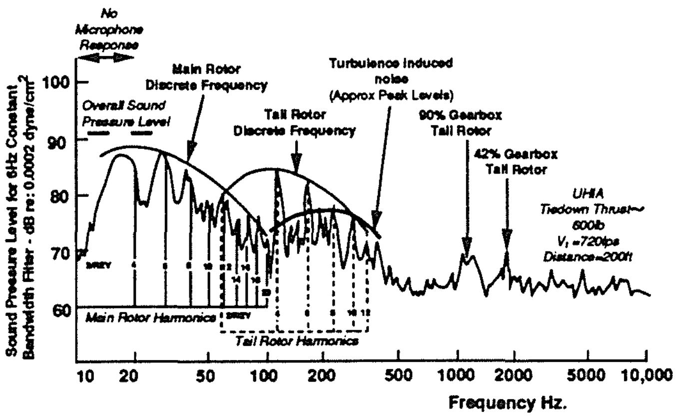

Figure 5 A Helicopter Noise Spectrum

noise, observed as a series of sharp repetitive cracks. There has been much discussion about the subjective effect of such noise, and of the need for special corrections to noise measures to account for the effect. A major study by Ollerhead (1982) demonstrated that, because impulsive noise was also associated with a forward throw, one of the principal effects under impulsive conditions was to extend the time over which the noise signal could be heard. A standard measure for aircraft noise including duration correction was already in being, the EPNdB (Equivalent Perceived Noise decibel). Ollerhead showed that this measure gave good correlation with noise annoyance tests carried out in the laboratory for recorded helicopter flyovers. This measure is the one used for certification, as discussed in the last paragraph. Almost certainly there are further subjective effects of the impulsive nature of much helicopter noise. But for the designer the message is clear: remove any impulsive noise content. As will be seen this is a far from trivial task.

Mechanisms

In order to discuss what can be done it is first necessary to identify the mechanisms which cause noise radiation from helicopters. Figure 3 gives a representation of the principal rotor noise sources. It will be observed that there are many different sources of noise radiation and that these are of quite different types. In following sections of the paper each source will be reviewed in turn, giving both the present state of understanding and the current ability to control the noise caused.

Figure 4 shows the result of a round robin exercise in which several manufacturers attempted to predict the noise from a selection of helicopters. Although this work is a few years old it provides an interesting measure of the state of understanding. The predictions have an error which averages around 5 dB. It may be assumed that each manufacturer had a prediction method which gave a reasonably accurate measure of the noise output of their own helicopters. Also, there is fairly good agreement between workers in the field about basic laws for noise variation with such crucial parameters as number of blades, tip speed, all up weight etc. However each manufacturer has a different approach to the details of design based on his own experience. Figure 4 thus also demonstrates that the difference between different detail design approaches can be very substantial in noise terms. Unfortunately it is not yet at all clear what causes these differences.

Figure 5 gives a frequency analysis of the sound from a typical helicopter. At low frequency the noise is dominated by the noise from the main rotor. This occurs at the blade passing frequency and its harmonics. At intermediate frequencies the noise is dominated by noise from the tail rotor, which occurs at the tail rotor passing frequency and its harmonics. At higher frequencies the noise is more broad band in nature, but comes principally from the main rotor. Other sources of noise from the helicopter, such as the engine, can also be of importance. In Figure 5 radiation from the gearbox can be identified.

Naturally, the significance of the noise sources will vary from design to design, but for a typical helicopter, the order of importance of the noise sources is

- High speed impulsive noise (when it occurs)
- Blade vortex interaction noise during manoeuvre or low speed descent
- Turbulence induced noise
- Tail rotor noise
- Other main rotor discrete frequency noise
- Other sources such as engine or gearbox

The relationship between the noise sources listed above, the physical features causing the noise shown

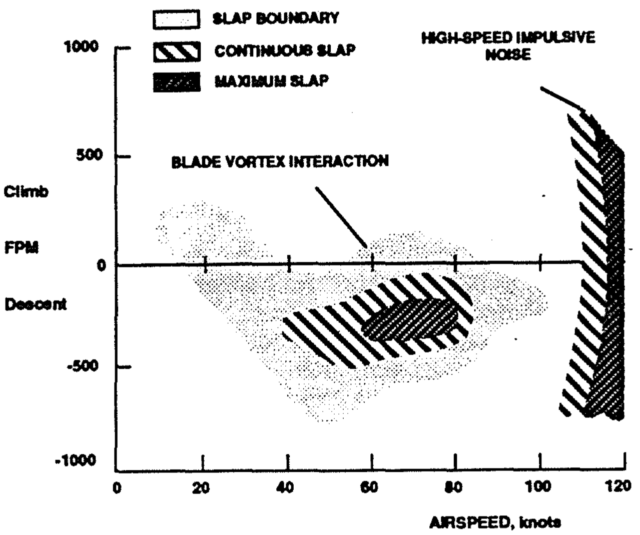

Figure 6 Operating Effects on Noise Radiation

in Fig 3, and the resultant output spectrum shown in Fig 5 will be explored in detail in subsequent sections of this paper.

One major area of importance for the helicopter is the influence of flight regime on noise radiation. An example for the UH-1 helicopter, Cox (1971), is shown in Figure 6. This defines parts of the flight envelope which are liable to result in high noise radiation. It will be observed that there are two major areas of interest. At high forward speeds the helicopter creates significant noise levels. This is a forward throw of noise due to shock formation by the advancing blade, sometimes known as advancing blade slap or HSI (high speed impulsive) noise. Operationally it may be avoided by avoiding high speed flight regimes. Data presented by Childress(1991) shows that careful choice of flight path to avoid the more intense noise regimes can give benefits of up to 6dB over the approach levels certified. From the design viewpoint the occurrence of the noise may be delayed by reducing rotor tip speed, and by thinner blades especially near the tip. Mechanisms will be discussed in more detail below.

It can also be seen that substantial noise levels are generated during low speed descent. This is due to the interaction of the rotor with its own vortex wake, and generates a typical "blade slap" noise. This noise mechanism is frequently referred to as BVI (blade-vortex interaction). The approach certification case shown in Figure 1 requires descent at a 6^{o} angle, chosen to coincide with a regime which is especially significant for noise generation on most helicopters. The same mechanism can give rise to considerable levels of noise radiaton during manoeuvres.

Fig 6 also suggests rather strongly that one important method for minimising noise radiation to the community is to avoid operating at the conditions which cause excessive noise levels. This concept was the basis for the original US "Fly Neighborly" program, and retains its validity today. However a major objective for the designer must be to create a rotor system which is immune to BVI radiation. This would both reduce the level for a critical certification case, and permit better access to heliports, where approach noise is frequently the critical issue in acceptance.

Theory

First the basic theory underlying the noise radiation will be outlined. An important, and now classical, description of the sound radiation by aerodynamic sources is given by the Lighthill (1952) equation. His approach was to rewrite the Navier Stokes equations, which exactly describe fluid flow, to extract the acoustic propagation terms on the left hand side. This meant that the remaining terms on the right hand side of the equation can be treated as acoustic sources. Although this equation contains no approximations, some form of approximation is necessary to obtain useful solutions. Unfortunately the subtlety of the equation often means that the form of the approximations used are extremely obscure. Thus the Lighthill equation must be used with considerable caution. Difficulties are likely to be encountered when compressibility terms become significant in the "source" terms on the right hand side of the equation.

Today, it is usual to start from the solution of the Lighthill equation in the form given by Ffowcs Williams and Hawkings (1969), which gives the radiated sound pressure in terms of three integrals viz:

$$4\pi p = \underbrace{\int_S \left[\frac{\rho_o}{r(1-M_r)} \frac{\partial}{\partial t} \left(\frac{v_i n_i}{1-M_r} \right) \right]_{ret} dS}_{thickness\ integral}$$

$$+ \underbrace{\int_S \left[\frac{r_i}{a_o r^2 (1-M_r)} \frac{\partial}{\partial t} \left(\frac{p_{ij} n_j}{1-M_r} \right) \right]_{ret} dS}_{loading\ integral}$$

$$+ \underbrace{\int_V \left[\frac{r_i r_j}{a_o^2 r^3 (1-M_r)} \frac{\partial}{\partial t} \left\{ \frac{1}{(1-M_r)} \frac{\partial}{\partial t} \left(\frac{T_{ij}}{1-M_r} \right) \right\} \right]_{ret} dV}_{quadrupole\ integral}$$

The equation has been written in a far field radiation form to bring out the importance of the Doppler shift ($1-M_r$) terms. As the component of Mach number in the direction of the observer M_r approaches 1, then the equations demonstrate there will be a substantial increase in sound radiation.

Each of these integrals has a physical meaning. The first term is that due to blade thickness, and is calculated by an integration of the local normal velocities over the surface of the rotor blades. The second term is that due to local forces on the blade, and requires an integration of local pressures over the blade surface. The third term is a volume

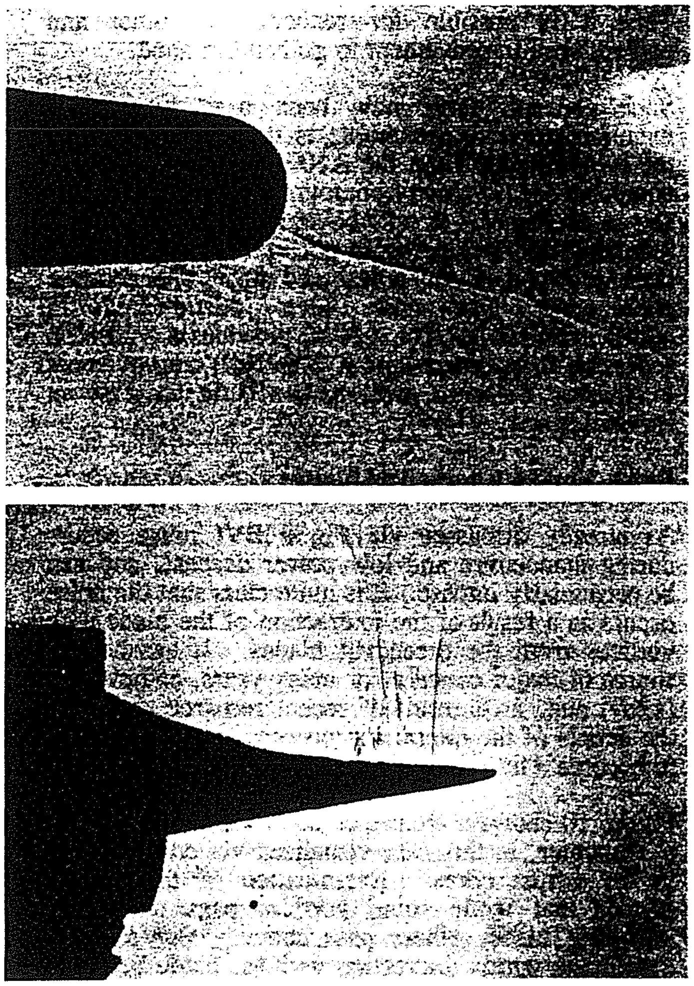

Figure 7 Shadowgraph Visualisations of Noise on a Rotor at a Tip Mach Number of 0.9

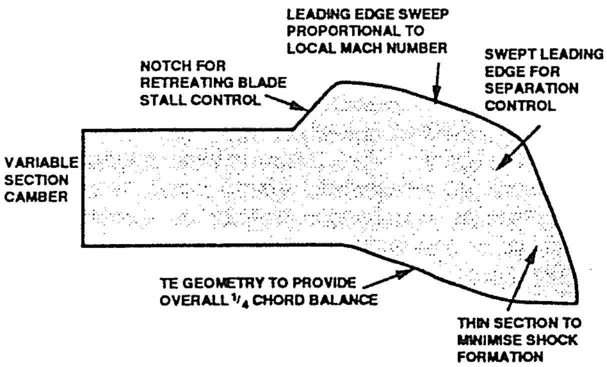

Figure 8 BERP Blade Features

integral of the remaining "quadrupole terms". This term is deceptively simple in appearance. Such quadrupole sources in fact represent the whole remaining aerodynamics of the rotor flow.

The Lighthill or Ffowcs Williams and Hawkings approaches are essentially formal, and are not the only methods for prediction of the noise. Although their formulation identifies some forms of noise radiation with precision, it conceals effects such as unsteady thickness noise, Hawkings (1977), Glegg (1987), and is complex or even actively misleading for consideration of effects of shocks. An alternative approach is via matched asymptotic expansions eg Crow (1970), Obermeier (1979) which, in many ways, reflects more of the physical reality of the aero-acoustic linkage.

Any full unsteady compressible calculation of the flow will implicitly include acoustic radiation terms. Thus an alternative approach is to perform this calculation, for example via a computer, over a suitable volume of the flow, and to use Kirchoff's integral equation (in effect the first two terms of the Ffowcs Williams and Hawkings equation given above) to relate the surface pressures and velocities on the bounding surface to the far field noise. Alternatively the whole aero-acoustic field can be computed directly. This is possible for carefully selected model cases by using the full power of modern computing equipment. Further comments on theoretical approaches are given in the last section of this paper.

High Speed Impulsive Noise

The physical cause of the noise radiation from a rotor at high speed can be seen rather clearly in the shadowgraph pictures of Figure 7. This is due to W.F. Hilton, and is one of a substantial set of shadowgraphs taken of a propeller at a test stand in 1934. A selection of his shadowgraphs has been published, Hilton (1938). Fig 7 was taken at a tip Mach number of 0.9, ie below the speed of sound. It will be observed that the flow around the rotor includes a significant shock system attached to the rotor and extending out beyond the end of the rotor disc. This feature is of extreme importance acoustically, since the shock wave field will be rotating at a local velocity exceeding the speed of sound somewhat outboard of the rotor. Once the pressure field reaches the "sonic circle" it will radiate directly to the far field at unit efficiency (apart from a relatively small non-linear decay). Thus the occurrence of such a shock system presages considerable increase in the sound level generated by the rotor, and is the cause of the major increase of noise from the advancing blade identified in Fig 6.

Forty years later equivalent results were also obtained by Tangler (1977) and, more recently, the process of shock formation beyond the blade has been termed "delocalisation", since the noise radiation is no longer a function of the local pressures and velocities at the blade. The complexity of the shock field on the rotor under these conditions is demonstrated by Fig 7. It is surprising that no further attempts appear to have been made to record the actual wave field from a rotor. However many of the mechanisms of impulsive noise generation have been identified. A complete review was given by Schmitz and Yu (1986).

Recognition of this feature was an important part of the design of the Westland "BERP" (British Experimental Rotor Programme) blade. (Fig 8), Lowson et al(1976). The detail aerodynamics of this

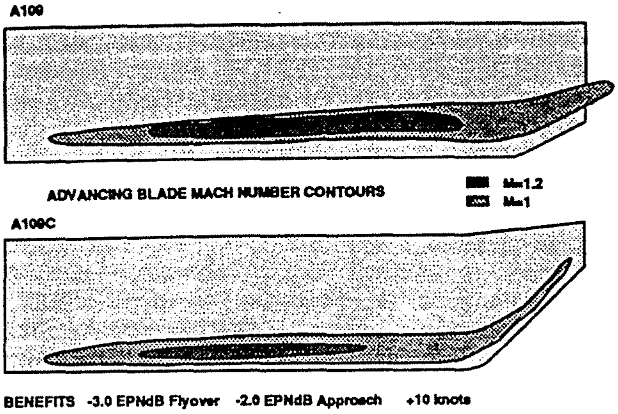

Figure 9 Noise reduction on the Agusta A109 via Aerodynamic Redesign of the Tip

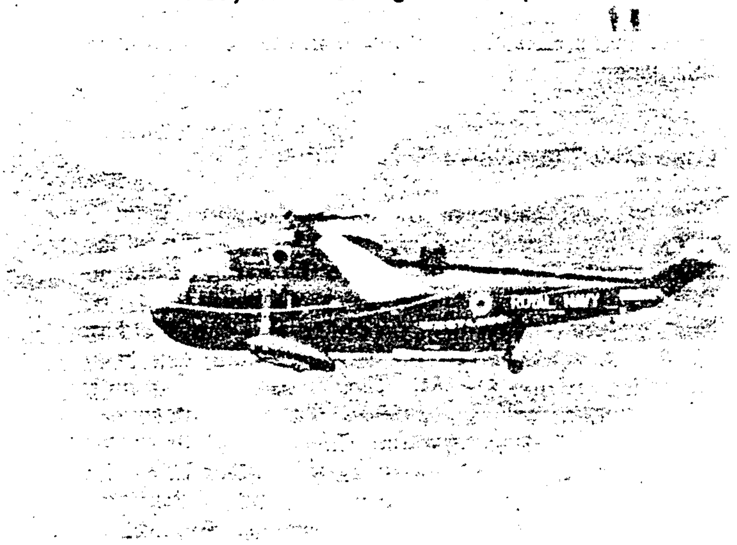

Figure 10 Visualisation of the Shed Vortex System on a Sea King Helicopter

blade has been described by Perry (1987), but the acoustic features built into the design have only been partially noted. Original computations of the flow on a conventional tip operating at a tip speed of Mach 0.9 suggested that velocities over the blade could be as high as M 1.3. This would have generated a considerable shock system beyond the blade. The BERP tip was designed to remove this by a combination of sweep and reduced thickness. The tip was reduced in thickness until computation indicated that all velocities would be below Mach 1 anywhere on the tip at the design tip Mach number, cf Lowson and Balmford (1980). This aerodynamic computation was combined with acoustic analysis which predicted a reduction of 13.5 dB in the level of the negative impulsive peak pressure radiated by the BERP tip compared to a conventional rectangular blade.

Such a design has obvious benefits in reducing transonic drag rise and associated control load problems at max forward speed. As is well known, this rotor system was the basis for a successful attempt on the absolute speed record for helicopters. Pike (1989) revealed that this form of tip also reduces the noise in low speed descent by up to 5dB.

Thus it is possible for reduction of noise and performance improvement to go hand in hand.

Such concepts have now been used by several manufacturers. An example is the development of the A109C blade from the A109A by Agusta. The computed local velocity contours at the blade tip are shown in Fig 9. It will be observed that a useful reduction in the supersonic portion of the blade has been achieved in the redesigned tip. The acoustic consequence has now been documented in certification trials. The A109C provides a 3 EPNdB reduction in approach and a 2 EPNdB improvement in flyover noise as well as a 10 kt increase in forward speed.

Blade Vortex Interaction Noise

As already discussed via Fig 6 BVI noise occurs during manoeuvre and low power descent, and can be particularly intense. It is quite clear that the noise occurs as a result of the interaction of the blade with vortices from the preceding blades. It has been a source of major concern for many years, cf Leverton (1989) and, as a result of recent research, some of the details of the interaction process are now starting to become a little better understood.

Figure 10 shows a picture of the vortex system from a helicopter, in this case visualised via condensation in the vortex cores. Examination of the picture reveals that while some vortices pass under the following blade, others pass above. For forward motion the vortex interaction with the blade becomes even more complex.

Figure 11 shows the original sketch due to Tangler (1977) for this case. The vortex wake is basically cycloidal in form but distorted by the inflow and self interactions. The interaction of the blade with the wake can occur on both advancing and retreating blades at higher advance ratios. Tangler showed that different rates of descent were associated with interaction at different parts of the rotor wake, as shown in the figure. The most severe interactions were in partial power descent, points 3 and 4 on Fig 11. The largest interaction might be anticipated when the vortex is almost parallel with the aerofoil. Experiments confirmed that this is the case, Cox (1977). The process has recently been thoroughly investigated in a series of tests in DNW cf Martin, Marcolini, Splettstoesser and Schultz(1990), who were able to define the location of the interaction process with some precision.

It appears that, contrary to intuitive expectations, the most severe noise output does not occur when a vortex is cut by a following blade, but rather when the induced velocities of the vortex system on the blade reach a maximum.

Figure 11, and pictures such as that of Figure 10, have led to a number of models which attempt to predict the strength and position of the trailing vortex and the consequent interaction with the following blades. Most workers follow the model first put

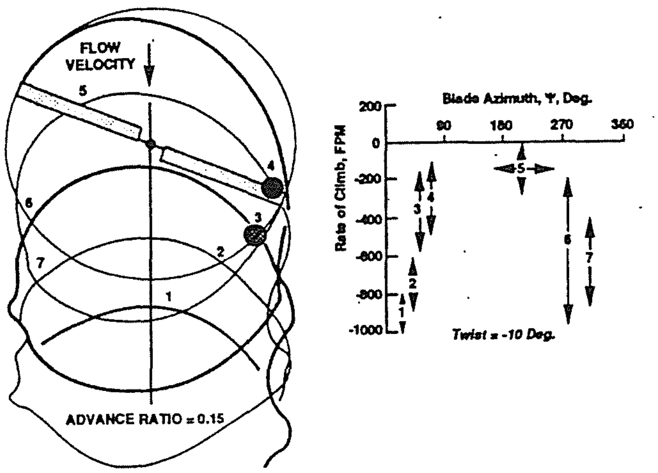

Figure 11 Blade Vortex Interactions

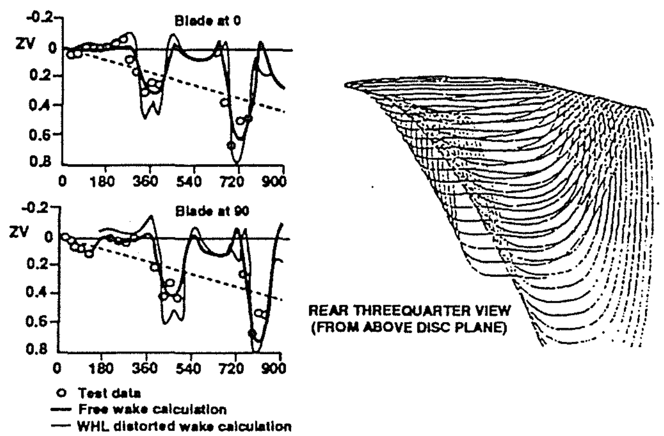

Figure 12 A Model for the Vortex Wake and Predicted Airload Comparisons

forward by Scully (1967) . He assumed that the whole bound vortex resulting from the rotor blade lift was shed from the tip. This assumption allows direct estimation of the vortex strength. The subsequent motion of the vortex can then be computed by the well known equations governing vortex dynamics. One empirical parameter that has to be included is a vortex core size. This parameter has little physical significance, and is chosen to remove the instabilities which are inherent in any concentrated vortex with a sufficiently small core, Batchelor (1967).

The essential geometry of Scully type models is due to the cycloidal nature of the shed vortex pattern resulting from forward motion of the blade. This is combined with an overall rotor downwash field which resembles that from an equivalent wing. The downwash reaches a maximum towards the centre but is small or even negative towards the outer parts. Recent work has extended this model to a point where it can provide remarkably good predictions of noise radiation under some conditions. Figure 12 gives some results due to Beddoes (1985)(1989). The basic geometry corresponds to the broad description just given. It can be seen that the effect is that much of the trailing vortex system is left close to the path of the following blade. Beddoes' model has provided acoustic predictions for the low power descent case which are within about a dB of experimental measurement, cf Pike (1987).

These models are in many ways very different from the real wake leaving a rotor. For example a real rotor wake will include trailing vorticity shed along the entire span. The shed vortex system must also include vorticity shed parallel to the trailing edge, corresponding to the considerable change in bound vorticity as the blade goes through its cyclic lift changes. Thus it is somewhat surprising that these models can be so effective for prediction.

The reason for their effectiveness can be inferred by an inspection of the geometry of figure 12. By the time of interaction with the following blade much of the trailing vorticity will have been rolled up into a strong spiral system. A useful approximate model of this spiral system is a concentrated vortex. The same approximation is used for the shed vortex system on swept wings at high angle of attack with good accuracy. For a helicopter this model may be expected to give good results provided the following blade is not too close to the shed vortex. Not only can the model give good estimates of induced force, but it will give reasonable estimates for phase speed of the interaction along the blade. This latter parameter is of particular importance for determining the acoustic radiation efficiency of the induced loads. However it seems unlikely that the same model can be successful for cases in which the vortex is actually intersected by the following blade.

For the more intense forms of BVI noise it was always apparent subjectively that some form of shock radiation process was involved. Recent theoretical, Obermeier(1991), and experimental - Meier,Schievelbusch,and Lent (1990), Lent et al (1990) - studies of the interaction of a vortex with a transonic aerofoil have demonstrated this shock formation and release process for BVI. The principal mechanisms are shown in Figure 13 for an idealised two dimensional case. It emerges that there are three separate sources of shock radiation. The first is a "compressibility" shock formed at the nose which is formed as the vortex passes beneath the aerofoil. The second is the "transonic" shock formed on the underside of the aerofoil due to the presence of local supersonic flow. The third is a shock which can be caused by separation from the aerofoil at sufficiently large induced angles of attack. The direction of propagation of these shocks differs. The compressibility shock radiates forward, while the transonic shock radiates downwards at about 30°.

The compressibility shock seems likely to be a consequence of conventional acoustic radiation processes intensified by the transonic conditions, relating directly to unsteady thickness noise radiation by the rotor. However the transonic shock is a separate phenomenon. Meier et al(1990) correlated their results against a simple model which combined the maximum Mach number generated at the aerofoil

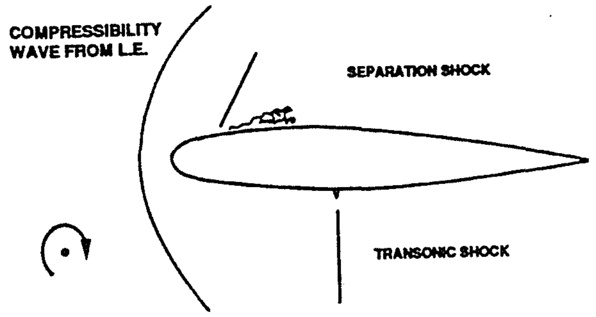

Figure 13 Shock Radiation Processes for BVI

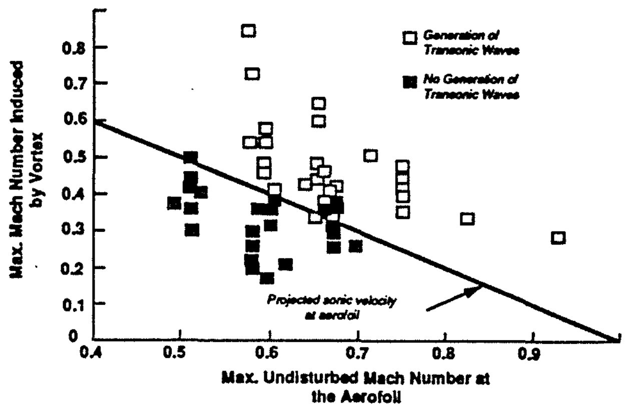

Figure 14 Generation of Transonic Shock Waves by Vortex Interaction

lower surface in steady flow with the maximum disturbance Mach number induced at the aerofoil surface by the passing vortex. The latter figure was estimated directly from the known strength and position of the vortex. Figure 14 is a replot of their data from their tests which identifies which conditions gave rise to transonic wave generation. It can be observed that the radiation of the transonic wave corresponds directly to the occurrence of sonic flow on the under surface of the aerofoil.

Tijdeman (1977) studied shock formation on a high speed aerofoil with an oscillating flap. He found that for low transonic Mach numbers (0.85), where the flow was just supercritical, shocks which formed on the aerofoil would be released and propagate upstream. At higher steady Mach numbers Tijdeman found that the shocks remained attached to the aerofoil. However, Figure 14 shows that, in all cases with supersonic flow, shocks formed from vortex inteaction will be released from the aerofoil to propagate to the observer. This gives a particularly simple rule for the designer: ensure that the combination of aerofoil supervelocity and vortex induced velocity remains subsonic. This may be the reason for the effectiveness of the BERP design in reducing BVI noise.

Similar results have also been obtained by Lyrintzis and George (1989) using transonic small disturbance theory. They call the compressibility and transonic waves Type I and II respectively. Their analysis gives a M^6 increase in sound with Mach number, but this seems too low to be fully representative of the physics of the process. Their work also shows that the strength of the shocks formed is related to the thickness of the nose of the aerofoil. This provides a further line of design attack on BVI noise reduction.

It is interesting to note that the geometry of the shed vortex requires that the induced velocity above the vortex is in the direction of flow while below the vortex it is against the flow. Thus the most severe increase in noise will occur when the vortex passes below the aerofoil, and increases local velocities on the blade.

All of the work on BVI just discussed relates to the two dimensional case, which is far easier to study both experimentally and theoretically. This also corresponds to an important practical case of intense BVI noise. However, most blade vortex interactions occur with the blade and vortex inclined at an angle, so that three dimensional effects are of importance. One critical effect pointed out by Lowson and Ollerhead (1968) and used by Widnall (1971) is that the trace velocity of the vortex along the blade can easily become supersonic. The appearance of sonic trace velocities must correlate with major increases in radiation efficiency, and with radiation to particular directions in the far field. Once a robust aerodynamic model is available it should be possible to calculate these effects directly. More recently, George and Chang (1984) have used this idea to give useful physical explanations of likely sound radiation strengths and directivities.

It may have been noted that the basic sound generation mechanisms discussed so far for the BVI case have been inconsistent. The Beddoes model uses blade loading, while the two dimensional models appear to relate more directly to surface displacement conditions, and in any case include the effects of shocks. In both cases reasonable agreement with experiment is observed. It is believed that this arises because the essential features of the radiation process are kinematic, and depend on the Doppler $(1-M_r)$ terms in the radiation equations. Further there is obviously a general relation between high local velocities and large changes in pressure. Thus use of any form of source term is likely to give similar answers. Unfortunately this is not a basis for design for noise control.

It has been demonstrated that BVI noise can be affected noticeably by design changes. An example is shown in Figure 15, which gives results from tests undertaken by ONERA/Aerospatiale, Streby and Marze (1991). It can be observed that the effects of tip modifications on noise radiation are pronounced, showing around a 6dB benefit in particular flight conditions. It can be seen that different tips have their maximum benefit in different conditions, with each tip actually being the loudest under some operating condition.

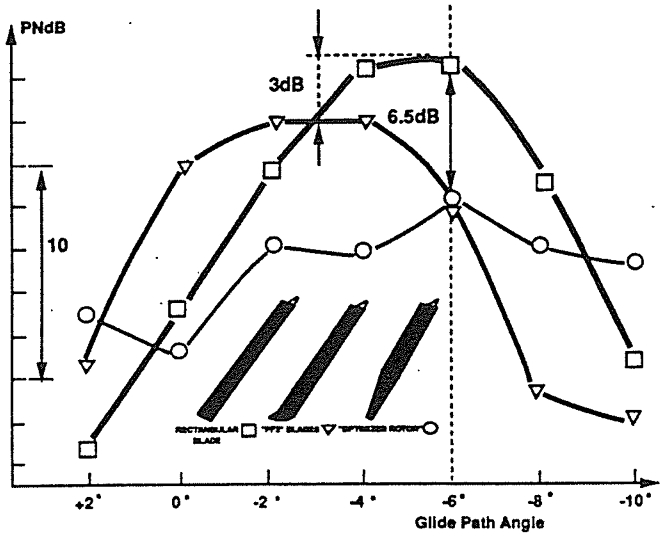

Figure 15 Effects of Tip Modifications on Noise Radiation

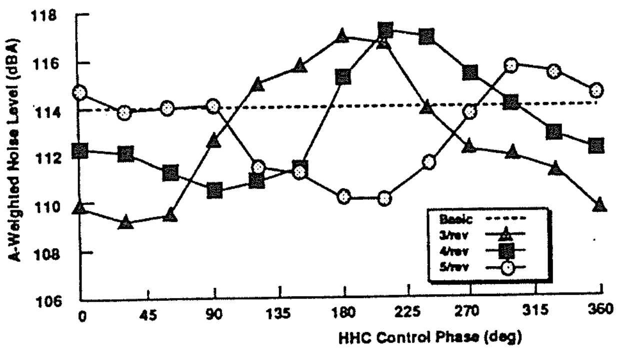

Figure 16 Results of Experiments on Higher Harmonic Control

It seems that the reason for the results shown in Figure 15 must lie principally in the modification of the trailing vortex structure caused by the tips (see also Fig 11 and associated discussion). It must also be recognised that no current analytic technique is able to predict these changes. This obviously offers a major opportunity and challenge for analysts.

A second known method for minimising BVI is via Higher Harmonic Control (HHC). Here inputs are made to the rotor system at a frequency greater than the cyclic rate of 1/rev. These can be inserted either below the swash plate or directly at the blade (individual blade control). Several tests, Brooks et al (1990), Spletstoesser et al (1990), have demonstrated that a suitably phased input of higher harmonic excitation does cause a reduction in the BVI noise. As shown in Figure 16, this can be as much as 5dB. Incorrect phase can result in an increase of noise output. The first papers on HHC indicated that reduction of noise was associated with increase in vibration, eg Splettstoesser et al(1990), but reports of more recent work, Brooks et al (1991), suggest that reductions in noise and vibration can be obtained simultaneously.

The mechanisms by which HHC causes noise reduction are not yet entirely clear. There are two candidate models. The first assumes that key effect of HHC is on the shed vortex wake, either its strength or position. The second is based on reducing the angle of attack of the blade as it is undergoing BVI. This second mechanism makes further implicit assumptions since, to first order, the level of unsteady force on the blade is the same for high or low incidence. However, if the blade flows were approaching sonic, then the local shock formation due to vortex interaction could be reduced at lower angle of attack (Fig 14). The second mechanism therefore implies a shock radiation process for the BVI noise, although Hardin and Lambkin (1987) have suggested that the level of response is directly related to overall lift even for a subsonic case. This is not the mechanism assumed in the present prediction models, eg that of Beddoes (1985). Attempts to model HHC results using a wake interaction and loading model produced rather mixed results, Brooks et al (1990).

At present the evidence is not sufficiently clear to be able form a definitive judgement about the mechanisms underlying HHC results. However it may be more than a coincidence that the levels of noise reduction achieved by tip modifications and by HHC are about the same viz: 5-6 dB. Referring back to Figure 3 it may also be observed that the error in prediction from different manufacturers is of about the same magnitude. It is not unreasonable to speculate that these errors are due to genuine differences in design approach reflecting the same underlying physical issues as appear in the tip or HHC results. It seems that there may be a 6dB benefit available to the designer once these issues are fully understood.

Turbulence Induced Noise

The noise caused by the interaction of turbulence with a rotor takes many forms. Originally this source was referred to as "vortex noise", since it was believed that it was dominated by a form of Karman vortex street shed from the trailing edge. It was then retitled "broad band noise", and much of the published work uses these words to describe the phenomena. Reviews by Brooks and Schlinker (1983) and George and Chou (1984) give useful summaries of the earlier work. However since, as will be shown below, turbulence can cause discrete frequency as well as broad band noise, a new description "turbulence induced noise" is used here.

Many of the relevant fundamental studies were motivated by fixed wing noise problems, since it was recognised that broad band "self noise" might provide a lower bound to noise reduction for jet aircraft. Virtually all the mechanisms which cause self noise radiation on fixed wing aircraft reappear on helicopters, albeit in a different frequency range.

Under many practical circumstances the most important noise source on a helicopter is ingestion of

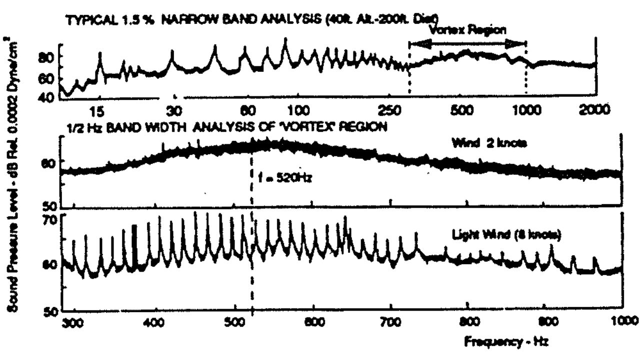

Figure 17 Effect of Wind on Helicopter Noise Radiation

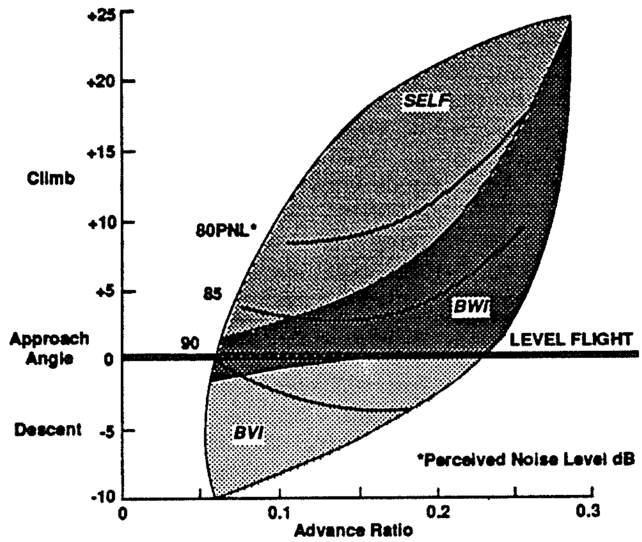

Figure 18 Noise Radiation Mechanisms Under Various Operating Conditions

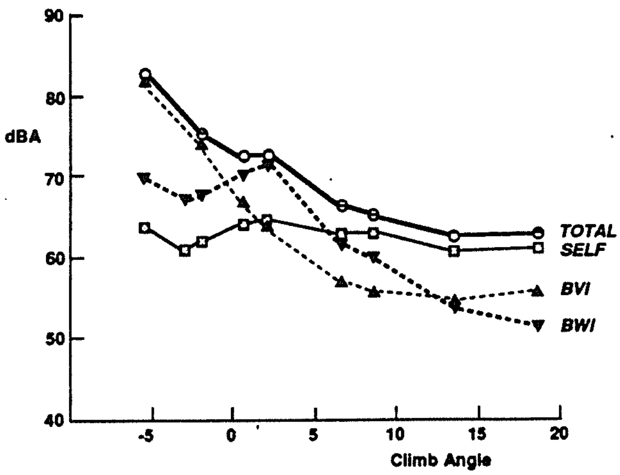

Figure 19 An Estimate of Source Contributions to Rotor Noise

turbulence by the rotor. Unsteady forces caused on the blades by turbulence ingestion are a direct source of radiated noise. Figure 17, taken from Leverton (1969), shows the rotor noise spectrum under exceptionally low wind conditions, and also with a modest wind speed. It will be observed that at low wind conditions there is a clear broad band background noise level. This confirms the existence of other broad band sources which will be discussed below. Leverton divided these into two categories, high frequency and low frequency.

Fig 17 also shows that for modest wind speeds discrete frequency peaks appear in the spectrum. These also result from the turbulence ingestion, via the acceleration of the eddies towards the rotor. This can provide sufficient stretching that the eddy can become correlated from blade to blade, as originally pointed out by Lowson (1973). As a result the ingestion of turbulence by the rotor leads to both discrete frequency and, at higher freqencies, broad band noise radiation. Theories for this were given by Homicz and George (1974), and a complete theory for the source has been given by Simonich et al (1986). They showed that the dominant parameter in the level of noise radiated was the stability of the atmosphere, with a 20dB increase in acoustic output between stable and unstable conditions. Unfortunately this parameter is not under the control of the designer. It may also be noted that helicopter noise is normally a problem in city operation where the turbulence parameters may differ considerably from the ideal cases of the model. Simonich et al also showed that the highest levels of noise occurred in low speed vertical ascent, with the quietest condition being high speed forward flight. Simonich, Schlinker and Amiet (1988) gave an experimental assessment of their prediction methods, and found an overprediction of discrete frequencies, and underprediction of higher frequency broad band noise. Since this source is of considerable significance in both design and in test evaluation further comparisons are certainly needed.

A second source of turbulence interaction on the blades is the shed wake. This has been termed Blade-Wake Interaction (BWI) noise. A full description is given by Brooks Marcolini and Pope (1989). They also give diagrams indicating the areas of the flight envelope under which various forms of noise were most important for their tests. A version of this is shown as Figure 18. Prediction models for this form of noise are available, although their success depends on the existence of accurate wake geometry models. Brooks, Jolly and Marcolini (1988) used further data from a DNW model rotor test to determine the relative contributions of various forms of noise source. Their results are replotted in Figure 19, and indicate that the broad band noise due to blade wake interaction is the most important source at normal flight conditions.

Figure 18 suggests that the principal source of noise under climb conditions is the direct self noise of the rotor blades. From the same results Brooks, Marcolini, and Pope (1989) suggested that the BWI noise was more significant than the self noise for frequencies below about 30 times the blade passing frequency (840 Hz full scale for these tests). Simonich et al (1986) suggest, following analysis for a single representative case, that the discrete frequencies due to turbulence ingestion will be more important than broad band self noise from the trailing edge for frequencies below 30 times blade passing. It appears that for real helicopters the BWI and turbulence ingestion sources may be important in similar frequency regimes. This explains the considerable difficulties encountered by earlier investigators trying to disentangle the mechanisms underlying noise radiation in this frequency range.

The third source of broad band noise is due to the direct radiation from the boundary layers on the blades. This is generally most important at the higher frequencies. Direct radiation from the pressure fluctuations under a turbulent boundary layer is surprisingly inefficient, basically because the pressure traces on the blade are moving at low speed, perhaps as low as half of free stream eg Lowson (1965), and are thus well below sonic. It has been shown by many authors, eg Ffowcs Williams and Hall (1970), that the key effect under these conditions is the interaction of the eddy with the trailing edge. This can be thought of in two ways: first, as the increased acoustic efficiency resulting from the diffraction around the trailing edge, or second, the radiation from the local fluctuating force terms near the trailing edge caused by passage of local turbulence. It was shown by Howe (1978) that these two approaches were essentially equivalent.

A complete prediction model for airfoil self noise has been given by Brooks, Pope and Marcolini, (1989) based on comprehensive measurements of noise from a series of NACA 0012 profiles. A prediction method was also given by Schlinker and Amiet (1981). There remain some uncertainties. Earlier

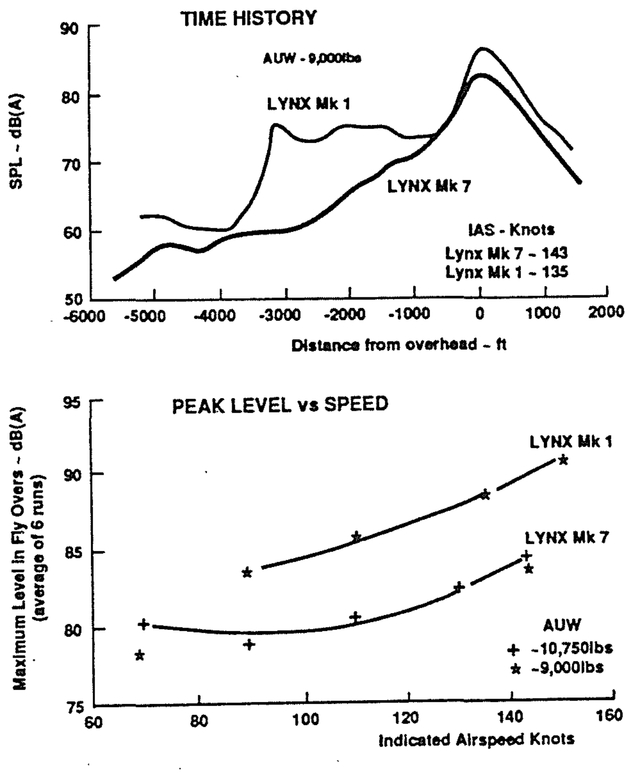

Figure 20 Results from a Quiet Tail Rotor

work suggested that tip vortex formation was an important source of noise. Brooks and Marcolini (1986) gave results suggesting an increase of noise of around 5-10dB. This was consistent with work on an open fan by Lowson, Whatmore and Whitfield (1973). The evaluation by George and Chou (1984) suggested that this source was only important in restricted circumstances. Noise from separated flows on rotor blades has also been reported to produce a 10dB increase over the attached boundary layer case, but no complete model is available.

The largest uncertainty appears to be the effect of the trailing edge. The radiation of noise from the trailing edge of an aerofoil can be remarkably complex. It has been established that discrete frequencies can be radiated from the aerofoil at lower Re Paterson et al (1973), when laminar boundary layers extend to the rear of the blade. These have been explained in terms of a local aeroacoustic instability within the boundary layer, and thus can be expected to be very susceptible to details of both aerofoil section and rotor operating conditions. An empirical correlation of the average frequency generated is given by the relation

$$f = 0.011\ (V/c)\ Re^{0.5}$$

where V is velocity, c chord, and Re Reynolds number based on chord. Within this general trend for frequency there is a fine structure. For further details reference should be made to Paterson et al. Fortunately, although laminar boundary layers can extend to the trailing edge on the pressure surface, the frequencies of the resulting tones are usually too high to be of interest for most helicopter rotors.

Brooks and Hodgson (1981) reported an experiment in which aerofoil discrete frequencies were found for conditions with turbulent boundary layers at the trailing edge. Brooks, Pope, and Marcolini (1989) give a rather complex empirical prediction formula, largely based on these results, involving boundary layer thickness and trailing edge geometry. A somewhat simpler formula using trailing edge thickness only has been put forward by Grosveld (1987) for wind turbine predictions. However an analysis of model rotor data by Brooks, Marcolini, and Pope (1989) shows that the trailing edge bluntness noise is overpredicted at higher speeds. Further work is required to clarify the contribution of these trailing edge effects.

Tail Rotor Noise

As indicated on Figure 4, the basic mechanisms of noise radiation from a tail rotor are essentially the same as on the main rotor. Blade vortex interaction and high speed impulsive noise will certainly be present under suitable circumstances. All the approaches used to control main rotor noise should again be available for the tail rotor. In fact tail rotor noise appears to be only occasionally approached using this logic. Part of the reason for this is that the tail rotor undergoes additional interaction phenomena which can be of considerable importance. On most tail rotors the interaction of the tail rotor with the separated flow coming off the fin and/or rear fuselage is an important noise source. Such noise levels are in principle fairly straightforward to calculate since good models of the flow and resulting fluctuating forces can be put forward. Some work along these lines has been reported, eg George and Chou (1986), Tadghighi (1989).

A second source of noise which only occurs on the tail rotor is interaction with the main vortex wake. It seems likely that this occurs on most tail rotors, but it was particularly significant on the Westland Lynx helicopter. Here this interaction was the source of a high intensity "burble" noise, radiating forward of the aircraft. It was concluded that the noise could be substantially reduced by changing the direction of rotation of the tail rotor so that the interacting blade moved with the shed wake rather than against it, Leverton (1982). Since a new gearbox was required to change direction, it was also decided to reduce the tail rotor tip speed from 717 to 650 fps. The net result of these changes is shown in Figure 20, which compares the noise from the original Lynx Mk 1 with the Lynx Mk 7 incorporating the changes. It may be observed that there is over a 15 dB reduction in the forward throw of noise. Maximum noise at overhead is also reduced, typically by around 5dB. Subjectively, the new tail rotor is undetectable against the main rotor noise. Spectra of the noise support this subjective impression.

An interesting feature of tail rotor noise measured on the Westland 30 aircraft, Pike and Dickens (1982) is that the measured levels of noise are considerably (10dB) lower than lower limit predictions based on steady loading and thickness terms only. This appears to be a result of considerable significance since it suggests that other mechanisms, perhaps fuselage shielding or wake refraction, have the potential to reduce observed noise levels.

An alternative approach to reduction of tail rotor noise is to discard the tail rotor entirely. This was originally done by Aerospatiale with their Fenestron design, which has been copied in other helicopters. Noise is increased under some circumstances by this modification. Removal of the open tail rotor also

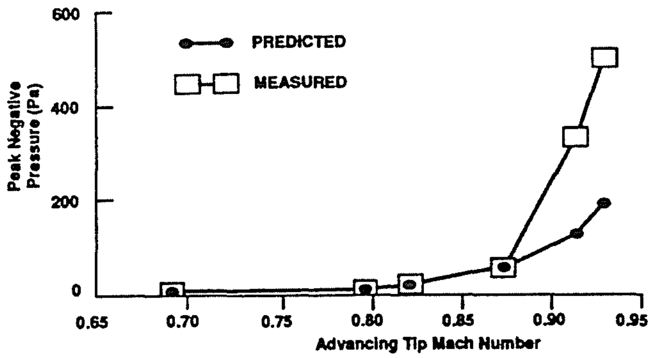

Figure 21 Acoustic Predictions Using Measured Pressures

has operational benefits. More recently McDonnell Douglas Helicopter have developed the "NOTAR" concept which replaces the tail rotor with a ducted fan. This reduces the tail rotor noise to an insignificant level. Because the force levels required from a tail rotor increase disproportionately on larger machines with high torque, such solutions are only likely to be effective on smaller helicopters. For larger helicopters the concept Leverton (1982) of reducing the tail rotor tip speed to give a balance between main and tail rotor noise output is likely to provide the most effective solution.

Other Main Rotor Discrete Frequency Noise Sources

High speed impulsive noise and blade vortex interaction noise occur at the blade passing frequency of the main rotor. However, both of these are extreme manifestations under particular operating conditions. As has been discussed the rotor will also radiate discrete frequency noise as a result of turbulence ingestion. But even in the absence of all these sources, under less demanding operating conditions, the main rotor will still radiate discrete frequency noise. This will be an important source for both flyover and take off. The mechanisms of noise radiation under these circumstances are essentially the same as in the more extreme cases.

The key cause of the radiation is the fluctuating forces on the blade and, at higher speeds, thickness noise radiation. The principal fluctuating forces are due to residual interaction between the main rotor and its trailing vortex system. Thus one method for prediction is the Scully type models discussed earlier for the BVI case. Experience suggests that under less extreme conditions the models are less able to provide good predictions. This indicates that a wider range of wake interaction processes are occurring than in the BVI case. Prediction will require more precise estimation of the strength and distorted geometry of the shed wake. There is also a need for better experimental data in quiescent wind conditions to minimise turbulence injestion noise.

There have been several wind tunnel studies in recent years which have combined a measurement of rotor acoustic output with a survey of the fluctuating pressures on the blades, eg Succi and Brieger (1981), Splettstoesser et al (1983), Visintainer et al (1990). All the studies have demonstrated that insertion of the measured blade fluctuating pressures into the Ffowcs Williams and Hawkings equation gives an excellent estimate of the radiated noise field. A typical result is given in Figure 21 taken from the paper by Visitainer et al. Fig 21 provides strong evidence of the importance of the fluctuating forces as a noise source on the blade, at least at rotor tip speeds below about 0.85.

An alternative method for noise prediction which is still used is that originally put forward by Lowson and Ollerhead (1968) (1969). They proposed the use of empirical power laws for the fluctuating force levels, which are used in an analytic model which starts from the same equation as later presented by Ffowcs Williams and Hawkings (1969). Their results are calculated in the frequency domain and are expressed as a series of Bessel functions. Although some judgement is required in the selection of the empirical power laws, reasonable predictions can be achieved by this technique eg Leverton (1989). Further details can be found in the references.

Other Sources

The principal remaining noise sources on the helicopter are the engine and gearbox. On many helicopters the gear box noise can be detected during overflight, and its spectrum can be observed in Fig 5. Gear box noise is not normally of critical importance since it is of high frequency, and tends to undergo higher levels of attenuation during propagation to a distant observer.

Engine noise is perhaps not given the importance that it justifies. Because engine noise has a broad band character it is often not immediately observed either subjectively, or in the spectral analysis. Papers by Damongeot etal (1983) and JanakiRam et al (1989) give practical examples of cases where engine noise has been found to be dominant is some flight conditions. Fortunately, if desired, engine noise can be reduced in many ways.

Impact on Design

Figure 18 gave an indication of the principal main rotor noise sources under various flight conditions. It will be observed that, although they relate to different helicopters, the general features of Figure 18 are similar to Figure 6. These figures are not valid for all helicopters, or even for all observer positions, but indicate the complexity of the task faced by the designer in making a balanced reduction in helicopter noise for all operating conditions.

In order to discuss the impact of noise on helicopter design use will be made of simplified expressions for noise radiation to draw general conclusions. Perhaps the most significant message is that, although such expressions are helpful, they are also, inevitably, wrong. Reduction of noise on a real helicopter design must take full account of the design detail, and will be a carefully judged trade off against performance and operating requirements. Even with this rather severe proviso, it is nevertheless worthwhile to examine the effects of noise on design via these generalised formulae, since they do give a first order estimate of the effects.

Simple laws for noise have been derived from data presented by Perry and Pike (1988), see also Pike (1981), for the effects of design changes on flyover EPNL. This combines the results from many acoustic predictions for different types of aircraft but, because of its source, is biased towards the larger transport helicopter. The principal laws are as follows:

Rotor tip speed	$V_T^{7.8}$
Aircraft all up weight	W^2
Blade Area	A_B^{-1}
Cruise speed	$V_C^{3.3}$
Blade Number	B^{-1}

This formula may be rewritten as a general (highly approximate) formula for flyover EPNdB values from any helicopter by relating these figures to the EH 101 flyover values given by Perry and Pike, viz:

$$\mathrm{EPNdB} = 91 + 10\log_{10}\left[\left(\frac{V_T(\mathrm{fps})}{670}\right)^{7.8} + \left(\frac{W(\mathrm{Lbs})}{31500}\right)^{2} + \left(\frac{B}{5}\right)^{-1} + \left(\frac{A_B\,(\mathrm{sqft})}{343}\right)^{-1} + \left(\frac{V_C(\mathrm{kts})}{160}\right)^{3.3}\right]$$

These formulae relate to reasonably well understood physical laws. The general dependence on thrust squared was predicted from the original Lighthill formulation and has been justified over many experiments, cf Lowson (1973). This gives the dependence on AUW. The predicted reduction in subjective noise level with increase in blade area is less obvious, but relates to lowering of the typical frequencies as scale is increased. Note that because, for a helicopter, the blade area required is proportional to weight the combined effects of the empirical blade area and weight laws give an overall first power law for weight, consistent with the experience built into the certification laws of Fig 1.

The high power of the velocity exponent is well known, and is due both to the strong dependence of aeroacoustic sources on velocity, and to increased subjective response to higher frequencies. What may not be obvious from the formula is that, for a given rotor, increase in tip speed will give a twelfth power law increment in noise, because thrust also increases as tip speed squared. (This can often give rise to major difficulties on derivative aircraft, which typically utilise higher rotor tip speed in order to give better AUW). The cruise predictions correspond to direct empirical modelling. Both of these velocity laws will be subject to gross change at higher tip speeds, when transonic effects become dominant.

The above formulae suggest that the dominant design feature for a quiet helicopter will be a low tip speed. This is essentially true. It is particularly true for reduction of noise at high speed. As is well known to the designer, choice of rotor tip speed is governed by the twin limits on the advancing and retreating blades at the maximum forward speed. The advancing blade limit is due to the appearance of transonic flow, and the retreating limit by stall. The advancing transonic limit affects not only noise but also drag rise and control loads. Although there are some possibilities for mitigation of this limit, as demonstrated by the BERP rotor discussed earlier, further major improvements appear unlikely.

Much recent work has concentrated on the advancing blade limit, both theoretically and experimentally, in part because of its critical military significance. However, for civil applications, the only realistic solution is to ensure that all helicopter operations are well away from any condition where significant advancing blade noise might occur. This sets clear limitations on the advancing blade Mach number.

If an advancing blade limit of around M=0.9 is regarded as near inviolate then any increase in forward speed is only available via reduction of tip speed. This is very attractive on noise grounds, but requires new thinking on the design of rotors for effective retreating blade operation. This appears to be a (somewhat) easier problem.

Conventional rotorcraft are still designed to operate at an advance ratio of around 0.4. There have been several studies eg Lowson and Balmford (1980), which indicate that rotor operation at much higher advance ratios, perhaps as high as 0.6, could be possible. This brings its own acoustic problems, in the form of blade vortex interaction on the retreating side aft quadrant. However it also permits the choice of much lower rotor tip speeds which have considerable benefits in take-off and landing. Possibly high advance ratio operation could be combined with some form of lift or thrust compounding. Such ideas appear to justify renewed study if flyover noise is going to be further reduced while still offering increases in cruise speed, cf Balmford and Benger (1991).

Take-off noise is certainly the least of the helicopters problems. During take-off the helicopter is, in effect, climbing away from its own wake. Thus rotor noise generation is limited to blade self noise, coupled with noise from turbulence ingestion. Under these circumstances noise from the tail rotor or the engine are likely to be the more important sources. These can be dealt with directly, as has been discussed previously.

Reduction of noise during approach remains a major issue. There are two problems. The first is reduction at the 6^{o} approach angle prescribed in the certification regulations. As is apparent from Fig 12, it is possible to achieve this, but not to improve, or even to worsen, noise radiation under other conditions. The second problem is noise reduction under the actual operating conditions of the aircraft. Alternate flight paths and routes, although "non-certification", have the potential to improve relations between helicopter operators and the surrounding communities, and justify continued study.

As has already been discussed the radiation of noise under approach is not at present accurately predictable. This is due to the inadequacy of the theoretical prediction methods for the detail aerodynamics of the rotor wake, which therefore are a major objective for improvement.

Achievements

So what has been achieved in helicopter noise reduction as a result of several decades of effort? Since the original discussions on certification in the 1970s, data has been collected from many manufacturers on the noise levels of their helicopters. Only a small proportion of the data has been formally agreed for certification. Indeed, much of the data has resulted from initial trials to establish the viability of the certification procedures proposed. Nevertheless such data has been taken carefully and, as far as possible, in conformance with the requirements. This data some of which has already been presented in Fig 1, provides an opportunity to give a quantified answer to the question posed above.

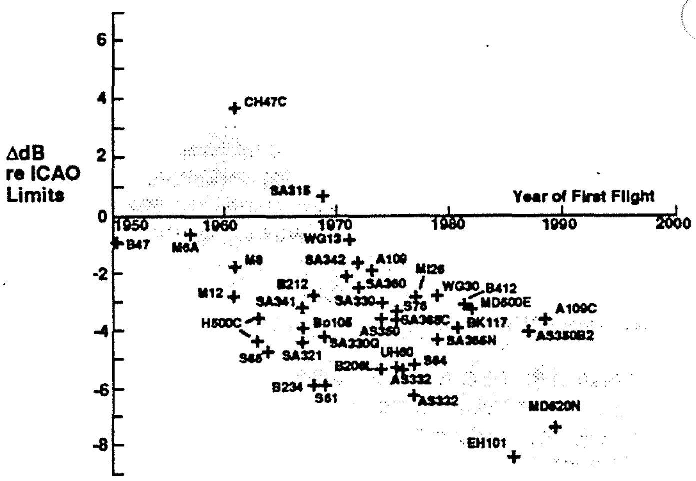

Figure 22. Progress in Reducing Helicopter Noise

The data has been replotted against a time base. The vertical axis of Fig 22 is the difference between the measured noise levels and the certification limit, averaged over the three conditions of take-off, approach, and flyover. This removes the effect of weight, and permits all helicopters to be compared directly. The time axis is the year of first flight. This was selected as being most representative of the age of design of the rotor system. Use of, for example, date of certification would result in an old design of rotor being recorded as new simply because of the later date of application. Use of date of first flight also presents difficulties. Later marks of helicopter, perhaps of greater performance, sometimes have a rotor system unchanged in its principal design parameters. However in other cases later aircraft do have changes to their rotor system. Figure 22 thus includes a judgement of whether a new type number included modifications which would be expected to have effects on noise output. In such cases the new noise levels have been plotted against time of first flight of the new type.

It will be clear that such assumptions can only give a chart which presents the broadest trends. Nevertheless, once the chart is available it does appear that there is a trend to be observed. Figure 22 shows that the industry has been able to produce helicopters which, on average, are quieter in recent years.

Closer study of Fig 22 shows that the scatter in noise output from helicopters designed in the 1950s was substantial. This is unsurprising, since noise was not a design parameter of significance at that time. This generation of helicopters was the first to have any reasonable commercial viability. Factors such as adequate payload, and cruise speed, dominated design consideration, while noise levels at that time tended to be dominated by the engine. The introduction of the gas turbine for helicopters in the 1960's gave a motivation for reducing the rotor generated noise. Since then the scatter in noise levels has been much reduced, and helicopter designs with excess noise radiation have been eliminated. There have also been some helicopters which are notably quiet. Two of these are the MD 520N which features the NOTAR and the EH 101. The figures for the MD 520N helicopter shown result from full certification trials, and demonstrate the acoustic benefits of this concept. Those for the EH 101 are based on predictions supported by preliminary measurements.

The EH101 helicopter is one of the few completely new helicopters designed after the original discussions on helicopter noise certification, and was designed from the start to meet the original CAN 6 limits which were 3dB more severe than those displayed in Fig 1. The EH101 includes many features which have been included to minimise noise, Leverton (1991). The key feature is the choice of low tip speed for the rotor (670 fps). This was possible by taking advantage of the aerodynamic performance of the BERP rotor system, which offered a further 30% improvement in thrust capability over the best two dimensional blade designs of the period. It has already been pointed out that the BERP rotor tip shape was designed to minimise the high speed impulsive noise. Following experience on tail rotor noise of Lynx (cf Fig 20), tail rotor tip speed was further reduced to 650 fps to provide a balance between main and tail rotor noise output. A further feature was a canted tail rotor to maximise the separation of the tail rotor from fin and rear fuselage. The consequence has been a predicted average 8.5 EPNdB improvement over the certification limits. These predictions are supported by initial measurements. This helicopter provides the target for future helicopter noise reduction efforts.

The figures given on Figure 22 are in a very similar form to those presented on Figure 2 for fixed wing aircraft, and it is possible to put these on the same diagram. If this is done, it will be found that a typical helicopter produces a sideline noise level about 10dB lower than that produced by the typical fixed wing aircraft. This comparison is not presented here since it is, in many ways, misleading. The weights of typical jet aircraft and helicopters are not the same, and neither are their passenger capacities. Further, although the sideline comparison shows up very favourably for the helicopter other comparisons, such as flyover, are not as favourable. Also, all certification procedures contain many features which are tailored specifically to the vehicle being certified, so that attempting to compare different types degenerates into a comparison of specific, and essentially irrelevant, features of the procedures. One point which can be drawn from comparison of the two figures is that the helicopter industry and the fixed wing industry have had a broadly parallel improvement in noise reduction in recent years.

Tilt Rotor Aircraft

There is much work at present on Tilt Rotor aircraft, notably the V 22 Osprey in the US. Protagonists claim that such aircraft will take over from the helicopter due to their higher cruise speed and better capability for long range operations. Helicopter proponents point out the inadequate payload and poor hover performance of the tilt rotor. Recent tests have started to identify some of the noise issues associated with the tilt rotor eg Sternfeld and Alexander (1991), Cox (1991).

Both XV 15 and V 22 have undergone trials representative of the ICAO requirements. The results from the two aircraft are broadly compatible and are summarised in the Table 1. The error band is about 5 EPNdB.

It can be seen that the tilt rotor, on average, appears an attractive aircraft from the noise viewpoint, and for flyover exceptionally so. Unfortunately, the noise radiation on approach has emerged as a major problem. The tilt rotor has about double the disc loading of a helicopter and a considerably higher rotor tip speed. Thus the blade vortex interaction noise is particularly intense, and causes major problems in meeting approach noise specifications. Since effective use of city centre heliports is a major market objective for the tilt rotor, considerable work is going to be required to overcome the problem.

There are two further noise problems for the tilt rotor which do not impact directly on certification, but which would affect its acceptability for heliport use. The first is an extremely strong BVI noise during some conditions of rotor tilt for the landing transition. This may be understood as the result of the same design parameters which give rise to the approach issue, and may reduced by choice of flight path. The second problem is unexpectedly high noise during hover. This results from the "fountain effect", a region of upwash between the rotor discs over the wing which causes high levels of fluctuating force on the rotor blades, and thus high noise radiation. This effect disappears at a forward speed of around 30 Knots. Problems of tilt rotor noise are not trivial. However the essential mechanisms are still those discussed in the case of the helicopter.

Future Developments

Some of the design possibilities for further reduction in helicopter noise have already been discussed in a previous section. As has been noted, at present the designer is frustrated in his attempts to reduce helicopter noise by the inadequacy of present prediction methods. Thus future developments will be paced by the rate of improvement of prediction technique. There are two principal lines in this development.

The first relates to improved computation of the high speed noise. Much of the theoretical development in the past few years has been an attempt to find fuller solutions to the Ffowcs Williams and Hawkings equation. Although this approach is formally exact, it introduces considerable approximations in a subtle and physically unrealistic manner. For example the LHS of Lighthill's equation, which is simply the wave equation, is linear, and therefore admits superposition of solutions. This is an excellent approach for low speed cases where aerodynamics and acoustics are uncoupled. But for high speed rotors the aerodynamics couples directly to the acoustics. As has been demonstrated (cf Fig 7) the local aeroacoustic field near the rotor can be heavily non-linear for tip Mach numbers well below sonic. Formally, estimation of quadrupole source terms should be continued well into the mid field to account for non-linear decay. Much of the apparent success of current aeroacoustic methods may well have resulted from the fact that the approach simultaneously ignores both strong non-linear source terms at the blade, together with nonlinear decay terms in the far field. This does not represent an adequate method for design of low noise rotors.

Further, conventional aeroacoustic approaches require the complete calculation of the aerodynamic field in order to estimate the quadrupole contributions, which must then be integrated over all space via the FfW-H equations. This is an entirely unnecessary procedure, since the full solution to the compressible aerodynamics required already contains within it terms at the boundaries which completely represent the radiated noise via the Kirchhoff formula. Thus a fully computational approach is more representative, more accurate, and simpler to apply. Such approaches have already been demonstrated, eg by Obermeier (1991) and Baeder (1991), and give not only good estimates of acoustic fields, but also excellent physical understanding of the flow processes which underlie the radiated noise. Because the radiated noise is only a small proportion of the aerodyamics, care must be taken that errors in aerodynamic calculation, particularly systematic error due to inadequate gridding or algorithms, do not lead to spurious results for radiated noise. With this proviso, computational tools can be expected to become an increasing part of the acoustic designers armoury.

The second, and more important, requirement for the better prediction is more precise models of the blade vortex interaction process which dominates noise during approach. Models such as that of Beddoes already give a useful predictive capability, but these rely on empiricisms, which would reqire validation for use in a new design. Unfortunately, the level of detail required for accurate prediction of the blade vortex interaction process is substantial. It is a problem which ultimately requires a full three dimensional unsteady Navier Stokes computation. There appears to be little hope of a complete computational solution this century.

Fortunately, the key problem is one of vortex dynamics, which should be adequately modelled by inviscid procedures. A characteristic approach is via panel methods, but more complex methods can be used. Even for these, the level of detail in the computations is at present insufficient to have much confidence in the outcome of the predictions. Naturally, under restricted circumstances, it is possible to infer useful results from such calculations, eg Lowson, Fiddes, and Aston (1990). However, there seems little short term prospect of, for example, predicting the results of the test series on tip shapes shown in Figure 12.

An issue which further complicates the vortex dynamics, which has not had much attention, is the possibility of vortex breakdown. This is the sudden change from concentrated to diffuse vortices observed in many vortex flows. Studies by Norman and Light (1987) showed a spiral instability in their shadowgraphs of flow from a tilt rotor, although it did not appear in the flows from conventional helicopter rotors. This was almost certainly some form of vortex breakdown. There has been little consideration of vortex breakdown effects in rotor flows, but it seems likely that the effects could be important, particularly for the tilt rotor.

An implicit assumption of much of the above discussion is that once the unsteady forces on the blades from BVI can be defined then the noise can be predicted straightforwardly via the Ffowcs Williams and Hawkings equation. Indeed Figure 21 gave strong support to this view. It should however be noted that Obermeier's work also demonstrates that unsteady vortex interaction processes, even at lower tip Mach numbers, can still generate significant sonic flows with associated shock systems which radiate to the far field. This does call into question the apparent success of purely force based methods for predicting the noise. On the other hand successful low noise helicopters must avoid transonic conditions, and will therefore operate in a regime where the Ffowcs Williams Hawkings approach can be expected to be acceptable.

Recent research has suggested that aerofoil profile shape may have a larger role in noise generation than previously supposed. Papers by Kerschen and Tsai (1989) and Tsai and Kerschen (1990) show that change of aerofoil shape can be a useful method for noise control. Equivalent results from Lyrintzis and

George (1989) have already been noted. All these papers use a matched asymptotic expansion technique in their theoretical development. The direct computations of Obermeier (1991) indicate similar effects. Although the effect of change of aerofoil shape has not yet been explicitly computed, there is certainly a (separate) anticipated effect from changes in pressure surface supervelocity. It seems likely that calculations using unsteady thickness noise models, Glegg (1987), would also give similar results.

None of these predictions about the effect of aerofoil shape in reducing BVI noise has been supported by direct experimental evidence, although the effect of the BERP rotor in this regard does offer some supporting evidence. Sternfeld (1988) also reported a reduction of noise by about 3dB from use of a new section design, but details are unavailable. Undertaking a suitable experiment is an obvious goal for research.

An indication of the potential for helicopter noise reduction can be gained from Fig 19, which gave an estimate by Brooks, Jolly and Marcolini (1988) of the contributions of various sources to the noise. Fig 19 suggests that reduction of only 6dB or so in interaction noise would leave the blade self noise as the critical source.

Conclusions

There has been useful progress towards quieter civil helicopters. Early types not designed for low noise have now been replaced with helicopters which meet the requirements of current ICAO noise legislation. Knowledge of the basic source mechanisms which control the noise is growing, although it is far from complete. New helicopters specifically designed to have low noise are demonstrating reductions in noise of around 8dB against the present ICAO rules.

Although new design helicopters have demonstrated low noise, there is little prospect of substantial noise reductions on existing types. The parameters which affect the noise, notably tip speed, are so central to the whole design that it is likely to be easier to design a new helicopter from scratch than to modify an existing aircraft. In cases where the noise is dominated by a particular source, eg tail rotor or engine there are possibilities for cost effective approaches. Some improvements by adjusting rotor blade shape and section have been noted.

The review has reinforced the established view that rotor tip speed is the crucial parameter controlling helicopter noise. This is particularly true for high speed impulsive noise, but also applies to the blade vortex interaction case. Future low noise helicopters must be designed with low rotor tip speeds. This puts an additional emphasis on the related performance issues, such as operation at high advance ratio. However, the established theories based on Ffowcs Williams Hawkings equation can be expected to be more reliable under these conditions.

Atmospheric turbulence has been demonstrated to have an important effect on noise, particularly at lower speeds. Further work is required to establish the issues involved in adequate depth, particularly since the sound radiated is in a frequency range in which other forms of noise from blade wake interaction can also be important.

There is evidence that aerofoils can be designed to minimise noise radiation, by shaping of the leading edge, and by reducing supervelocities on the blade, perhaps particularly on the pressure surface. Although the benefits here will be limited, a study of the trade off between noise reduction and general performance requirements for aerofoil design would appear to offer an interesting line for further development.

The overall rate of reduction of noise by the industry broadly parallels that being achieved by fixed wing aircraft. In both cases the ultimate limit is the self noise radiation by the turbulent flow around the lifting surfaces.

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	Take-off	Flyover	Approach	Average
Margin over ICAO, EPNdB	-7.7	-12.5	-1.6	-7.3

Table 1 Comparison of Tilt Rotor Noise with ICAO Requirements

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