NINETEENTH EUROPEAN ROTORCRAFT FORUM

Paper no. B5

DIRECTIONALITY OF BLADE VORTEX INTERACTION NOISE

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September 14-16, 1993
CERNOBBIO (Como)
ITALY

ASSOCIAZIONE INDUSTRIE AEROSPAZIALI
ASSOCIAZIONE ITALIANA DI AERONAUTICA ED ASTRONAUTICA

DIRECTIONALITY OF BLADE VORTEX INTERACTION NOISE

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Summary

A simple computational model has been developed to predict the phase speed of the blade vortex interaction process. Intense Blade Vortex Interaction (BVI) noise is related to supersonic phase speeds along the blade. A. George has pointed out that such radiation produces noise which will be localised in a Mach cone associated with the phase speed. Thus each BVI process is associated with a particular direction of radiation, and localised effects at the ground. The directionality of such BVI interactions has also been computed.

Initial work was undertaken using a simple kinematic model. Fuller studies have also been undertaken using the Beddoes model of the free distorted wake from the rotor. The results demonstrate the strong directionality of the noise under BVI conditions at moderate and high advance ratio. The results indicate test points for examination during fuller computational studies of the problem, and should be of immediate value to determine ground locations which could be particularly impacted by BVI noise, and to examine the possibility of choice of rotor parameters which might minimise the effects.

1 Introduction

1.1 Background

The operation of helicopters over urban areas is limited by the high levels of noise they can produce during certain flight conditions. This is a major disadvantage to helicopter flight and it prevents wider application of civil helicopters. Blade Vortex Interaction (BVI) noise is the most intense source of noise occurring during helicopter operations. The appearance of this form of noise is sensitive to operating conditions, and it is also found that the noise can be highly localised. The certification requirements for a helicopter include noise level tests at three modes of flight, including flyover, approach and landing. It is the aim of the designer to ensure that the helicopter will meet the certification requirements. Few rules or methods of design are available to the designer to predict and/or minimise the noise levels that will be produced by a particular helicopter design. Different types of noise in terms of intensity and frequency are produced by a variety of sources around the helicopter, including the engines and main and tail rotors. A greater understanding of the various noise mechanisms present should enable development of design methods which reduce noise, making the wider use of helicopters much more attractive. A fuller review of present understanding and developments in methods to reduce helicopter noise is given by Lowson (1992).

BVI noise is both intense and in the frequency range of the human ear. Reducing this type of noise would considerably lower the Percieved Noise Level. Redesigning the rotor blades or avoiding operating conditions that cause the highest levels of noise are seen as the most likely methods of reducing this type of noise from helicopters.

Most studies of BVI noise have centred, for obvious reasons, on establishing the levels of the noise as a function of rotor parameters. There have also been a variety of theoretical and experimental studies which model BVI noise as a two dimensional interaction process. However the key features of the BVI process are three dimensional, and it is possible to obtain information about features of the noise field by a simple approach which retains the key three dimensional features of the situation.

1.1 First Principles

It is assumed that vorticity shed by a blade rolls up into a concentrated vortex at the tip by the time the following blade gets to the same position. From a viewpoint perpendicular to the rotor disc, there is a distinctive cycloidal geometry to the wake. The basic two-dimensional kinematics of the interaction process between the main rotor blades and wake are also described by Figure 1. As the blades rotate, a blade may intersect a wake vortex in such a fashion that the two are either nearly orthogonal or nearly parallel, or at some skew angle in between. The geometry of the wake is very sensitive to flight conditions and this is covered in **Theory**. However, there is always some interaction between the blades and the wake in the manner described above. 'Blade Slap' is the term used to describe when the interaction is of the more parallel type, since the intensity of noise produced is high.

Beddoes' Free Wake Model (Beddoes (1985)) is a three-dimensional model that approximates the main features of the wake geometry. The cycloidal pattern of the x and y coordinates of the vortices is displayed by the model. Also, the axial displacement component of the wake geometry is determined. This displacement is in the z-direction, perpendicluar to the plane of the rotor. With a three-dimensional wake model, the three-dimensional interaction process between the blades and the vortices can be analysed. In other words, although a blade and vortex may intersect when viewed perpendicular to the rotor disc plane, the vortex may actually pass above or below the blade.

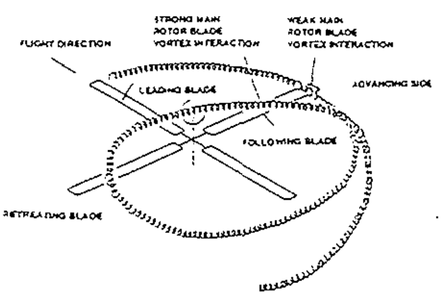

Figure 1 Formulation of BVI for a four-bladed rotor *(from Schlinker and Amiet (1983))*

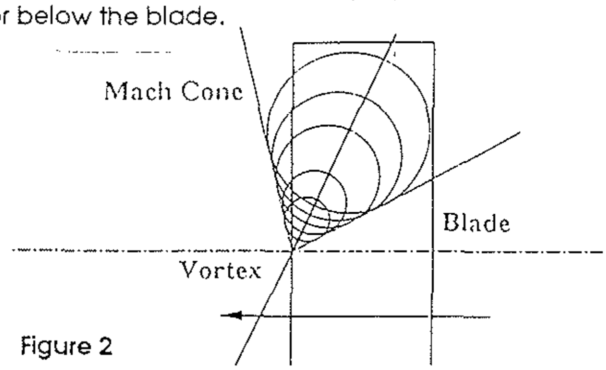

Figure 2
Schematic Geometry of Mach Cone Formation

There is a change in the velocity of flow over the blade as a consequence of the induced velocity from the vortex. This may be to either decrease or increase the total flow velocity at the blade section, depending on whether the vortex passes above or below the blade at the point of intersection. The mathematical model of the vortex used is due to Scully (1975). The local lift force produced by a section of the blade is proportional to the square of the velocity of flow over that section. If there is a sudden change in the magnitude of the local flow velocity, as would be the case with the intersection of a blade with a vortex then there would be a sudden and considerable change in the local blade loading. The three-dimensional geometry of the interaction process between the blade and the vortex is analysed to implicitly predict the increased local loading. In other words, the change in local loading causes a pressure pulse to be emitted from the point of intersection. The static pressure at the leading edge of the blade changes rapidly from a steady value to some peak value and back again to the steady value as the vortex passes the aerofoil. It is this pressure pulse that is radiated from the observed point of interaction. If the interaction process causes a pressure pulse of such magnitude that there is a release of sound energy, then this energy, or noise, is radiated in all directions from the observed point of interaction.

The point where the interaction of the blade with the vortex is most intense is called an intersection point, since the blade and the wake intersect here. As the blade continues to rotate, it may continue to interact with the same wake. If the geometry of interaction is observed at discrete time steps, a string of intersect points is created along the blade. See Figure 2. The rate at which these intersect points occur along the blade may be termed the 'phase speed'. In other words, as the time step between observations gets very small, the intersect point effectively moves continuously along the blade leading edge with the phase speed. When the phase speed of the intersection point is supersonic, the result is a highly efficient acoustic radiation process. This noise mechanism was first identified by Lowson and Ollerhead (1968) and investigated in detail by Widnall (1971). The propagation of the pressure pulse along the blade is such that the wave fronts from a series of intersections combine to form an 'envelope'. This 'envelope' is physically similar to a Mach cone. The interaction process described above was first termed the 'Mach cone' noise mechanism by George and Chang (1984). The result is very intense noise which is highly directional to the far field as a result of the kinematics of the interaction.

1.2 Aims of this Research

It was hoped that this study should give a better understanding of the kinematics of the three-dimensional Mach Cone noise mechanism that produces intense BVI noise. The detailed physics of the interaction process are not modelled, to keep computation time low. The accuracy of the results, it was hoped, should be good since the dominant feature of the interaction process under study is the kinematics, rather than the detailed physics of the event at the blade. The locations of the intersections in the rotor disc area will be associated with locations in the far field where the intense noise is directed. Various operating conditions will be studied to assess the effect of varying certain parameters on the resulting directions of noise propagation.

2 Theory

Blade Vortex Interaction is a complex phenomenon that can only be fully described by firstly solving the Navier-Stokes equations which exactly define the air flow through the rotor (Srinivasan et al (1992)). In this paper, assumptions and generalisations will be made to greatly simplify the situation, while retaining the most important features of the interaction process.

2.1 Locating the Intersection Points

As already suggested, the wake geometry has a cycloidal pattern. The rotation of the main rotor blades through the wake will cause interactions between the two. The interaction may be nearly orthogonal, parallel or at some skew angle in between. The points of intersection can be plotted in the disc plane and the significant regions are approximately

i) for the advancing blade, 30-90°,

ii) for the retreating blade, 270-330°

since this is where the more parallel interactions occur. The more parallel intersections occur at various radial positions throughout the range of azimuth angles. The location of blade vortex interactions is very sensitive to operating conditions. Most fall within the ranges of blade azimuth angle, as above. Considering the angle of interaction alone, the strength of the BVIs is strongest when the interaction is parallel.

2.2 The Three-Dimensional Wake Geometry

The geometry of the wake has been described as being cycloidal in nature. In short, the 'wake geometry is defined by the coordinates of the vortices trailed from the blade tips' (Beddoes (1985)). The density of the individual wakes left by the rotation of the blades is dependant on the forward speed (advance ratio) and the number of blades on the rotor. With time, it has been shown that there is a marginal contraction of the wake. For this research, the contraction of the wake was assumed negligible. This assumption is reasonable for our purposes, since only the wake within the rotor disc area is of concern.

The downward component of air flow through the rotor, gives the wake an axial, or z-, displacement. The loading along the blades (or across the disc) is not constant, since the air flow rate through the rotor disc is not constant across the disc. Therefore, the axial displacement of individual wake elements is not constant across the disc. Indeed, the axial displacement of the wake is complex.

Any accurate 3-dimensional wake model will take account of the fundamentals of helicopter flight mechanics. If this is done, then the structure of the wake model will be dependent on operating conditions described by parameters such as helicopter mass, advance ratio and tip-path plane angle of incidence, for example. Beddoes' free wake model is one such model that approximates the principal three-dimensional features of the wake geometry. This wake model is based on the blade loading concept.

2.3 The Mach cone BVI noise mechanism

If the interaction of a blade with a vortex is observed at discrete time steps, a series of pressure pulse sources is created along the blade (see Figure 2). The pressure pulse signal that is generated radiates away from the emission point at the speed of sound. If the rate of propagation of the point of intersection is greater than the speed of sound, then a Mach cone is effectively formed. Interaction between a blade and a vortex has been deemed of interest when the two are almost parallel. The induced velocity normal to the blade leading edge will be high in this case, giving a high level of noise. Further to this, the kinematics of such an interaction are more likely to produce an intersection point propagating at supersonic speed. The significance of the parallel interaction process is therefore twofold, and much experimental work has involved the study of an aerofoil interacting with a vortex with such an (almost) parallel geometry. The envelope formed is the same fundamental principle in the formation of a Mach cone. The wave front of the Mach cone is simply made up of the continuous string of radiated pressure pulse wave fronts from the continuous string of sources. Therefore, the wave front signal is the same as that of the pressure pulse.

It is possible that the detailed physics of the process would reveal some abiguity in determining the exact position of the pulse, specifically whether or not it is exactly at the position of the intersection. However, it is reasonable to assume that the pulse is effectively at the intersection point.

Taking observations of the interaction process at discrete rotation (or time) intervals, reveals the simple principle behind the formation of the Mach cone, as described above. However, the cone may 'bend' i.e. the pressure pulses causing a cone may not lie along a straight line. This will, of course, be due to the geometry of the interaction process. The more parallel the blade and vortex length are, the 'straighter' the Mach cone will be. There is no stretch of the wake that is perfectly straight and so there will always be some curve to the Mach cone. The effects of this curve are seen when the locations of BVI noise on the ground are determined.

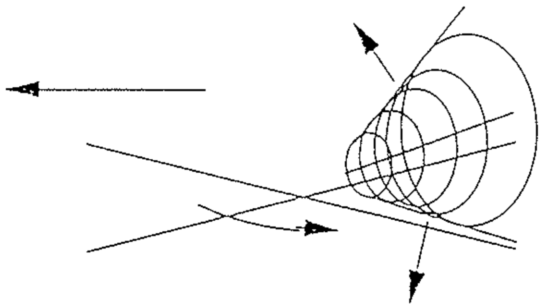

Figure 3 Growth of the Mach Cone

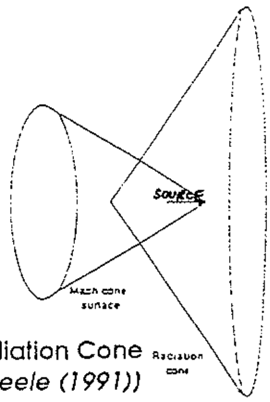

Figure 4

The Mach Cone and the Radiation Cone
(from George, Ringler and Steele (1991))

While the point of intersection continues to move at supersonic speed, the cone continues to be formed as the envelope of sources continues to grow in length. As soon as the propagation of the pressure pulse is at a subsonic speed, the Mach cone ceases to be formed. Figure 3 describes how the cone formed then 'grows' as the wave fronts that form the surface radiate in a direction which is normal to the centre-line of the Mach cone. The centre-line of the cone remains stationary in space as the helicopter moves forwards, and as the wave fronts propagate.

2.4 Formation of the Radiation cone

Returning to the idea of the Mach cone being made up of a series of circles, each corresponding to an earlier intersection between a blade and a vortex. The parabolas marked out on the ground are the loci of points from the intersections between each of the individual circles and the ground plane. A circle will radiate normal to the wavefront, and describe a 'Radiation cone'. See Figure 4. The intersections of the radiation cones with the ground mark out parabolas. The direction of the noise becomes asymptotic to two directions in the far field from a single Blade Vortex Interaction.

2.5 Vortex Induced Velocity and Relative Noise Intensities

The sudden change in pressure at the blade section (due to the velocity induced by the vortex) causes a change in the local blade loading, or local lift force produced. Before the interaction, the local lift,

$$L \propto (U)^2$$

where U is the flow normal to the blade section. When there is a BVI, there is a velocity induced by the vortex, u, such that the local lift becomes,

$$L \propto (U+u)^2$$

Therefore, neglecting small terms, the change in local lift is proportional to uU. Calculation of this term, uU, is analogous to determining the magitude of the pressure pulse, or acoustic signal.

The vortex induced velocity is determined using the method below. This calculation involves a more detailed study of the vortex structure which can be modelled mathematically. The vortex circulation strength (Γ) is given by:

$$\Gamma = \frac{2.4 C_T c R \Omega}{\sigma} \qquad (2.1)$$

where C_T is the thrust coefficient, c the blade chord, R the blade radius, Ω the rate of rotation, σ the rotor solidity.

This equation was used by Beddoes (1985), and therefore consistency is maintained in the approach to the analysis of the wake. For a circular vortex, the circulation is given by,

$\Gamma = q \cdot 2\pi r'$ where q is the velocity, r' the radial distance from the vortex centre. (2.2)

A widely used model for the structure of the vortex, which gives the variation of circulation with radius, is that of Scully (1975):

$$\Gamma_{eff}(\kappa) = \Gamma\left(\frac{\kappa^2}{1+\kappa^2}\right) \qquad \text{where } \kappa = \text{radial distance} / r0 \qquad (2.3)$$

The effective radius of the vortex, r_0, is then given by (Glegg (1991))

$$r_o = \beta R\sqrt{(\pi\psi_w C_T/B)} \qquad (2.4)$$

where B is the number of blades, ψ_W the wake age angle and β a constant in the range 0.15 to 0.5. An estimate of 0.5 was used for β. This was satisfactory as we were only looking at the relative and not absolute noise strength.

A single equation is derived for the velocity induced by the vortex at a particular radius,

$$q = \left(\frac{2.4cR\Omega C_T}{2\pi\sigma r'}\right)\left(\frac{\kappa^2}{1+\kappa^2}\right) \qquad (2.5)$$

The velocity of flow at the surface of the blade will change by a finite amount as a result of the interaction. The static pressure will also change, either decreasing for accelerated flow or increasing for decelerated flow. Only the magnitude of this change is of interest, and it does not matter whether the pressure has decreased or increased. This gives the magnitude of the pulse signal that is radiated from the point of emission.

It is now possible to calculate the total velocity of flow at the blade during the interaction. The change in the velocity of flow is solely due to the vortex induced velocity and this changes the dynamic pressure at the blade. The change in static pressure at the intersection point can be assumed to be of an equal magnitude. Therefore, the change in the velocity of flow at the point of intersection is analogous to the change in the static pressure here; where the two differ only by a constant factor. An estimate of the relative level of noise emitted can therefore be based on the relative change in velocity at the blade, induced by the vortex. This assumption bypasses the need for an accurate analysis of the magnitude of the pressure pulse signal from the point of emission.

The strength of the noise deteriorates with distance from the point of emission. As the Mach cone grows, the sound energy on the surface, i.e. the wave front, is distributed over a wider surface area. The drop in noise strength is inversely proportional to the square of the distance from the emission point at the blade. However, the relative strengths of noise between wavefronts remains the same since the deterioration factor is constant for all wavefronts. As a result, if only the relative strengths of noise are to be predicted, there is no need for a noise deterioration factor to be included in the analysis. This method was simply designed to facilitate comparison of the relative magnitudes of noise from Blade Vortex Interactions.

3 Procedure

3.1 Positions of the Interactions

The method used for finding the positions of blade-vortex interactions involved approximating the vortices by a series of straight lines, projecting these lines into the rotor plane, and then finding the intersection points between the blades and these lines. This not only simplified the geometry involved, but also made it easy to try different wake models. Equations describing the wake explicitly were not needed, only the x, y, z coordinates of enough points on the vortices to describe the geometry sufficiently accurately.

The blade was defined in terms of centre coordinates, x_c and y_c, and an angle from the positive x-direction, θ. (See Figure 5). The wake element was defined in terms of its end points (w_{x1}, w_{y1}, w_{z1}) and (w_{x2}, w_{y2}, w_{z2}). However, the z coordinate becomes zero when the wake element is projected into the rotor plane.

First of all a simple check was carried out to see if either end of the wake element fell into a rectangle defined by the ends of the blade, as shown in Figure 5. If neither end of the element was within this rectangle then there could not be an intersection between the element and the blade, and further calculation for this element and blade was unnecessary. This speeded up the calculation process considerably by avoiding long calculations for a large number of the wake elements. If either or both ends of the element were within this rectangle, the calculation proceeded as follows (see Figures 5 and 6 for definitions of the notation):

$$x_i = \frac{w_{y1} - w_{x1} \cdot m_w - y_c + x_c \cdot \tan\theta}{\tan\theta - m_w} \qquad (3.1)$$

where $m_w = \dfrac{w_{y2} - w_{y1}}{w_{x2} - w_{x1}}$

Once x_i has been found, it is checked to see if it is an actual intersection, or just one between the extensions of the wake element and blade. If x_i is between x_c and x_e, and also between w_{x1} and w_{x2}, then it is an actual intersection.

$$y_i = m_w \cdot (x_i - w_{x1}) + w_{y1} \qquad (3.2)$$

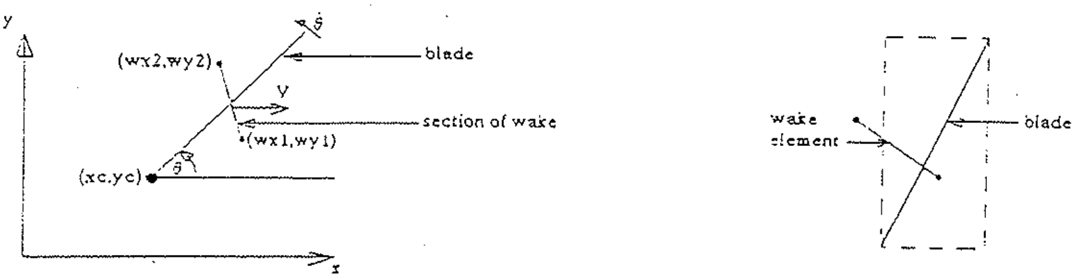

Figure 5 Intersection of a Blade with a section of wake

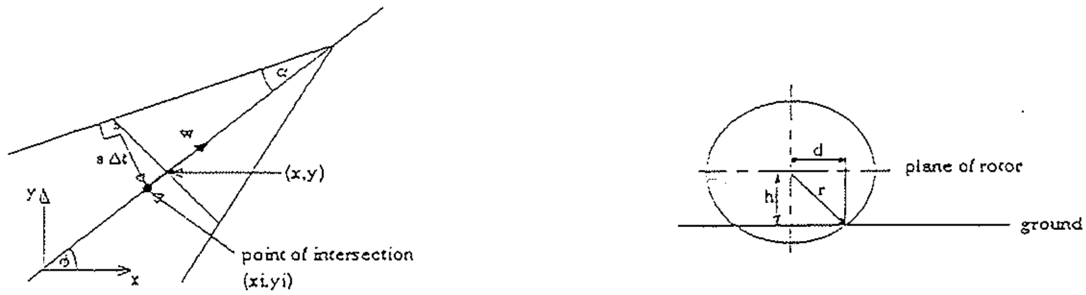

Figure 6 Radiation of Noise from an Intersection

3.2 Calculating the Phase Velocities

The phase velocity of a blade-vortex interaction is the velocity at which the point of interaction moves due to the relative motion of the blade and the wake. As mentioned earlier, the highest velocities will occur when the vortex and the blade are nearly parallel (theoretically, if they were parallel then the phase velocity would be infinite). The velocity at which an intersection moves is found as follows.

Differentiating Equation 3.1 w.r.t. time gives

$$\dot{x}_i = \dot{\theta}\,\frac{(\tan\theta - m_w).x_c - w_{y1} + y_c + w_{x1}.m_w - x_c.\tan\theta}{((\tan\theta - m_w)\cos\theta)^2} - \frac{V.m_w}{(\tan\theta - m_w)} \qquad (3.3)$$

where V is the free stream velocity.

Note that Equation 3.3 above does not apply when $\theta = \pm\pi/2$. This case is avoided in our computation by having a finite number of steps of the blades per revolution, and starting the calculation with the blades rotated from the axes by half the angle they move in each step. This ensures that the blades will never become aligned with the axes, and hence θ will not be $\pm\pi/2$.

Differentiating Equation 3.2 w.r.t. time gives

$$\dot{y}_i = m_w(\dot{x}_i - V) \qquad (3.4)$$

The resultant velocity is therefore

$$w = \sqrt{(\dot{x}_i^{\,2} + \dot{y}_i^{\,2})} \qquad (3.5)$$

at an angle to the positive x-direction of

$\phi = \tan^{-1}(\dot{y}_i / \dot{x}_i)$ (for $\dot{y}_i > 0$ and $\dot{x}_i <> 0$); $\phi = \tan^{-1}(\dot{y}_i / \dot{x}_i) + \pi$ (for $\dot{y}_i < 0$ and $\dot{x}_i <> 0$);

$\phi = \pi/2$ (for $\dot{y}_i > 0$ and $\dot{x}_i = 0$); $\phi = -\pi/2$ (for $\dot{y}_i < 0$ and $\dot{x}_i = 0$). (3.6)

3.3 Finding the Noise Propagation Direction

Once the phase velocity is known, the geometry of the Mach cone associated with it can be determined. The noise from this intersection will propagate perpendicular to the surface of this cone as shown in Figure 6.

In order to find the areas on the ground affected by the noise, the following method was used. Imagine a circle on the surface of the Mach cone which is the part of the cone produced by a particular point intersection. This is the circle where the sphere of radiated noise from the intersection is tangential to the Mach cone. See Figure 6. The centre of this circle will move in the direction of the phase velocity, w, with a speed a.sin α, and expand its radius at rate a.cos α. Therefore at a time Δt after the interaction has taken place, this circle will have a radius r of

$$r = a\Delta t \cdot \cos\alpha \qquad (3.7)$$

and a centre at (x,y) where

$$x = x_i + a\Delta t \cdot \sin\alpha \cdot \cos\phi + V\Delta t \qquad (3.8)$$

$$y = y_i + a\Delta t \cdot \sin\alpha \cdot \sin\phi \qquad (3.9)$$

The $V\Delta t$ expression in Equation 3.8 is to allow for the distance which the air will have moved downstream of the rotor in the time since the interaction occurred.

Therefore, the position and size of this circle are known as a function of Δt. The next step is to find where this circle intersects the ground plane as shown in Figure 6. In general, there will be two points of intersection between the circle and the ground (x_1,y_1) and (x_2,y_2) where

$$(x_1,y_1) = (x - d\cdot\sin\phi, y + d\cdot\cos\phi) \quad (3.10); \qquad (x_2,y_2) = (x + d\cdot\sin\phi, y - d\cdot\sin\phi) \quad (3.11)$$

$$d = \sqrt{(r^2 - h^2)} \qquad (3.12)$$

4 Discussion of Results

In this discussion the term 'noise' will be used to refer to that part of rotor noise produced by BVI Mach cone radiation. Figures 7 to 18 are results for a range of flight conditions.

The main window has the rotor disc at the centre. Each line in this window is the intersection between the radiation cone from a particular blade-vortex interaction and the ground. In other words each line is the path traced out on the ground by the wavefront from an intersection. A plan view of the wake geometry is displayed in the top right window. The locations of the intersections within the rotor disc area are given in the bottom right screen. The location of the intersections moving with supersonic phase speed and the location of the corresponding BVI noise at the ground are of most interest.

4.1 Effect of Advance Ratio

For low advance ratios the advancing blade causes interactions with supersonic phase speed between approximately 30° and 60°, and the similar interactions for the retreating blade are from approximately 300° to 330°. (See the intersection windows in the bottom right of Figures 7 to 18). As the advance ratio, μ, increases, the locations of the intersections in the disc area change. The consequence of this is that at some of the higher advance ratios, the region of critical intersections extends towards the centre of the rotor. Physically this means all of the intersections from the root to the tip of the advancing blade have supersonic phase speeds. In other words the entire length of the blade is creating Mach cone radiation.

With regard to the location of the noise on the ground as μ increases, two effects are noticed; the

BVI noise becomes much more directional due to the fewer Mach cones formed, and louder because the wake gets closer to the blade. The extremes of this effect are illustrated in Figures 7 and 12 which show results for the lowest and highest advance ratio presented respectively. The advancing blade interacts with up to seven sections of wake at the lowest advance ratio displayed, $\mu=0.10$. Increasing μ means that the advancing blade intersects fewer wakes. Figure 7 shows that there is a lot of relatively low intensity noise, almost all around the rotor. There are a large number of interactions in the rotor disc area, causing this rather complex pattern of noise. In Figure 12 (at high advance ratio) the blade reacts with more recently formed wake. This is because the wake is moving back faster relative to the rotor. For the same reason, the wake is closer to the blade in terms of axial displacement. However, there are fewer interactions, causing the noise to be more directional.

The advancing and retreating blades may interact with wakes such that the point of intersection may move inwards or outwards along the blade. Also, both of these effects may be observed on the same blade at once: the advancing blade may react with the same wake at the root and the tip simultaneously. When this occurs, the intersection point at the tip moves inwards and the intersection point at the root moves outwards along the blade. When the blade and the wake intersect such that locally they are parallel, the phase speed of the intersection point is theoretically infinite (many intersections are created over a length of the blade at once). Since the model moves the rotor in finite steps, and because the phase speed is so high at this point, subsequent intersection points are a long way apart. This produces a 'gap' in the intersections plot. The positions of parallel interactions can therefore be identified by the positions of these gaps. These gaps are located at an azimuth of approximately 45° for the advancing side and 300° for the retreating side.

A repetitive pattern can be observed in the directivity of the advancing blade noise as μ increases. Figures 8-11 illustrate this recurring pattern. Initially, refer to the bands of noise curving from approximately 180° to 270° in Figure 8. There are basically two bands of noise in this region; one is relatively loud (bold solid lines), highly directional and close to the rotor, while the other is much quieter (dotted lines) and further out.

Moving to Figure 9, the band closer to the rotor becomes louder and more directional. Meanwhile the outer band (dotted lines in Figure 8) 'spreads', becomes louder and moves inwards towards the rotor. When μ is increases further (Figure 10) the inner band moves 'across' the rotor and joins the band curving from 90° to 0° on the noise plot. At the same time, the outer band becomes louder and moves towards the rotor.

In Figure 11, what was the relatively quiet outer band in Figure 8 has become the loud, highly directional (bold) band. Meanwhile a new relatively quiet (dotted) outer band has formed. By comparing Figures 8 and 11 it can be seen that there is a repetitive cycle here.This cycle continues to repeat as advance ratio is increased.

The noise bands discussed above come from advancing side interactions which are moving inwards along the blade. As μ increases, this line of intersections moves backwards in the disc area and the phase speed of the intersections increases. This causes the outer band to spread and become louder. The spreading is due to a longer stretch of the intersections locus having supersonic phase speed.

The outer band of noise comes from a region of intersections with higher phase speeds As μ increases, the gap in the intersections moves outwards, and the number of intersections outwards of the gap is reduced. As mentioned earlier, these intersections outwards of the gap are moving inwards (towards the rotor centre). Eventually, one the gap reaches the blade tip radius, there will be no more points moving inwards on this line of intersections. Instead, the intersection point will be moving outwards along the whole length of the blade. This causes what was originally the inner band in Figure 8 to move 'across' the rotor and join the group of lines curving from 90° to 0°. As μ increases further, the noise band will move progressively to the top right of the noise plot, and eventually disappear. This is because the section of wake responsible for this band will be swept downstream of the blades before any intersection can take place.

The retreating blade also produces noise. This is represented on the noise plot by lines curving from about 45° to 180° and 0° to 270°. With reference to the intersections plots, the intersection points inwards of the gap move inwards while those outwards of the gap move outwards. This is the opposite of what happens for the advancing blade (see above). The lines on the noise plot from 45° to 180° are from a point of intersection moving outwards, while those from 0° to 270° are from a point of intersection moving inwards along the retreating blade. The majority of noise from the retreating blade is relatively quiet. Certainly, the noise produced is secondary to that produced by the advancing blade. However, this retreating blade noise is not of negligible intensity and cannot be ignored. At high advance ratios (e.g. Figure 13) there is no BVI noise from the retreating blade. This is because the wakes are swept behind the rotor disc before the retreating blade can intersect with them.

4.2 Effect of Tip-Path Plane Angle of Incidence

Figures 12 to 14 show results for different angles of tip-path plane to the freestream velocity, α_{tpp} at μ=0.3. Positive and negative angles were investigated, but only positive angles are presented here.

The directivity of the noise does not vary significantly with α_{tpp}. This is because the positions and phase speeds of the intersections remain unchanged. However, the intensity of the noise does vary, and is loudest at 0°-2° α_{tpp}. At negative α_{tpp} (nose down) the wake passes beneath the blades. As α_{tpp} is increased, some sections of the wake move from being beneath the rotor disc to above the disc. Note that the noise level deteriorates as α_{tpp} increases and the vortices involved in interactions get further above the blades. The noise generated by a BVI is loudest when the velocity induced on the blade by the vortex is highest. This is not when the blade cuts through the centre of the vortex, but rather when the blade is at an 'optimum' distance from it. Figures 12 to 14 illustrate how this effect. In Figure 13 there is a relatively loud band of noise curving from 180° to 270°. The noise is caused by a section of wake passing just below the advancing blade. In Figure 12, the same section of wake now passes much closer to the advancing blade, due to the change in α_{tpp}, but the band of noise produced is quieter. In Figure 14, at relatively high α_{tpp}, the wake passes further above the blade and the relative intensity of this band of noise reduces.

4.3 Comparing Results for Different Numbers of Blades

Figures 12 and 15 to 17 show the effect of increasing the number of rotor blades for constant operating conditions at μ=0.30. It can be seen from these figures that the number of critical intersections increases with number of blades. This has the effect of making the BVI noise less directional. The intensity of the noise from each intersection decreases with increasing number of blades. This is because for a larger number of blades, each blade is producing less lift, and so each tip vortex is weaker.

The overall effect of increasing the number of blades is to produce relatively low intensity Mach cone radiation in all directions rather than relatively loud noise in specific directions.

4.4 Effect of Changing the Rotor Height

Figure 18 shows a result with the rotor height above the ground, h=0, but otherwise the same operating conditions as Figure 9. Effectively, the ground plane is now in the plane of the rotor. It can be seen from Figure 18 that in the plane of the rotor, the noise radiates out in straight lines. The 'slices' through the radiation cones made by the ground plane are now along the central axes of the cones. At h=0 (Figure 18), it can be seen that the lines of intersection of the radiation cones with the ground are densest close to the rotor. This is where the noise will be loudest. However, h=150m (Figure 9) the maximum density of lines does not occur directly beneath the rotor, but some distance away from it. This implies that the loudest noise is not directly below the rotor when the rotor is at altitude.

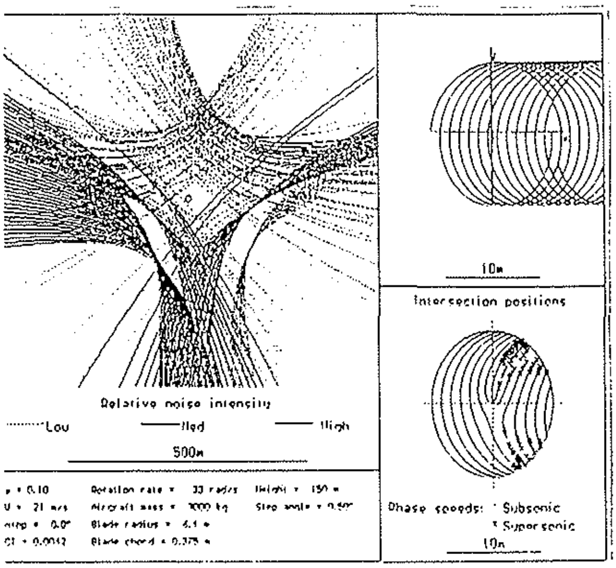

Figure 7 αtpp=0.0°, μ=0.10, 4 blades

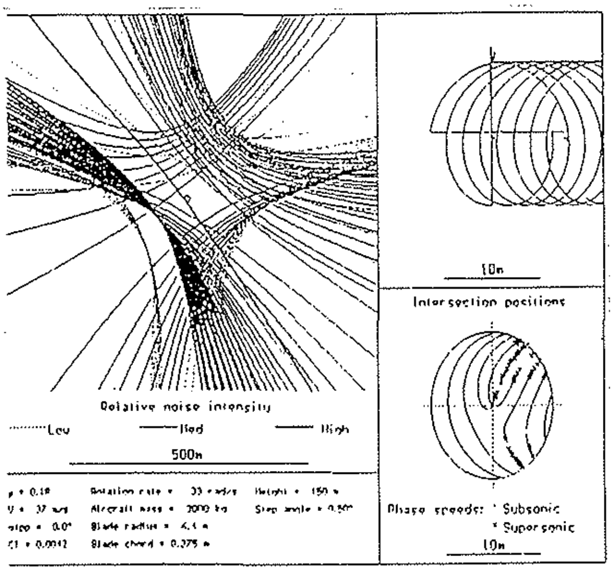

Figure 8 αtpp=0.0°, μ=0.175, 4 blades

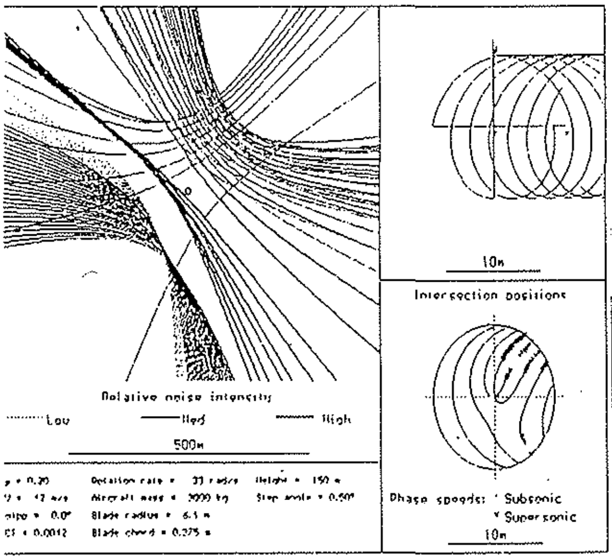

Figure 9 αtpp=0.0°, μ=0.2, 4 blades

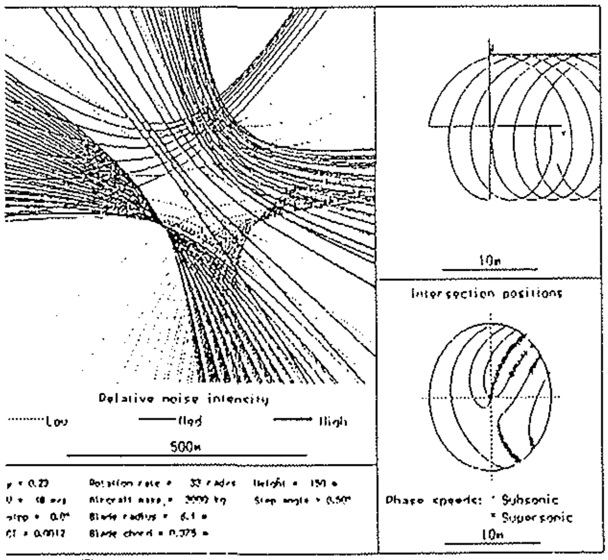

Figure 10 αtpp=0.0°, μ=0.225, 4 blades

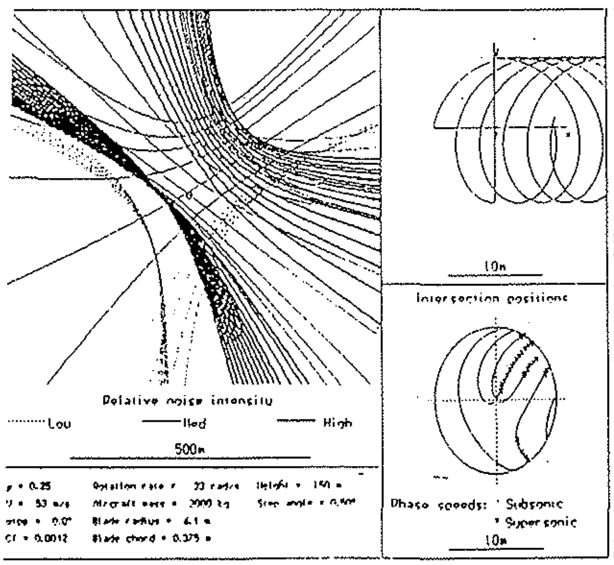

Figure 11 αtpp=0.0°, μ=0.25, 4 blades

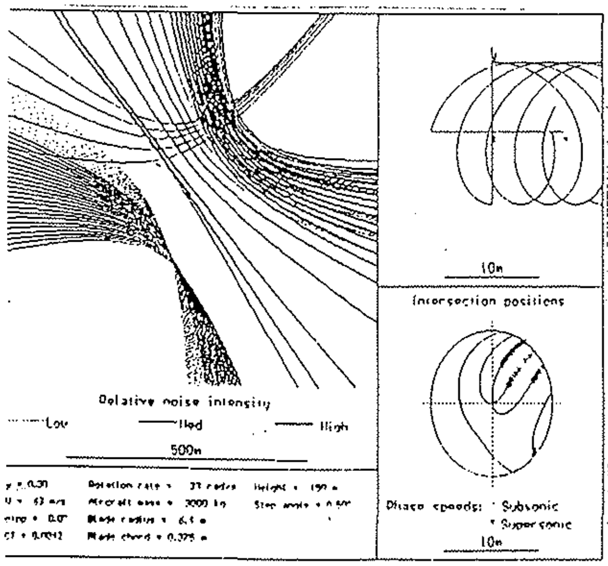

Figure 12 αtpp=0.0°, μ=0.3, 4 blades

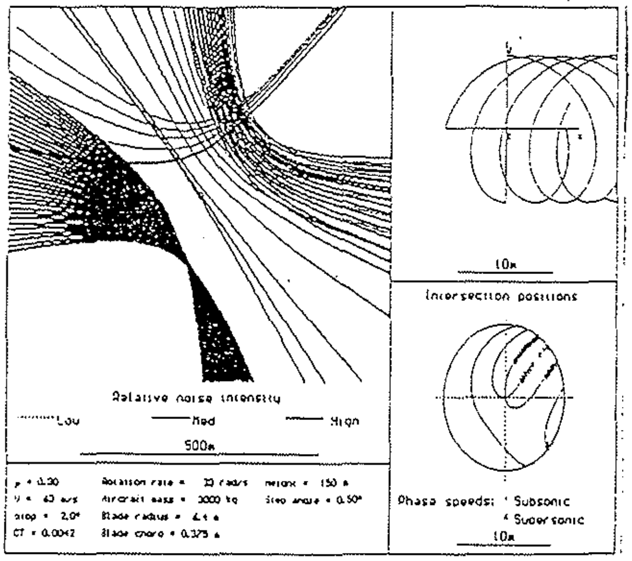

Figure 13 αtpp=2.0°, μ=0.3, 4 blades

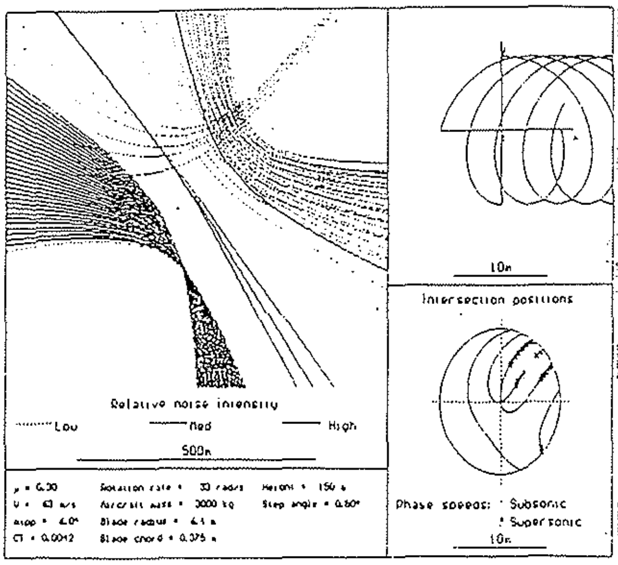

Figure 14 αtpp=6.0°, μ=0.3, 4 blades

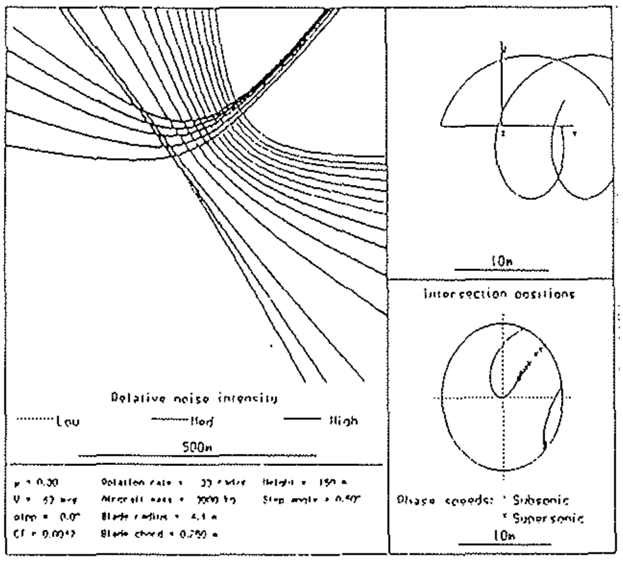

Figure 15 αtpp=0.0°, μ=0.3, 2 blades

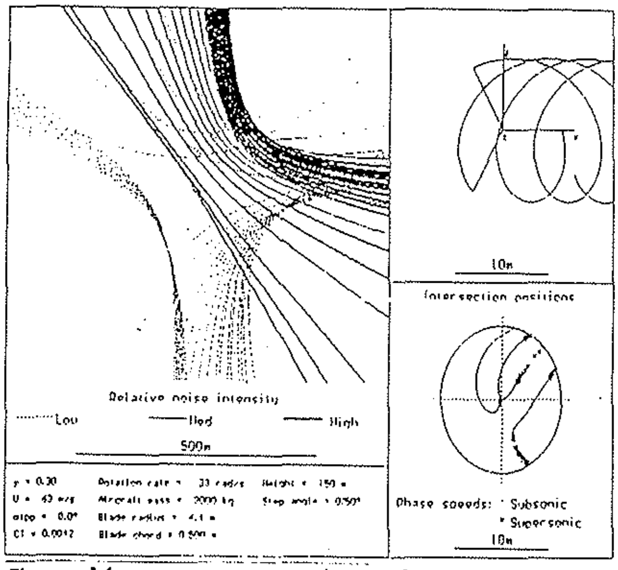

Figure 16 αtpp=0.0°, μ=0.3, 3 blades

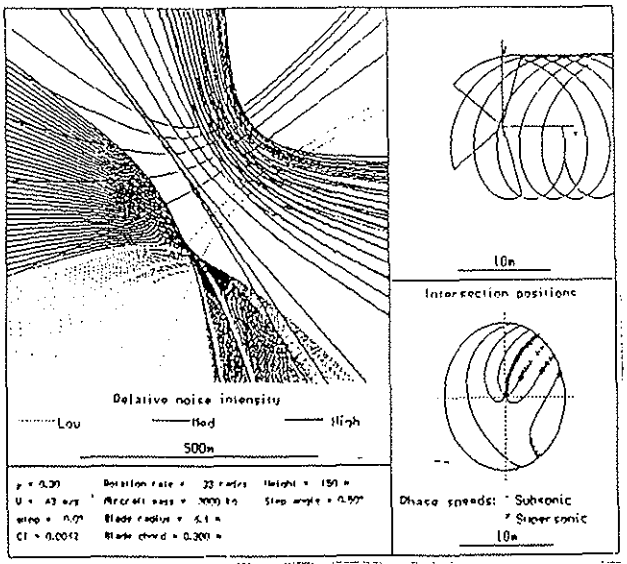

Figure 17 αtpp=0.0°, μ=0.3, 5 blades

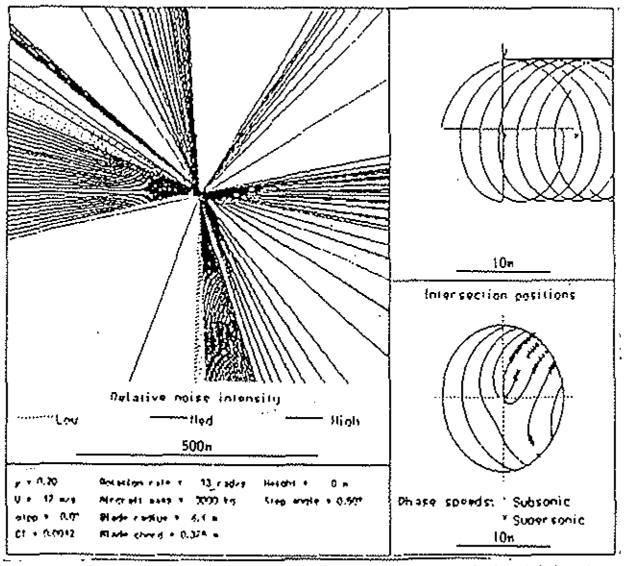

Figure 18 αtpp=0.0°, μ=0.2, 4 blades, h=0m

5 Conclusions

A computational model has been developed to predict the phase speeds of blade vortex interactions. The model also predicts the directivity of BVI noise due to the Mach cone radiation process. Further, a simple model was used to predict the relative strengths of the BVI noise produced by each interaction. The model can be used to support and explain results obtained from experimental and analytical research.

The model was used to study the directivities of BVI Mach cone radiation for a variety of flight conditions. Particular directivities were attributed to specific areas of blade-vortex interaction. The geometry of interaction and corresponding noise directivities were found to be strongly dependent on operating conditions. The positions of the blade vortex interactions with supersonic phase speeds for the advancing blade were between approximately 30° and 60°. Those for the retreating blade were between approximately 300° and 330°.

The advancing blade causes the majority of the critical interactions since there are always wakes present in the disc section from 0° to 90°. The retreating blade causes fewer interactions due to the fewer number of wake points present. The retreating blade may just miss a wake, and the quantity of noise from this blade will drop significantly. The directivity of noise from the advancing blade is located from approximately 90° to 190°, and 270° to 360° in the far field. The retreating blade produces noise from approximately 0° to 70° and 160° to 270° in the far field.

As the advance ratio increases, BVI noise becomes more directional and louder. The advancing and retreating blades may interact with wakes such that the point of intersection may move inwards or outwards along the blade. Both of these effects may be observed on the same blade at once as it interacts with the same wake at two points. The directivity of the noise is different for each of these cases. A repetitive pattern in the noise directivity is observed as m increases. This was attributed to repetition in the corresponding positions and phase speeds of interactions.

The noise was found to be loudest at 0° to 2° tip-path plane angle.

The overall effect of increasing the number of blades is to produce relatively low intensity Mach cone radiation in all directions, rather than relatively loud noise in specific directions.

Acknowledgements

Special thanks to Professor M. V. Lowson for his encouragement and generous assistance in the course of this research and helpful comments on the drafts of this paper.

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