DIRECTIONALITY OF HELICOPTER NOISE AND ITS EXPLOITATION

Final Technical Report

by

Martin V. Lowson

Jan 1996

United States Army

European Research Office of the U.S. Army

London England

Contract Number N68171-94-C-9140

Flow Solutions Ltd
Alpenfels, North Road
Bristol BS8 3PJ England

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
Jan 22nd 1996

3. REPORT TYPE AND DATES COVERED
Final Report Aug 1994 - Dec 1995

4. TITLE AND SUBTITLE
DIRECTIONALITY OF HELICOPTER NOISE
AND ITS EXPLOITATION

5. FUNDING NUMBERS
Contract #
N68171-94-C-9140

6. AUTHOR(S)
Martin V Lowson

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Flow Solutions Ltd
Alpenfels, North Road
Leigh Woods, Bristol BS8 3PJ
England

8. PERFORMING ORGANIZATION REPORT NUMBER
96-01

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
European Research Office US Army
223 Old Marylebone Road
London NW1 5TH England

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT
This report is intended only for the internal management use of the Contractor and the US Government

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

The work during the present contract has shown that helicopter BVI noise will have local regions of focused propagation in which the decay rate is less than inverse square. This finding has significant consequences for helicopter detection. Instantaneous maximums in helicopter noise during flyby are frequently observed. These have normally been ascribed to non-uniform aerodynamic effects at the rotor. The present model shows that such peaks are a result of the detailed geometry and kinematics of the blade vortex interaction, and a fundamental feature of the associated acoustic propagation. The model gives both a prediction of where the peaks will occur at any flight condition, and of the region of the rotor disc where the most acoustically important interactions are caused. The model also allows a search for flight conditions under which noise from Rotor BVI will be minimized. The work has been summarized in a report presented to the European Rotorcraft forum, and a paper to be published in the Journal of Sound and Vibration. An extended version of the paper to be presented in the Journal of Sound and Vibration, with the key diagrams in color, is attached.

14. SUBJECT TERMS

15. NUMBER OF PAGES

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT

18. SECURITY CLASSIFICATION OF THIS PAGE

19. SECURITY CLASSIFICATION OF ABSTRACT

20. LIMITATION OF ABSTRACT

ATTACHMENT 1
PAGE 1 OF 2.

DIRECTIONALITY OF HELICOPTER NOISE AND ITS EXPLOITATION

Final Technical Report

by

Martin V. Lowson

Jan 1996

United States Army

European Research Office of the U.S. Army

London England

Contract Number N68171-94-C-9140

Flow Solutions Ltd
Alpenfels, North Road
Bristol BS8 3PJ England

Abstract

The work during the present contract has shown that helicopter BVI noise will have local regions of focused propagation in which the decay rate is less than inverse square. This finding has significant consequences for helicopter detection. Instantaneous maximums in helicopter noise during flyby are frequently observed. These have normally been ascribed to non-uniform aerodynamic effects at the rotor. The present model shows that such peaks are a result of the geometry of the rotor wake interaction, and a fundamental feature of the associated acoustic propagation. The model gives both a prediction of where the peaks will occur at any flight condition, and of the region of the rotor disc where the most acoustically important interactions are caused. The model also allows a search for flight conditions under which noise from Rotor BVI will be minimized. The work has been summarized in a report presented to the European Rotorcraft forum, and a paper to be published in the Journal of Sound and Vibration. An extended version of the paper to be presented in the Journal of Sound and Vibration, with the key diagrams in color , is attached herewith.

FOCUSING OF HELICOPTER BVI NOISE

by

Martin V. Lowson

Flow Solutions Ltd, Bristol BS8 3PJ England

and

Department of Aerospace Engineering, University of Bristol, Bristol BS8 1TR, England

Note: This is an extended version of a paper to be published in the Journal of Sound and Vibration in March 1996, giving coloured versions of the more important diagrams.

Summary

The paper reports results from an exact analytic model for the kinematics of noise radiation due to blade vortex interaction which gives new predictions of the directionality of BVI noise from helicopters. It is shown that the blade-vortex interaction process will give rise to focused regions of intense noise, which can decay locally at a rate less than inverse square law. This finding has obvious consequences for helicopter detection and community annoyance. However the model also gives explicit prediction of the location of the regions of intense noise, and of the location in the disc of the interaction source responsible. Thus the model can also be used to suggest methods for exploiting directionality effects to reduce noise from helicopter operations.

Introduction

Noise radiation by helicopters is of considerable significance in both civil and military operations. As a result much work has been undertaken to understand this source of noise, both theoretically and experimentally cf. eg Refs1,2. The first reasonably complete theory for helicopter noise radiation was developed by Lowson and Ollerhead [Refs 3,4]. This demonstrated that the principal cause of the noise radiation by helicopters at moderate speeds was the unsteady loading on the helicopter blades.

The most intense source of helicopter noise is high speed impulsive noise. This is fundamentally due to the effects of blade thickness. At the highest forward speeds this causes the direct radiation of noise by the advancing blade shock system, which has been found to extend outside the blade beyond "delocalisation" speeds, typically around M 0.9 for conventional rotors [Ref 2]. At lower operating speeds the most intense source of noise arises from Blade Vortex Interaction (BVI) processes. Both of these impulsive noise phenomena were the focus of a series of carefully constructed and realised experiments, summarised in the review paper by Schmitz and Yu [Ref 1].

Useful progress has been made towards quieter helicopters, as has been summarised in a recent review paper by Lowson [Ref 5]. An interesting feature of this work has been co-operative studies in the DNW acoustic wind tunnel. Although much information has been learned from this work (eg Ref 6], it is not possible to determine far field effects, notably detail directionalities, from this type of experimental set-up. There are also questions about the accuracy of scaling of the vortex processes in model tests [Ref 1].

In recent years theoretical work has concentrated on full computational solutions to the problem. Progress in developing understanding via this approach has been slow. This is unsurprising, since the problem requires solution of the full compressible unsteady Navier Stokes equations for complex boundary conditions. It is generally agreed that many years of computational and algorithmic development will be required before any acceptably complete model is available from these computational studies.

A further difficulty is the exceptional complexity of the radiated noise field from the helicopter. Small changes in flight condition, eg descent rate, are known to give major changes in the noise. This can be related to the changes in the interaction process between rotor and shed wake. It is also well known that there are major local maxima in the rotor noise field. Because of the difficulties in experimental data capture in these complex noise fields, such peaks have not been adequately recorded.

The strong directionality effects cause further theoretical and computational problems. Each far field point requires a separate retarded time integration. This is computationally time consuming, and it is traditional to examine the noise at a selection of far field points. However, because of the complexity of the radiated noise, especially from the blade vortex interaction process, it is likely that major maxima in the noise field could be missed. Thus without an extensive, and computationally irksome, search it is very difficult to obtain a clear idea of the noise field actually predicted by the computer models.

Helicopter noise BVI directionality effects remain a matter of considerable uncertainty from both the theoretical and experimental viewpoint. As noted in Ref 1, understanding of this problem remains incomplete, despite the fact that it is well known to be a significant feature of the helicopter noise field. This paper is aimed at improving understanding of this important area.

The key to the new approach is the recognition that supersonic phase speed at the source gives rise to highly efficient acoustic radiation. This was a fundamental feature of the original theory for helicopter noise [Ref 3]. In that work the unsteady loading on the rotor was described in Foùrier series form, and this approach has generally been followed by others since. However, it was pointed out in Ref 3 that a particularly efficient form of acoustic radiation could be anticipated when the phase speed (or trace speed) of the intersection of shed vortex and blade became supersonic. The same idea was at the heart of the theory of Widnall [Ref 7] on blade vortex interaction noise.

Figure 1 gives a diagram explaining the effect. The phase speed V_p of the location of the intersection of the blade and vortex is related to the speed of convection of the vortex past the blade V via the angle of intersection Θ.

$$V_p = V / \tan \Theta$$

If Θ is small then the phase speed V_p can be considerably greater than the convection speed V. The consequence of this is shown in Figure 2.* Emission of two sound signals with a distance-time relation dx/dt which gives phase velocities V_p which are supersonic causes reinforcement along the Mach cone. Sound propagated in the direction β as shown in Figure 2 will add directly. At the Mach cone the term $(1-M_r)$ in the normal aeroacoustic equations goes to zero. As a result the acoustic analogy and related models indicate a singularity at the Mach cone. This is known to be an integrable singularity (cf. Hawkings and Lowson Ref 9). Figure 2 also shows that the sound can be computed by simple superposition of the individual signals. However for the purposes of the present work the key issue is that the noise emitted in the direction β will be of considerably increased intensity.

The increase in intensity for the radiated noise arises from the effects of the retarded time calculation. Retarded time effects have a dominant effect on the intensity of radiated sound. In Ref 3 it was shown how the variation of effective phase speed from subsonic to supersonic for a sinusoidal wave could give increases of noise level of 90 dB. The present approach provides a method for assessing these effects. It can also be inferred from Figure 2 that the sound radiated in the principal direction undergoes part of its propagation in 2 dimensions rather than 3 and may thus decay at r^{-1} rather than the usual r^{-2}. This can have significant consequences.

The effects of supersonic rotor speeds have been examined in several previous papers. Initial studies were presented by Lowson and Jupe [Ref 10] and Hawkings and Lowson [Ref 9]. More general studies of the effects of supersonic speeds have been put forward by Ardavan in a series of papers [Refs 11,12]. In these papers the possibility of equivalent effects at superluminal speeds in rotating galaxies is also examined. These correspond to the extreme effects of two and even one dimensional radiation arising from supercritical sources. For the supersonic propeller, papers by Myers Ref 13, and Myers and Farrassat, Ref 14 have examined the propagation of noise to the far field. Myers and Farrassat point out that the propagation field for these sources will not be spherical, and that Mach surface singularities which arise in the near field will persist throughout. This was re-emphasised by Ffowcs Williams, [Ref 15] who pointed out that supersonic sources would give rise to focused waves, and also noted the connection to the radiation processes described in terms of wave "missiles" or "bullets". These will be discussed further subsequently.

---

* A version of this diagram, and its consequences for directional radiation from supersonic rotors, was first given by Lamb in an Appendix to a paper by Bryan (Ref 8)).

In all these papers the source is assumed to have a *physical* speed which is in excess of the critical velocity, i.e. the speed of sound. It does not seem to have been widely appreciated that exactly equivalent effects will arise from *phase* speeds which are supercritical. As has been discussed BVI processes do possess supersonic phase speeds. This implies not only high radiation efficiency, but also highly localised radiation peaks which could decay in particular directions at less than inverse square law rate. This obviously has important consequences for helicopter noise.

Parts of the source field which have supersonic phase speeds can be expected to be considerably more efficient as acoustic radiators. The effect of retarded time i.e. phase speed can be of far greater consequence than changes to physical parameters such as source strength. In many analyses estimates of source strength are given, but in general the effects of direct source strength are of much less significance than the effects of phase. The effects of retarded time tend not to be obvious, so that its implications are only rarely fully recognised. The same effect can also be interpreted in terms of "cut-off" or "cut-on " radiation for example in the noise from fans or compressors, where there is a radical increase in acoustic efficiency as the equivalent phase speed of the radiation becomes sonic. Retarded time effects are likely to dominate any explicit calculation of the radiated field, but often will only be apparent after completion of the full integrals. This means that important information for noise control can easily be overlooked.

Phase relations in the BVI process have not previously been analysed to give better information about the helicopter noise field. Experimental data on this effect is very difficult to obtain directly, and little theoretical work has been undertaken. One paper which did exploit some of these concepts was by Ringler, George and Steele [Ref 16], who noted, for the reasons described above, that noise radiation from a blade vortex interaction process with supersonic phase speeds is highly directional as well as highly intense. George et al [Ref 17] applied these ideas to the tilt rotor problem, and demonstrated a useful improvement in understanding. Application to the helicopter is incomplete, although a different application of very similar ideas was made by Lowson and Jupe [Ref 10] to describe wave forms from a supersonic rotor. A recent application of these ideas to helicopter BVI noise was presented by Sim and George [Ref 18] , although this paper concentrated on a load prediction scheme.

The key requirement is to make a good estimate of phase speed of the interaction process. This can be obtained by a simple epicycloid model of the vortex wake interaction process, as noted by Schmitz and Yu [Ref 1]. A computational approach to this problem was presented at the recent European Rotorcraft Forum [Ref 19]. This used the Mach cone effects described but did not include the peak directivity effects at angle β discussed. An initial mathematical model of the full process has now been developed. It has been found possible to give exact explicit solutions which describe the interaction process under certain realistic assumptions. These solutions may be used to provide information on the structure of the noise field and the locations of the peak noise level as a function of rotor parameters.

2. Theoretical Model

The basic geometry of the blade wake intersection process assumed is shown in Fig 3. The rotor wake is assumed shed from the tip and to be carried downstream, thus giving the cycloidal form. Figure 3 is based on a rotor centred co-ordinate system, and shows how each part of the wake shed at an earlier time T simply convects back at free stream velocity, while the blade continues to move around the rotor axis.

The mathematical analysis is restricted to a plane cycloidal wake. However it should be noted that the principal velocities in the wake are normal to the rotor plane, and these will not affect the phase speed of the intersections. At this stage the theory does not include any effects of wake contraction, or the self distortion of the wake, so that some of the predictions will be incorrect in detail. However, it is believed that the key feature of the aero-acoustics is the local phase speed. This will be dominated by the basic kinematics of the shed wake/blade interaction process, which is fully captured in the theory to be presented.

The wake from any one blade at angle Φ is composed of elements shed from the blade tip at earlier times T and carried away at the free stream velocity V. Using axes x, y, with x in free stream direction allows the wake to be defined by

$$\begin{aligned} x &= R \cos (\Phi - \Omega T) + VT \\ y &= R \sin (\Phi - \Omega T) \end{aligned} \tag{1}$$

where Ω is the rotational speed of the rotor.

Non dimensionalising by dividing by R, and writing

$$x' = x/R, \quad y' = y/R, \quad \Omega T = \theta, \quad VT/R = V\theta/\Omega R = \mu\theta$$

gives

$$\begin{aligned} x' &= \cos (\Phi - \theta) + \mu\theta \\ y' &= \sin (\Phi - \theta) \end{aligned} \tag{2}$$

where μ is the advance ratio $V/\Omega R$.

Consider another blade at angle α to the first i.e., at

$$\begin{aligned} x' &= r \cos (\Phi - \alpha) \\ y' &= r \sin (\Phi - \alpha) \end{aligned} \tag{3}$$

where $0 < r < 1$.

If an intersection occurs between this blade and the wake, then for some value of r

$$\begin{aligned} \cos(\Phi - \theta) + \mu\theta &= r\cos(\Phi - \alpha) \\ \sin(\Phi - \theta) &= r\sin(\Phi - \alpha) \end{aligned}$$

Eliminating r gives

$$\sin(\theta - \alpha) + \mu\theta\sin(\Phi - \alpha) = 0 \tag{4}$$

This equation may be solved to provide values of θ, Φ, α where intersections will occur. For a conventional rotor

$$\alpha = 2\pi b/B$$

for the b'th blade of B.

These results are well known and give the location of the blade vortex intersection points on the rotor disc, as shown in Figure 4. This illustrates the complex nature of the blade vortex interaction process as a function of advance ratio.

It may be noted that a direct solution for (4) is given by

$$\tan\alpha = \frac{\sin\theta + \mu\theta\sin\Phi}{\cos\theta + \mu\theta\cos\Phi} \tag{5}$$

but this is only of value in cases when Φ, θ are given, i.e. for given values of shedding location and vortex age. This is only a potential solution if a suitable value of α is available. In fact there is no guarantee that a blade would be present at that location .

A fuller solution may be found by expanding equation (4) as

$$\mu\theta\sin\Phi\cos\alpha - \mu\theta\cos\Phi\sin\alpha + \sin(\theta - \alpha) = 0 \tag{6}$$

which can be written as

$$a\sin\Phi - b\cos\Phi + c = 0 \tag{7}$$

where

$$a = \mu\theta \cos\alpha$$

$$b = \mu\theta \sin\alpha$$

$$c = \sin(\theta - \alpha)$$

Writing $\cos\Phi$ in terms of $\sin\Phi$ shows that equation 7 is a quadratic in $\sin\Phi$ which can be solved in the normal way. After some rearrangement the solution for $\sin\Phi$ can be found as

$$\sin\phi = \frac{-\cos\alpha\sin(\theta-\alpha) \pm \sin\alpha\sqrt{\mu^2\theta^2 - \sin^2(\theta-\alpha)}}{\mu\theta} \qquad (8)$$

This expression allows the location of the intersection between blade and wake to be defined for any specified value of wake age and blade number. Note that some of the solutions given by this equation will give results which are on the extension of the blade at angle α beyond the end of the blade. These should be disregarded.

Calculation of Phase Speed

It is also desired to calculate the phase speed of the intersection along the blade. In equations (1), (2). Note that T is an age parameter, and is not relevant to speed calculations. The dynamic term is Φ, the instantaneous blade angle around the disc. It is therefore required to calculate the rate of change of the intersection point with Φ.

Differentiating (2) gives the components of velocity in the x and y directions as

$$\begin{aligned} \frac{dx'}{d\Phi} &= -\sin(\Phi - \theta)\left\{1 - \frac{d\theta}{d\Phi}\right\} + \mu\frac{d\theta}{d\Phi} \\ \frac{dy'}{d\Phi} &= \cos(\Phi - \theta)\left\{1 - \frac{d\theta}{d\Phi}\right\} \end{aligned} \qquad (9)$$

but from (4)

$$\frac{d\theta}{d\Phi} = -\frac{\mu\theta \cos(\Phi - \alpha)}{\cos(\theta - \alpha) + \mu\sin(\Phi - \alpha)} \qquad (10)$$

Thus putting $\Phi = \Omega t$, the local phase velocity v of this intersection can be calculated from the equation above via

$$v' = \left(\left(\frac{dx}{d\Phi} \right)^2 + \left(\frac{dy}{d\Phi} \right)^2 \right)^{1/2} \tag{11}$$

where $v' = v/\Omega R$, the ratio of the local phase speed to the tip speed.

If the phase velocity is supersonic then the noise will radiate to the far field at an angle of

$$\beta = \cos^{-1} (1/M)$$

to the phase velocity vector (see Fig. 5).

The angle of the phase velocity vector is given from (9) by

$$\tan \gamma = \frac{\cos (\Phi - \theta) \{1 - d\theta / d\Phi\}}{- \sin (\Phi - \theta) \{1 - d\theta / d\Phi\} + \mu \; d\theta / d\Phi} \tag{12}$$

Radiation is at angle $\gamma \pm \beta$.

Thus after time t after emission the sound wave is at position $\begin{cases} x + ct \cos (\gamma \pm \beta) \\ y + ct \sin (\gamma \pm \beta) \end{cases}$

The complete wave form from the BVI process is found by using these relations over the whole of the rotor cycle.

3. Initial Results

Some initial results from the work are shown in Figure 6. This shows the location of in phase radiation in the far field in the plane of the rotor for an advance ratio of 0.2. This, and all calculations presented in this paper, are for a four bladed rotor operating at a tip Mach number of 0.66. The plots show the locations of the lines where rotor signals will add in phase. These would be expected to coincide with significant peaks (positive or negative) in the observed pressure signal. The radiation from the blade is highly directional. Figure 6 shows the shape of the field at an early stage in the radiation process. Each element of the wave will continue in a direction normal to the wave front, so that an impression of the likely far field directivities can be found by inspection of the shapes of the wave shapes. This provides an explanation for the very strong directional effects observed with BVI noise. The actual pressure signature to be anticipated can be inferred by examination of the number of wavefronts progressing towards any particular observation point.

Figure 6 also shows that cusps can occur in the wave forms radiated. This is somewhat surprising, although cusps are an established feature of the radiation from supersonic rotors (eg Ref 10]. Cusps represent points of double accumulation of the acoustic signal, and can be expected to correspond to exceptionally strong areas of noise radiation.

A coding scheme has been used in Figure 6 to distinguish parts of the radiation which arise from different phase velocities. Only supersonic phase speeds will give rise to efficient radiation conditions. The radiation pattern in figure 6 is divided into nine areas corresponding to angle of Mach radiation in ten degree increments between 0 and 90 degrees. The 0° radiation correspond to a phase Mach number of unity, i.e. radiation which is just cut-on, and the 90° case to infinite phase speed, i.e. the blade and vortex meeting parallel to each other (as in the usual two dimensional model of the problem).

The analysis shows, perhaps unexpectedly, that the phase speed of the radiation for any specified advance ratio is a function only of position in the disc. The effect of blade number is simply to select particular points of the disc for the interaction loci, cf. Figure 4. Using equation 5 it is possible to identify the phase speeds which will result from interactions in any part of the disc. This is shown in Figure 7. Figure 7a gives the results for an advance ratio of 0.2, while Figure 7b gives the phase speeds are shown for four advance ratios, 0.1 to 0.4. The same coding as in the previous figure is used for the supersonic elements. For the subsonic phase speeds the phase velocity is divided into six equal parts. Since a tip speed of 0.66 has been chosen, the four lowest areas correspond to phase velocities which are below the tip speed. It will be observed that, except towards the centre of the rotor on the retreating part of the blade, all of the front half of the disc has vortex interaction phase velocities which are lower than the tip speed.

The results of figure 7 have several implications. From the observation noted above it appears that any vortex interaction over the front of the disc will have low phase speeds and thus be inefficient acoustically. This is quite fortunate since the vortices are normally much closer to the rotor over the front of the disc. It will also be observed that the key supersonic phase region is confined to a limited area of the advancing and retreating side of the disc. It is vortex interactions in this area which will have the highest acoustic radiation efficiency. It will also be noted that although there is an effect of advance ratio, the general form of the phase speed distribution remains essentially constant across the disc at all advance ratios. Equation 5 shows that the results scale directly with tip speed, so that the actual speed up ratio shown in Figure 7 would be the same for any tip speed. For a lower tip speed the supersonic region would be confined to a smaller area of the disc.

4. Estimation of Radiation Efficiency

Although the results presented have several important acoustic implications they do not provide a full description of the intensity of the noise radiation. The observation of cusps in the radiation field suggests that there may be regions of high local acoustic intensity. A simple physical argument appears to provide a large part of the answer. Figure 8 gives a diagram of the process occurring.

The angle β of the radiation is given by

$$\sin\beta = 1 / M$$

It can be seen that radiation from a length dx of the radiation path will result in peak noise appearing in the far field over a length ds. If the phase speed changes then the radiation from the point x+dx will be at a different angle to that at x. The relation of dx to ds can be readily determined as

$$ds = \frac{dx}{dM} . \frac{r + r_o}{r}$$

and

$$r_0 = 1 / (M\, d\beta/dx) = -M\ (M^2 - 1)^{0.5} / (dM/dx)$$

The equations above show that the radiation will appear from a false origin. Further, if $dM/dx = 0$ then there is no variation of the sound level with distance r. Under these circumstances the radiation becomes two-dimensional, and will decay at a lower rate in the far field.

These circumstances have major implications for the noise radiation. Whenever the phase velocity of the interaction is constant there will be a local 2-D radiation to the far field. This will give rise to major local maxima. It will also be noted that if the phase velocity has even a modest change then the radiation remains three dimensional, obeying the inverse square law sufficiently far from the rotor. However there will be a divergence from the inverse square law in the near geometric field closer to the rotor. An additional effect results from the curvature of the generation locus. This will also give rise to focusing effects, which will combine with the focusing effects from the varying phase Mach number. Figure 8b shows the process of formation of the peak noise at the cusp, combining both the Mach effects and the geometry of the source curvature.

The condition that dM/dx = 0 corresponds to a maximum or minimum in the phase speed as a function of distance. This also corresponds to the appearance of cusps. Thus the cusp locations shown in Figure 6 are of special interest since they imply large levels of sound radiation in that direction.

Thus the current model implies that the acoustic radiation from a helicopter will possess a number of highly localised maxima at which the sound level is significantly higher than anticipated from an inverse square law decay. The level of the increase can be calculated by establishing the area over which the energy from any particular source element is distributed. This can be readily calculated from knowledge of the locations of the radiated sound from each location.

5. Results for Field Strength

The analysis above has been used to give an estimate of the far (acoustic) field levels resulting from the radiation processes. The results are shown in Figure 9 for the advance ratio 0.2 case. The wave forms here are coded against a notional dB level. The (arbitrary) datum level is, in effect, the highest level of sound observed anywhere in the far field over all advance ratios. The calculation of level has been made at a time delay of one complete rotor revolution. This has been done in order to give an approximation to a far field case. In the near field, i.e. as shown in Figure 9, the shape of the cusps etc will undergo some change, so that it is thought to be more representative to calculate the levels at a modest distance from the rotor. In turn this means that the peak levels shown do not precisely coincide with the cusp locations illustrated, which are based on the radiation field somewhat closer to the rotor. The levels shown coincide with the cusp location after a time delay of one revolution. Nevertheless the Figure shows that the highest levels of noise occur close to the cusp locations, as anticipated.

The peak locations (red or pink in the colour coding) are very restricted in extent. Three peak locations can be seen in Figure 9. The most obvious is in the forward top quadrant at the cusp near the rotor. There is a further peak in the aft top quadrant at the end of the outermost wave. The cusp in this case cannot be distinguished at the scale at which the diagram is drawn. This feature is characteristic of the cusp shapes at greater distances from the rotor where the two arms of the cusp almost overlay each other. The final peak noise location is found almost of the origin in the diagram. This corresponds to a wave which is in the early stages of formation, and will produce clear cusp forms as it propagates down and forwards.

Figure 10a gives equivalent results for the case of advance ratios of 0.1, 0.2, 0.3, 0.4. It can be seen that the same general effects occur at all advance ratios, but the detail of the radiation patterns varies significantly. The number of waves reduces as advance ratio increases. This corresponds to a reduced number of vortices within the disc, as discussed previously. Note also that the number of peak noise areas also reduces as advance ratio increases. Figure 10b gives results for the advance ratio cases 0.18, 0.19, 0.20, 0.21. Even these very modest changes of advance ratio cause significant changes to the radiated patterns. In particular it can be seen that the cusp locations vary considerably in azimuth as a function of advance ratio. This means that the peak levels of noise from the rotor interaction process will appear in quite different parts of the far field depending in the exact value of advance ratio. This is both a difficulty and an opportunity, since it suggests that careful control of helicopter speed could control the locations of the peak disturbance.

Figure 11 shows the source locations within the rotor disc of the peak noise for the cases shown in Figure 10a. It will be observed that the location in the disc of the peak noise generation is very restricted. This suggests that it should be possible to control the peak noise generation by very local control of the source strength i.e. local aerodynamics at prescribed disc positions. The critical location of the crucial radiation will vary with advance ratio, but the model provides a clear definition of the locations of the sources.

Figure 12 presents data on the predicted location of the major noise peaks as a function of advance ratio. Only peak levels within 20dB of the maximum observed at any advance ratio are shown. Figure 12a gives the full diagram, with a magnification of part of the diagram shown in Figure 12b. The absolute peak levels in the range 0 to -10dB are very limited in extent, but it should be recognised that the peaks shown in the range -10 to -20dB remain of considerable magnitude, but are closely confined in their directional behaviour. For clarity, lower levels of noise shown in the previous cusp diagrams are not given here. The systematic nature of the change in direction with advance ratio can be clearly seen. The repetitive nature of the azimuthal distribution results from the nature of the blade vortex interaction process. At low advance ratios many vortex paths will lie within the confines of the disc. As speed is increased the vortices will successively leave the disc, thus leading to a repetitive directional pattern in the noise. Figure 12 offers opportunities for choosing advance ratio to minimise noise in specific directions. For example, according to the present model, advance ratios of 0.2 or 0.3 project the noise peaks furthest from the forward direction.

All the figures in the present paper refer to the efficiency of the acoustic processes only. There will be two further effects. The first is the directionality of the radiation as a function of blade shape, often described in terms of lift and drag dipoles. The second is the actual strength of the source, which will be a function of the aerodynamic detail of blade vorteex interaction process. This in turn will be a function of the disc attitude. As is well known, maximum BVI noise occurs in partial power descent when the blades run close to their shed wake. The location of the minimum miss distance between blade and vortex will move inboard at higher descent rates. Thus for a full description of the BVI process it will be necessary to combine an estimate of source strength (for example using the model of Beddoes Ref 20] with the acoustic efficiency effects described here.

However it should be noted that the acoustic efficiency effects are very powerful. Thus even quite modest source strengths which have the correct phase relations can radiate significant noise levels.

6. Acoustic Missiles and Bullets

There have been several recent papers which have analysed radiation phenomena described as "bullets" or "missiles" (eg Refs 21,22,23]. These include solutions to the scalar or vector wave equation which demonstrate far field propagation at a decay rate which is lower than inverse square. Because these phenomena are essentially a function of the wave equation, they can be observed in both electromagnetics and in acoustics. Some authors have used the descriptions interchangeably, but in general wave phenomena which demonstrate a lower than inverse square law radiation have been called missiles. The description of "bullets" has been used for wave phenomena which are confined to a prescribed cone of radiation, but which continue to obey the inverse square law.

The full range of effects associated with these phenomena has not yet been explored, and there are alternative physical explanations for the process. The simplest explanation is that the missile is a focusing process. The range at which a focus can be achieved is a function of the ratio of the aperture to the wavelength. Thus if the wavelength is sufficiently small a focus can be achieved at considerable distance. In the electromagnetic case there is no theoretical lower limit to wavelength, so that localised missiles can be found at arbitrarily large range. This would not apply in the acoustic case since high frequencies undergo significant atmospheric attenuation. In the acoustic case the localisation of sound is subject to significant limitations, although the observed levels of an acoustic missile could be high in local regions of the far field.

From the acoustic point of view the existence of acoustic missiles is unsurprising. If a plane shock wave could be formed, for example after propagation down a tube, it would be expected that this shock wave would propagate to the far field according to ray theory, and not be subject to inverse square law decay. The shock wave would be subject to attenuation processes, due to both atmospheric absorption, and to the shock steepening/decay effects of weak shock theory. If the shock formation process had circular symmetry, (as in the case of rotors or jets) then the shock would propagate with inverse first power decay. This is familiar from the case of sonic boom, and has also been observed in local far field wavelet effects in the radiation from supersonic jets. Incidentally, this discussion demonstrates that the high speed impulsive noise from helicopters, which is directly due to shock effects, must also contain regions which decay at less than inverse square law.

Thus the formation of local regions of high acoustic intensity, which do not obey the inverse square law radiation process, is not in principle an unexpected phenomenon. The analysis of the BVI process above demonstrates that this local formation of high sound levels is a direct consequence of the phase relations associated with the blade vortex interaction process.

The practical consequences of this observation appear significant. It is common experience that the passage of a helicopter overhead produces a noise which has substantial variation in observed level. This effect appears to be explained by the local appearance of high levels of noise. This process has not be examined properly in previous experimental work, basically because it has been assumed that all the noise radiation processes must obey an inverse square law. It is the case the noise intensity as a whole will obey an inverse square law. This is required by the principle of conservation of energy. But this does not apply to every element of the sound field in isolation, so that localised variations from inverse square law decay do not violate conservation of energy.

The strength of the focusing effect depends on the geometric scales of the rotor acoustic processes. It would be expected that the effects would generally be more significant close to the rotor, but creation of focused regions for BVI noise could occur at significant distances from the rotor under unfavourable combinations of rotor parameters. This feature of the process has not yet been investigated in detail.

7. Discussion

The initial results demonstrate that the directionality of the rotor noise varies systematically with advance ratio (cf. Fig 12) , as was also shown in the computational approach of Ref 19. This is a result of the repetitive nature of the shed vortex wake. In turn this suggests that the directionality of the BVI noise radiation from a helicopter could be a strong function of advance ratio, and thus that it might be possible to advise pilots of speed selections which would minimise the noise in any direction of interest. This could have considerable tactical potential, and also has clear interest for civil applications.

Figure 12 also offers the possibility of searching for advance ratios which have minimum noise generally. It will be clear that there are so many maxima at low advance ratio that there is little prospect of identifying any useful flight regime for low noise. However, at higher advance ratios the effects are more helpful. It would appear that a minimum in the BVI noise for this particular rotor would be found at an advance ratio of around 0.3. However, it seems possible that other combinations of rotor parameters could be found which might provide a cruise speed optimum which would minimise noise in nearly all directions.

Further, as shown in Figure 11, it is possible to identify the region of the disc where the interaction which generates the critical noise process occurs. Thus in principle it should be possible to target aerodynamic modifications to the rotor to minimise the source strength at the disc location where maximum acoustic radiation efficiency might be anticipated.

The current model has been considerably simplified for analytic convenience. In particular it does not include any wake contraction effects, or any other effects caused by self interaction of the shed wake. These will cause variations in the position and shape of the vortex wake, which will in turn cause variations in the efficiency and directivity of the radiated noise. However the basic principles outlined will still apply. Further, since the physical basis of the model is simple, it should be straightforward to calculate the equivalent effects from prescribed experimental or computational results. In a recent paper by Tung et al [Ref 24] it has been shown that although the general form of the blade vortex interaction geometry follows the simple theory, details of the geometry can vary quite significantly from prediction, whether of the simple kinematic type, or from more complex computational approaches. Thus it must be expected that the detail predictions of the present simple model will be subject to error. However it appears that the general conclusions and trends predicted by the model should reappear in any fuller analysis.

In the present paper no examination of noise peaks away from the rotor disc has been presented. Extension to observation points outside the plane of the disc is simple. A more complex task is to undertake the systematic inspection of the results to determine the major features which justify further study. The analysis has demonstrated that the detailed description of the rotor radiation is astonishingly complex. However the use of the present kinematic model should provide a tool for identifying potential areas of concern from the noise view point which can be studied in more depth with a fuller computational approach.

The model proposed will only provide details of the kinematics of the helicopter noise, and thus the location of noise maximums as a function of rotor configuration. An analytic solution to the model problem allows the solution space to be searched effectively. Further work is in progress on the possibility of extending the model to include an estimate of noise levels. Ringler, George and Steele [Ref 16] used the basic accelerating source model of Lowson [Ref 25] to provide estimates of level. This approach can be considered, but does have mathematical difficulties at the peak condition because of singularities in the integral, as discussed previously. The same problem applies to the Ffowcs Williams and Hawkings formulation [Ref 26]. A suitable extension of the model could give a first order prediction of levels at the peaks. This would appear to offer the possibility of a rapid prediction model for helicopter noise, which could be used effectively for design optimisations.

The existence of highly localised areas of peak noise from helicopter rotors appears to offer an explanation for many features of the process which have previously been obscure. Anyone who has listened to helicopter noise will have noted the appearance of major peaks in the signal. Previous explanations would have centred around the strong variability of the aerodynamics of the shed wake. It can now be seen that this variability is an essential part of the acoustic radiation process. However, it would be predicted that passage of a helicopter at precisely controlled operating conditions would always cause peak noise levels in the same direction. This prediction could be checked by a carefully controlled experiment.

The fact that the high intensity parts of the field will decay at a rate less than inverse square law raises a number of new issues. All examination and estimation of community noise response has explicitly assumed that the sound will vary as the inverse square. In many cases laboratory tests have given results which appear to be at variance with experience in the field. It is well known that helicopter noise is often found to be more annoying than equivalent fixed wing aircraft noise of the same nominal level. This has previously be attributed to psychological effects etc. The existence of strong localised peaks in the sound field provides an alternative potential explanation for this issue. If this explanation is correct then new approaches to estimation of annoyance may be required. On the other hand the model also offers new approaches to minimise the problems which result.

8. Conclusions

A kinematic model for acoustic processes in helicopter blade vortex interaction noise has been developed which provides new information on the key features of the directionality. New explicit expressions for the noise radiation directivity as a function of helicopter rotor parameters have been presented. The model captures the key effects of the retarded time integral, and equivalent results would be found from any analytic or computational study which included the full phase effects of both source and propagation. Some further effects will be expected from the variation of the aerodynamic source strength, for example due to blade vortex separation, as a function of operating condition.

The model has demonstrated the exceptional complexity of the radiated noise field from a helicopter. The most interesting feature of the results is to show that parts of the radiated field do not decay according to the inverse square law. The BVI process produces local regions of intense focused noise. This phenomenon is parallel to effects described in other applications as "acoustic missiles". This finding appears to have wide consequences both for the evaluation of community annoyance and for detectability of helicopters

The model gives direct information on the directionality of the noise radiation from the helicopter. This can be used to suggest possible operational approaches which can minimise the noise radiated to particular locations in the far field. It can also be used to identify regions of intense noise radiation for particular helicopter configurations, which can become the focus for more detailed computational attack. The work also gives improved understanding of the relation of details of the vortex interaction process to noise radiation, and can thus provide suggestions for local aerodynamic control to reduce noise. Finally, the work gives suggestions for noise control which can be examined experimentally.

Acknowledgements

The work reported herein has been supported under contract from the US Army to Flow Solutions Ltd and by a Grant from the EC to the University of Bristol. A version of this paper was presented at the recent European Rotorcraft Forum [Ref 27]

References

1. F.H. Schmitz, and Y.H. Yu, 1986 *J. Sound Vib.*,Vol 109 Pt3 pp361-422, "Helicopter Impulsive Noise: Theoretical and Experimental Status"
2. F.H. Schmitz, and Y.H. Yu, 1981 *Vertica* Vol 5 1981 pp55-74 "Transonic rotor noise - theoretical and experimental comparisons"
3. M.V. Lowson, and J.B. Ollerhead, 1968 *USAAVLABS Technical Report* 68-60 "Studies of Helicopter Rotor Noise",
4. M.V. Lowson, and J.B. Ollerhead, 1969 *Journal of Sound and Vibration*, 9, pp. 197-222 "A Theoretical Study of Helicopter Rotor Noise"
5. M.V. Lowson, 1992 *Aeronautical Journal* pp209-223 " Progress Towards Quieter Civil Helicopters"
6. R.M. Martin, M.A. Marcolini, W.R. Splettstoesser, and K-J Schultz, 1990 *NASA Technical Paper* 3015 "Wake Geometry Effects on Rotor Blade-Vortex Interaction Noise Directivity"
7. S.E. Widnall, 1971 *J. Acoust. Soc. of America*, Vol. 50, No. 1. (part 2), pp354-365, Helicopter Noise due to Blade-Vortex Interaction
8. G.H. Bryan, 1920 *Aeronautical Research Council R&M* 684 The acoustics of moving sources with application to airscrews
9. D.L. Hawkings, and M.V. Lowson, 1974 *J. Sound Vib* Vol 36 pp1-20 (1974) Theory of Open Supersonic Rotor Noise
10. M.V. Lowson, and R.J Jupe, R.J 1974 *J.Sound Vib* Vol 37, pp475-489. Wave Forms for a Supersonic Rotor
11. H. Ardavan, 1994 *J. Fluid Mech.* Vol 266 pp33-68 Asymptotic Analysis of the Radiation by Quadrupole Sources in Supersonic Rotor Acoustics
12. H. Ardavan, 1989 *Proc Roy Soc Lond* A Vol 424 pp113-141 The speed of light catastrophe
13. M.K. Myers, and R. Wydeven, 1991 *AIAA J* Vol 29 N09 pp 1374-1382 Sep 1991 Asymptotic/Numerical Analysis of Supersonic Propeller Noise
14. M.K. Myers, and F. Farassat, 1987 *AIAA* 87-2676 Structure and Propagation of Supersonic Singularities from Helicoidal Sources
15. J.E. Ffowcs Williams, 1994 *Paper in Symposium on Aerodynamics and Acoustics, Ed K.-Y. Fung World Scientific* pp39-48 Supersonic Sources Make Focused Waves

16. A.R. George, C.D. Coffen, and T.D. Ringler, 1992 Paper 92-02-087, *DGLR/AIAA Aeroacoustics Meeting* Advances in Tilt Rotor Noise Prediction
17. T.D. Ringler, A.R George, and J.B. Steele, 1991 Paper at *AHS/RAeS meeting on Rotorcraft Acoustics, Philadelphia,* A study of blade vortex sound generation and directionality
18. B. W-C Sim, and A.R. George, 1995 Paper at *AHS 51st Meeting* Development of a Rotor Aerodynamic Load Prediction Scheme for Blade Interaction Noise Study
19. C.J. Open, and R.J. Patrick, 1993 Paper at *17th European Rotorcraft Forum* Directionality of Blade Vortex Interaction Noise
20. T.S. Beddoes, T.S., 1985 Paper at *AHS Conference* A Wake Model for High Resolution Airloads
21. J.N. Brittingham, 1983 *J. Appl Phys* 54(3) pp1179-1189 Focus wave modes in homogeneous Maxwell's equations: Transverse electric mode
22. T.T Wu, 1985 *J.Appl Phys* 57 (7) pp 2370-2373 Electromagnetic Missiles
23. H.E. Moses, and R.T Prosser, 1990 SIAM J. Appl Math Vol 50 No5 pp1325-1340 Acoustic and Electromagnetic Bullets: Derivation of New Exact Solutions of the Acoustic and Maxwell's Equations
24. M.V. Lowson, 1965 *Proc Roy Soc* A Vol 286 1965 pp 559-572 The Sound Field for Singularities in Motion
25. J.E. Ffowcs Williams, and D.L. Hawkings, 1969 *Phil. Trans. Roy. Soc.* A264, pp. 321-342, Sound Generation by Turbulence and Surfaces in Arbitrary Motion
26. C. Tung, J.C. Gallman, R. Kube, W. Wagner, B. Van der Wall, T.F. Brooks, C.L. Burley, D.D.Boyd Jr., G.Rahier, and P. Beaumier 1995 *Paper at AeroAcoustics Conference* CEAS/AIAA-95-051 Prediction and Measurement of Blade Vortex Interaction Loading
27. M. V. Lowson 1995 Paper No I-10 at *21st European Rotorcraft Forum, Saint Petersburg Russia* Directionality of Helicopter BVI Noise

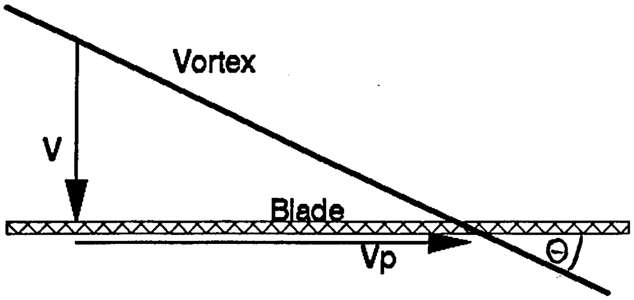


Figure 1 Blade Vortex Interaction

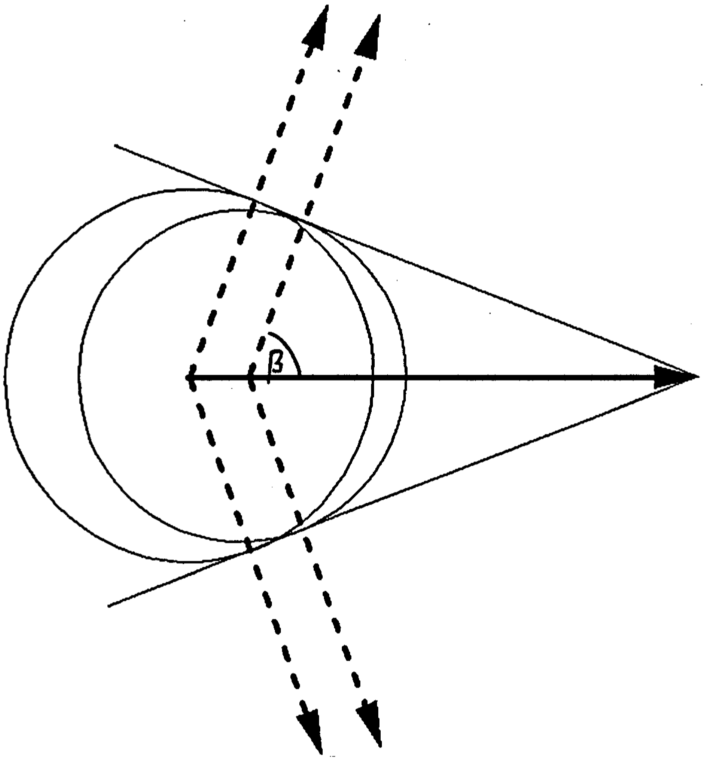


Figure 2 Formation of Mach Cone

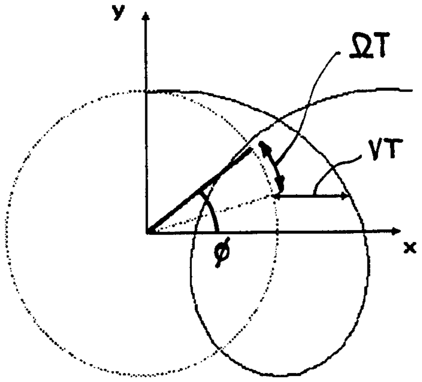


Figure 3 Wake Interaction Geometry

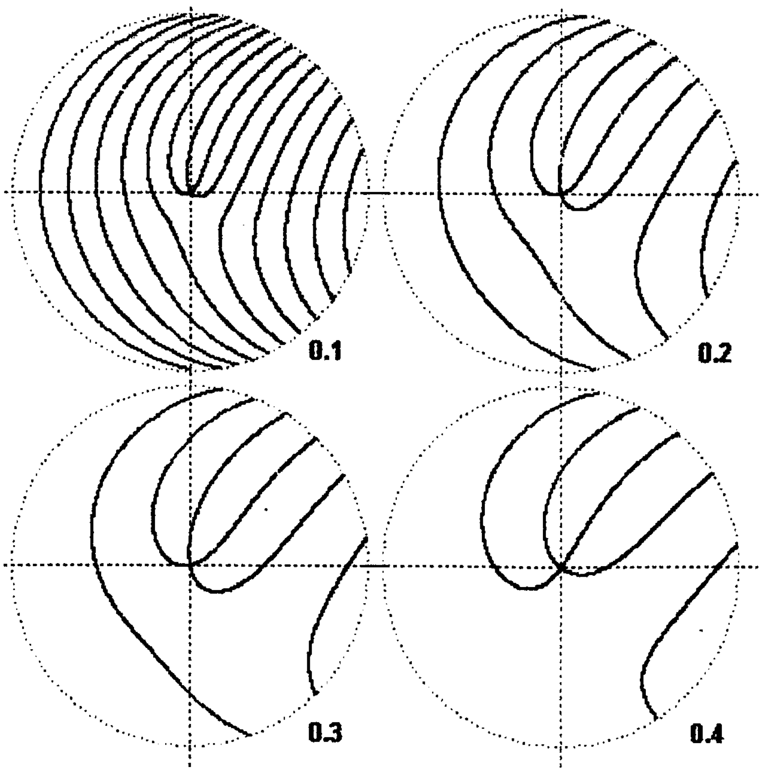


Figure 4 Blade Vortex Interaction Loci in Disc

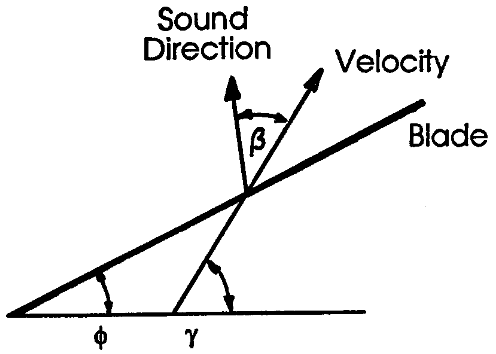


Figure 5 Directionality of Radiation from Blade Vortex Interaction

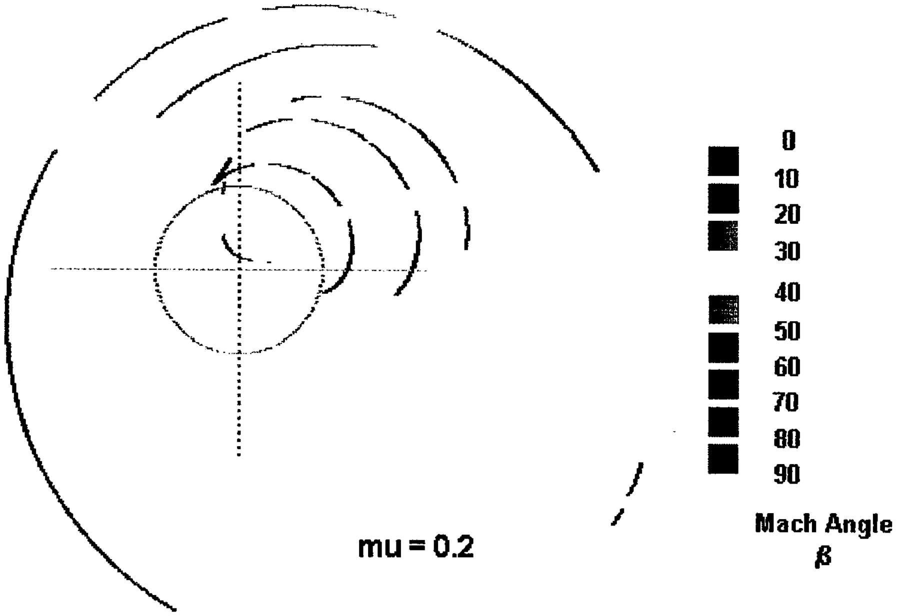


Figure 6 BVI Radiation Patterns for Advance Ratio 0.2

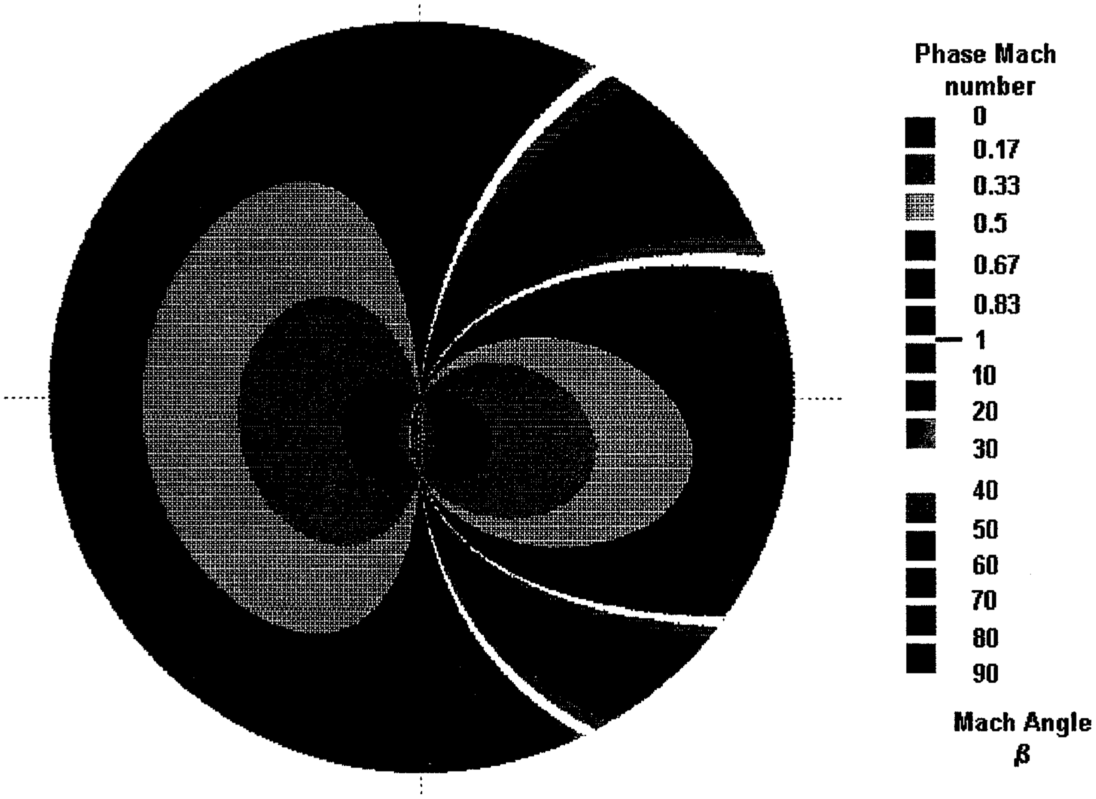


Figure 7a BVI Phase Speeds Over Disc Advance Ratio 0.2

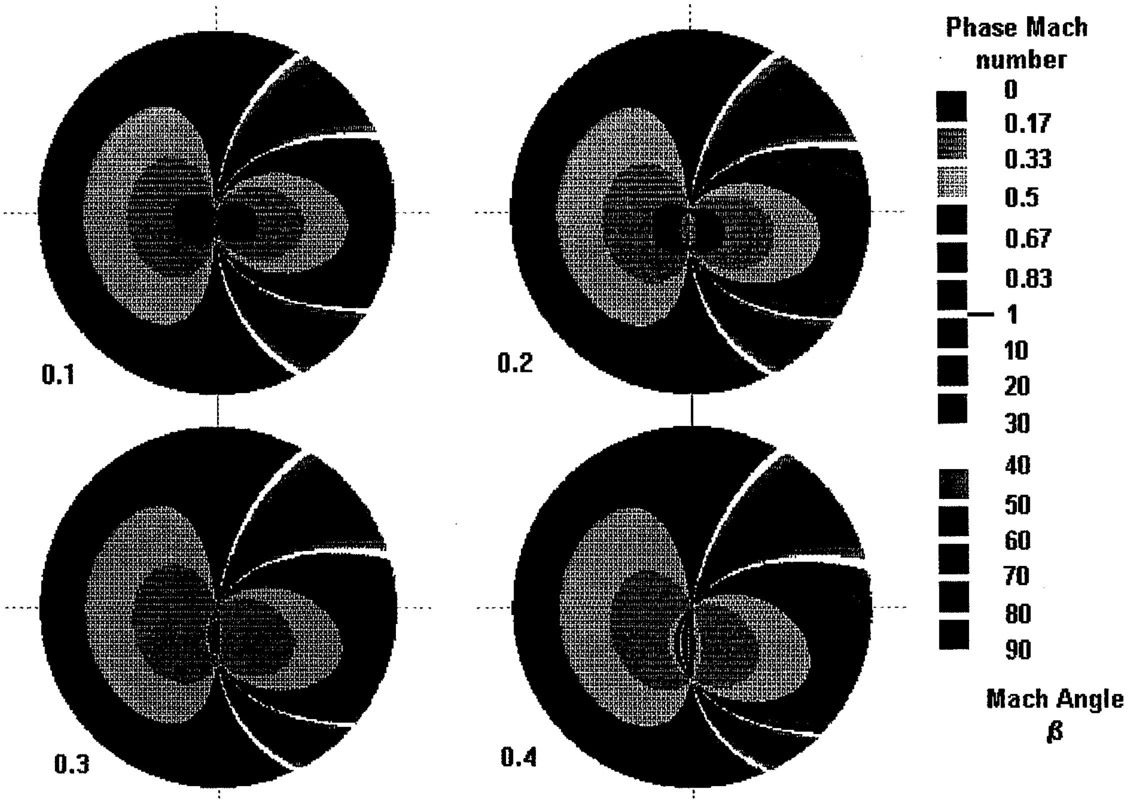


Figure 7b BVI Phase Speeds Over Disc for Several Advance Ratios

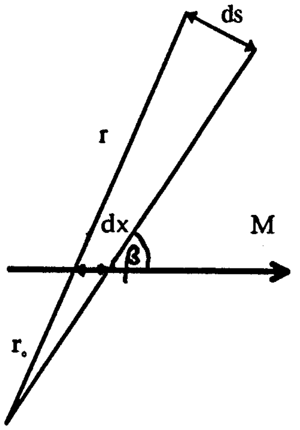


Figure 8a Diagram Showing Formation of Far Field Acoustic Signal

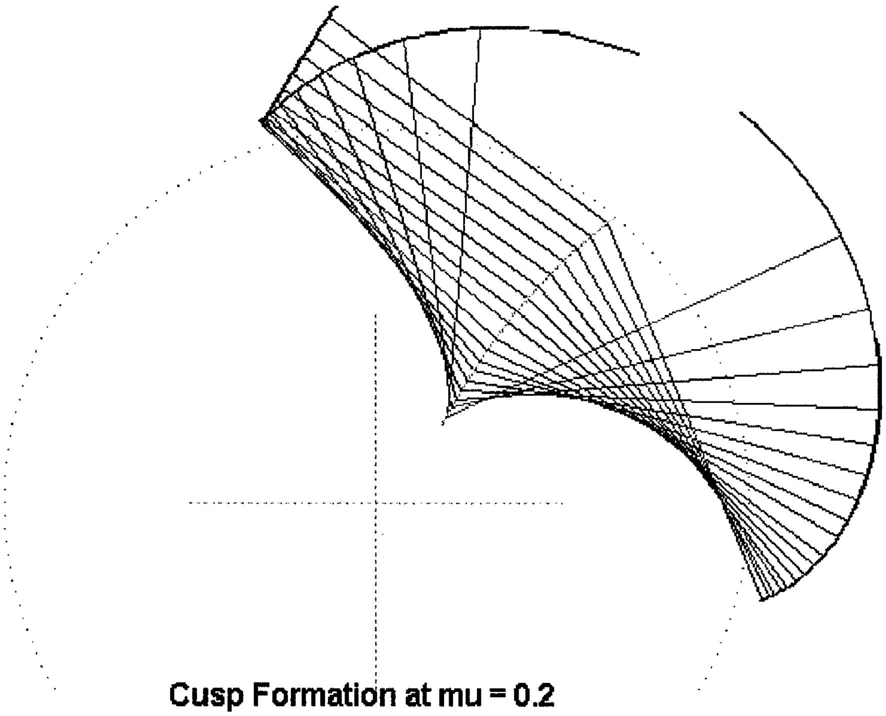


Figure 8b Focussing for Advance Ratio 0.2

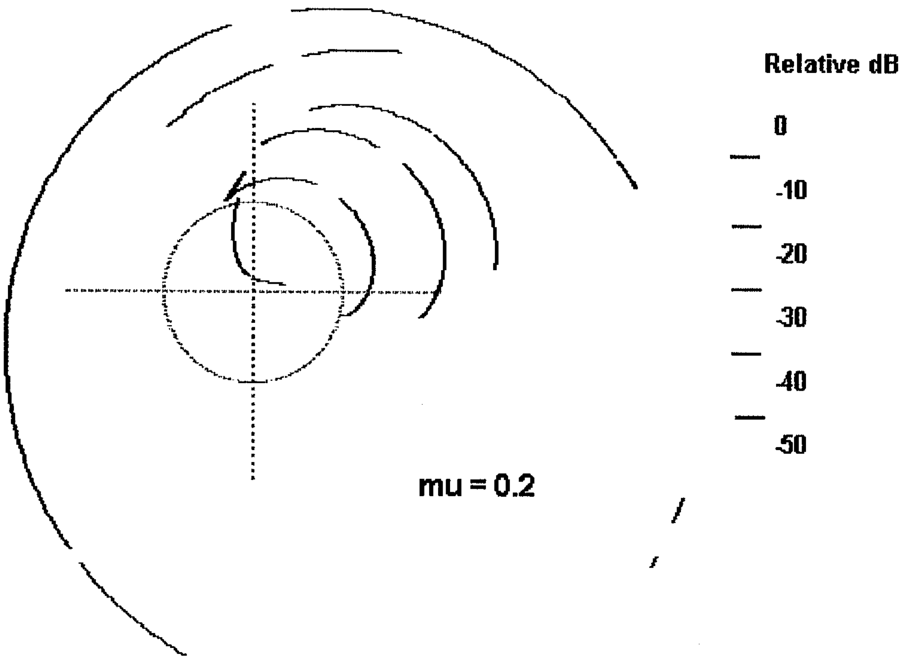


Figure 9 BVI Radiation Patterns for Advance Ratio 0.2 Showing Relative Strengths

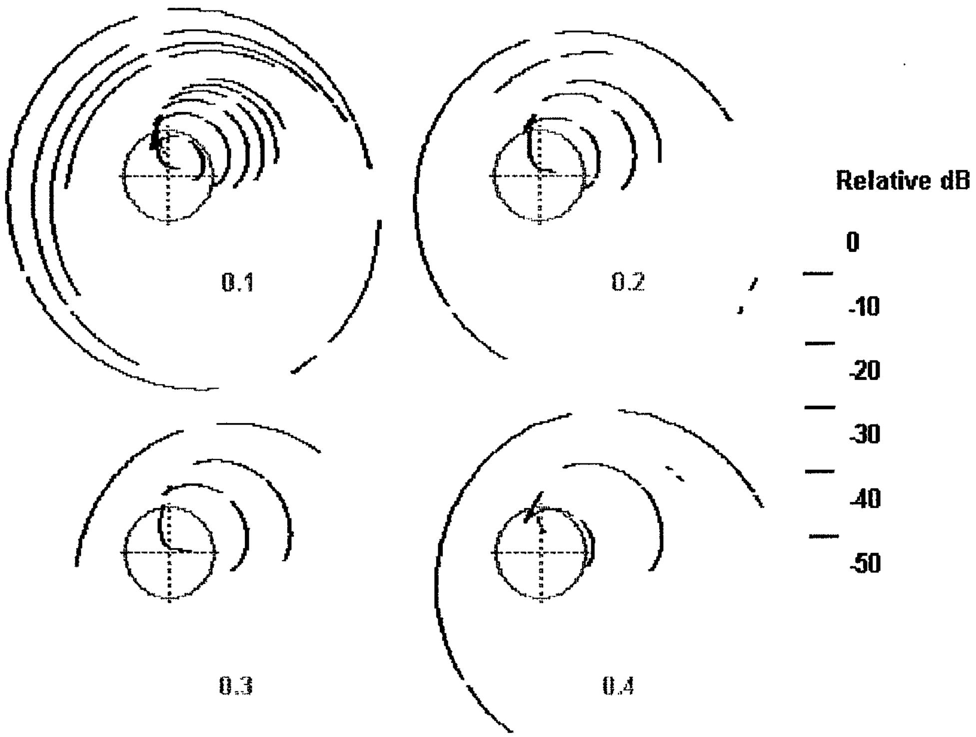


Figure 10a BVI Radiation Patterns for Advance Ratios 0.1 - 0.4 Showing Relative Strengths

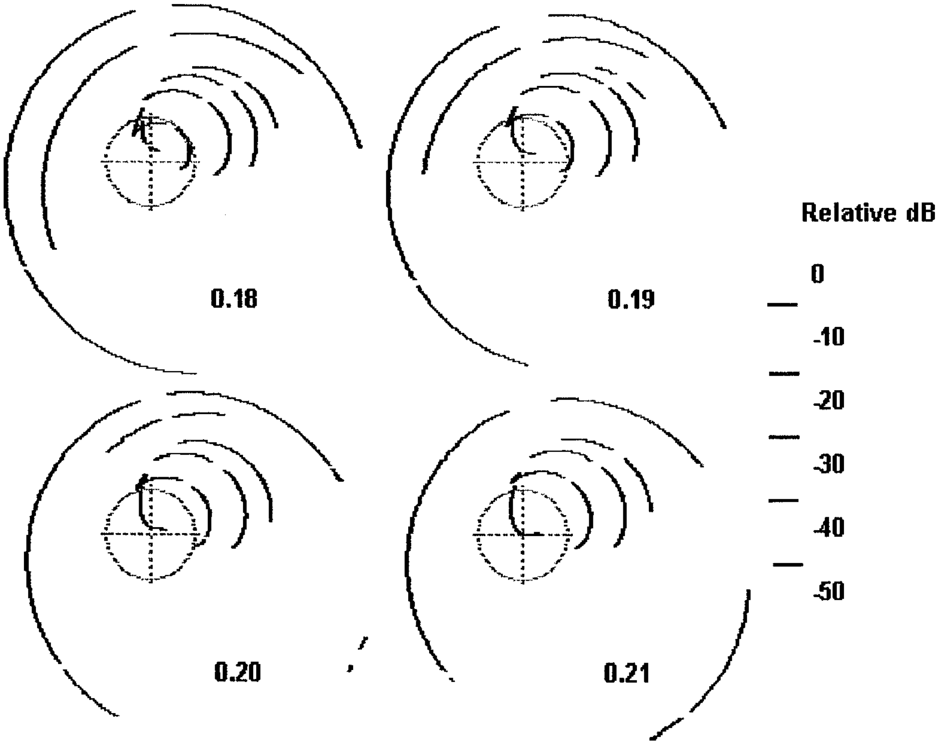


Figure 10b BVI Radiation Patterns for Advance Ratios 0.18 - 0.21 Showing Relative Strengths

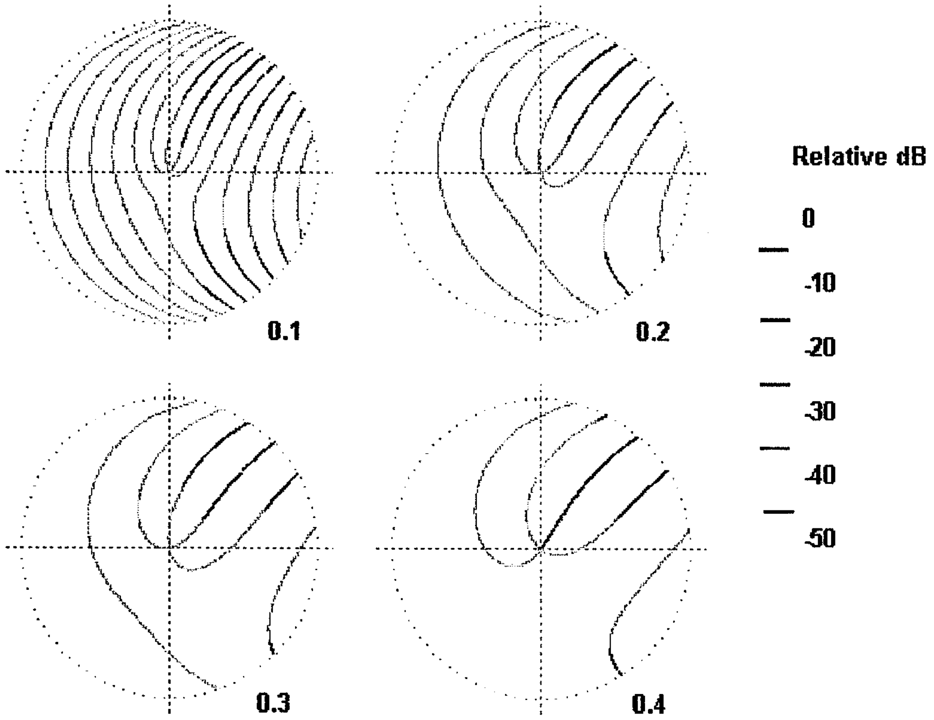
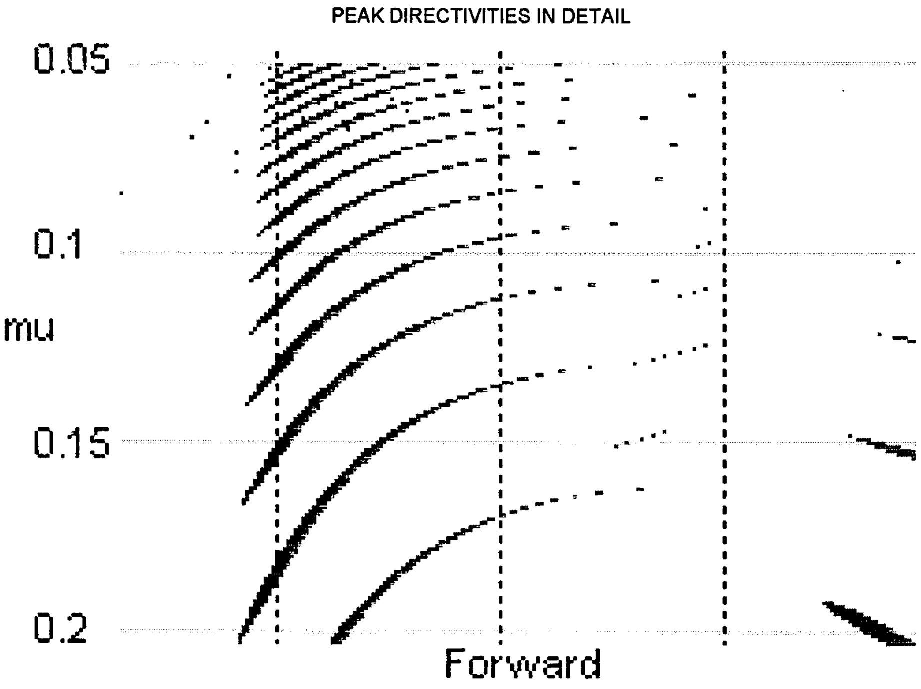


Figure 11 Source Locations in Disc Plane for Advance Ratios 0.1 - 0.4



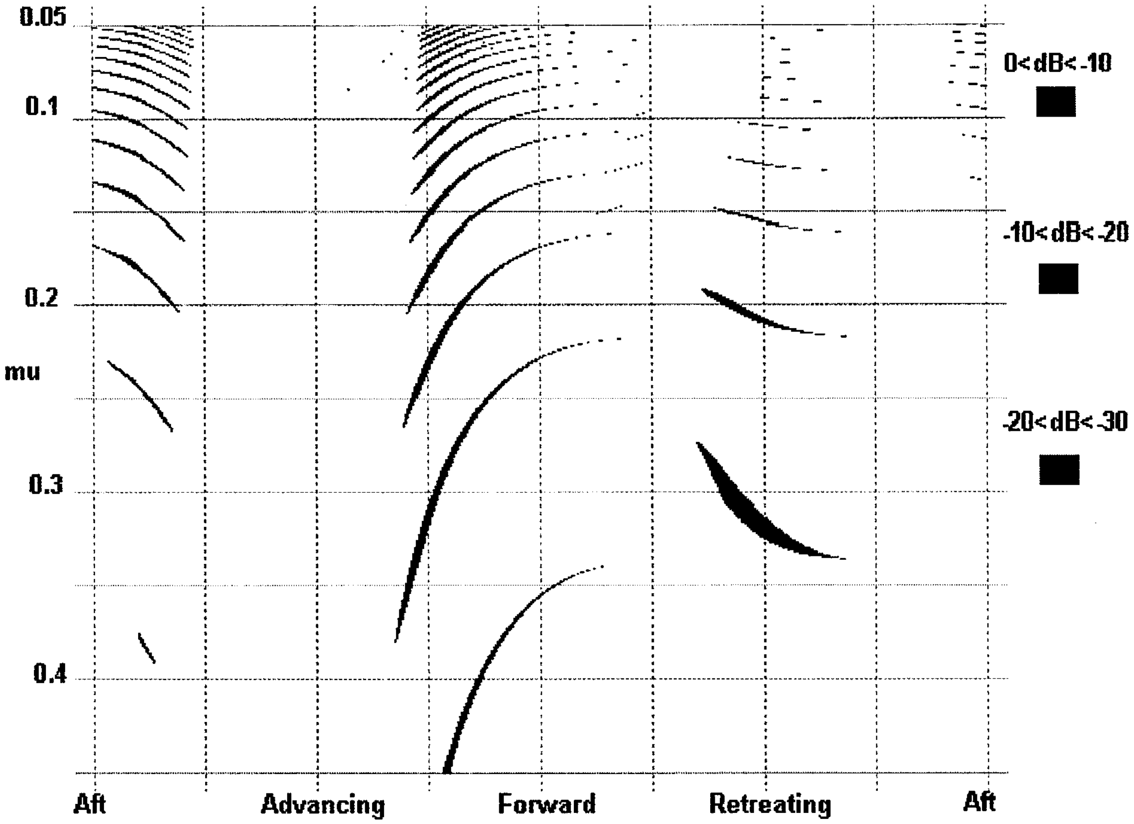


Figure 12 Location of BVI Radiation Peaks in Disc Plane versus Advance Ratio