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THEORETICAL STUDIES UNDERTAKEN DURING THE HELINOISE PROGRAMME

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Summary

Work undertaken by various partners in the EC supported HELINOISE programme is described. The work covers both basic mechanisms of acoustic radiation and unsteady aerodynamic predictions related to the noise. Comparisons of prediction and experiment obtained to date will be given.

Introduction

The EC BRITE-EURAM supported HELINOISE programme has now completed its first Phase. The work included both theoretical and experimental studies. This paper summarises the work undertaken during the theoretical parts of the study. Participants in the theoretical study reported here included

Agusta
CIRA
Eurocopter Deutschland
IST Lisbon
University of Bristol

The paper provides an integrated view of the theoretical work undertaken by these partners.

At the present time understanding of helicopter noise is incomplete, and there are a number of alternate approaches to theoretical description of the noise radiated by the helicopter. In principle an exact solution exists. The noise field must be fully described by the unsteady compressible Navier-Stokes equations. However the noise radiation by a helicopter represents a mere "trace" field in these equations. Even under conditions of intense sound radiation the noise power radiated only amounts to 1/10000 of the power used by the helicopter (cf Ref 1). Ensuring that the mathematical solutions to these complex equations retain an accurate description of these small effects is highly demanding. As a consequence there have been a variety of suggestions as to the most suitable technique to derive solutions to the equations. Each of these has advantages and disadvantages, and each may be of particular value for particular sources in one phase of flight. Thus the initial work under the HELINOISE programme has involved several distinct approaches, which are described separately here.

As is well known, the compressible Navier Stokes equations were rewritten by Lighthill to provide a form of forced wave equation with source terms specified by the distributed aerodynamics. An exact solution to the Lighthill equation in the presence of moving boundaries was given by Ffowcs Williams and Hawkings (Ref 2). This solution has in turn been reinterpreted by Farassat to provide a number of solution methods for helicopter and other sources. The Ffowcs Williams Hawkings equation is widely used as the most fundamental basis for the description of noise from a helicopter. For compact sources an alternative approach to the solution of the Lighthill equation was given by Lowson (Ref 3), which was subsequently used by others.

At low enough speeds the Lighthill equation, and thus also the Ffowcs Williams Hawkings or Lowson approaches, separate the acoustic radiation process from the aerodynamic source terms. This approach is valid up to speeds when shock waves appear in the rotor field, and thus covers a considerable range of interest for helicopter noise radiation. Under these circumstances the noise prediction process can be divided into two parts; first the calculations of the unsteady aerodynamic field on the rotor and resulting rotor surface pressure field, and then the calculation of the noise radiation resulting. At higher speeds the acoustic and aerodynamic fields cannot be separated, and more complex procedures for calculation of the effects are necessary.

Thus there have been two principal themes in the present work. The first has been to develop solutions to the Ffowcs Williams Hawkings equation which relate the noise radiated to the sources present on the blade. Computational solutions have been developed, based on alternative approaches, including techniques based on the Farassat and Lowson formulations of the noise radiated. Various approaches to extending these solutions to the transonic case have been investigated.

The second theme has been primarily concerned with prediction of the complex shed vortex wake from the rotor, the effects of which dominate the noise radiation by the rotor. Approaches here have been based on panel methods of various forms. The key problem here is to compute the self interaction of the wake. The two principal approaches have been via relaxation from a prescribed wake solution, and via an impulsive start.

The work has provided a starting point for more detailed studies for the noise which are now about to be undertaken in the successor EC programme "HELISHAPE".

2. Combined Aerodynamic Acoustic Method for Rotor Noise Prediction

A study has been undertaken of a combined aerodynamic and acoustic approach to the prediction of rotor noise. This was performed at the University of Bristol. The model used was based on the basic theory due to Lowson (Ref 3) for accelerating sources, which describes the noise due to the rotating pressure field on the blade. Prediction of the force field on the rotor was made via a non-linear lifting line model specially developed for the present problem. The overall model was further developed to include a full description of the noise due to thickness noise sources. A full description of the models developed and preliminary results has been given in Ref 4.

Before the loading noise can be predicted, a sufficiently accurate description of the aerodynamic loading must first be established. What constitutes 'a sufficiently accurate' loading prediction was an important part of the study, as the aerodynamic loads calculation for a helicopter is not an inconsiderable task. The approach adopted at Bristol was to use a lifting-line representation of the rotor and its wake. The vortex system of the rotor is represented by a series of bound vortices, each trailing a pair of helical legs (i.e. a helical horseshoe vortex). The wake shape is initially prescribed and of semi-infinite extent.

The wake is modelled in two parts - a near field region where it is represented by a series of straight line segments, and a far-field region, where an asymptotic solution for a helical vortical filament of fixed pitch and diameter is used. The unknowns are the wake shape and strengths of the horseshoe vortices. These are solved in an iterative fashion, by first calculating the velocities induced on the blade by the wake using a guessed distribution of vortex strengths, then combining this with the rotational and freestream velocities to obtain the total velocity relative to the blade at a set of collocation points. The relative velocity is then used to determine the effective blade angle of attack which in turn fixes the lift and drag coefficients from aerofoil section data. This in tum gives a new set of vortex strengths so the process is repeated until no change in vortex strength occurs. The near-field wake is subsequently allowed to relax with each vortex strength iteration, while the far-field helix parameters are fixed by the shape of the final turn in the near field. This initial `complete-wake' approach should be contrasted with an impulsive start calculation where no initial wake is present by `grows' as the calculation advances in time. Further details of the method can be found in references 5 and 6.

The information required for the thickness noise is purely geometrical and obtained simply from the definition of the blade shape. To solve the Ffowcs-Williams-Hawkings equation the fundamental solutions of this linear equation are used. These are integral expressions involving a retarded time and are evaluated numerically by a trapezoidal rule. Note that by using a lifting-line representation of the rotor, a compact source model is implied for the loading noise.

Conventionally, to predict the pressure field at particular point at a given time, retarded-time iterations are required for the source terms appearing in the integral. However, this iterative process has been avoided in the work for the important case where the pressure field is a periodic function of source and observer time, e.g. for an observer moving with (or in) the helicopter, or a stationary observer with a helicopter in hover. A Fourier series is used to fit the pressure field at a particular observer position due to a rotation of each `point' source arising in the numerical solution of the integrals. The Fourier series for each source are then summed to give total pressure signal.

The complete loads and noise prediction method makes no use of empirical data or assumptions, apart from the aerofoil section properties used in the loads prediction.

To test the method, experimental data for a propeller obtained in the DNW tunnel (Ref 7) has been used. In this experiment the sound radiation fields ahead of, in the plane of, and behind the propeller disk were measured for propellers with subsonic tip speeds. The propeller thrust and torque and tunnel speed were also measured. The first part of the assessment of the method was to establish how many horseshoe vortices were required to represent the aerodynamic loading in sufficient detail to give a converged prediction of the sound pressure field. In the course of the study it was found that a careful choice of the position of the vortices along the blade and the location of the collocation points, where the velocities on the blade are sensed, is crucial in determining a good solution, and a good choice of vortex positions can yield excellent results even with very few vortices. This is demonstrated in figure 1, which shows the predicted pressure signature at a particular location where 5 and 13 vortices per blade have been used. The results are indistinguishable and close to the experimental result shown in the figure.

In figure 2 the power spectrum for the sound harmonics measured in the plane of the blade is shown, along with the predicted power spectrum. The agreement is excellent.

Some insight into the sound pressure field is given by study of the predicted relative contributions of the thickness noise and loading noise. This revealed that ahead of the disk plane loading and thickness terms contribute equally and in phase to the total signal, while in the disc plane the thickness noise is less and lags the loading noise in phase. Downstream of the disc plane the sound pressure field is almost entirely due to the loading noise. Further work is underway on extending the wake model to the case of translational flight, retaining the essential feature of the method of relaxing an initially prescribed periodic wake, rather than growing one from an impulsive start.

3. **Ffowcs Williams Hawkings Farassat Approach**

A new numerical code, named HERNOP (HElicopter Rotor NOise Prediction) has been developed at C.I.R.A. for the project. A first stage of validation for HERNOP code has been conducted in 1992 (Ref 8) especially devoted to comparisons of results for high speed problems. Starting with the Ffowcs Williams-Hawkings differential equation, the code is based on the well-known Farassat time domain formulations 1 and 1-A (Ref 9), for the determination of the thickness and loading noise, and allows diversified analysis of the quadrupole source term for high speed problems. It may be run with different blade models and simulates real helicopter rotor motions during the revolution period; the requested aerodynamic data for loading noise calculation may be input either as lifting coefficient at some stations along span, or directly as pressure distribution on blade surface. The possibility to use the formulation 1 and 1-A at the same time allows to compare the resulting noise signatures and to choose the numerical algorithm on the grounds of the available data and computational power. The comparison with analogous results from NASA code WOPWOP (Ref 10) shows a good agreement for linear terms signatures, both for hover and forward flight conditions (Figure 3).

Because of the increasing velocity of the modern helicopter rotor blades, the research interest has moved to the analysis of the non-linear source term of the FWH equation. A lot of theoretical studies have been conducted to treat the quadrupole sources and investigate the very complex generating noise mechanisms related to it; the manipulations performed on the differential equation, as well as the integral expression of the sound field derived from it, have produced different forms of solution. HERNOP treats this important contribution by following two different approaches: implementing the Schultz approximation (Ref 11) and applying a three-dimensional integration in a prescribed volume around the blade. The Schultz approximation is based on a reduction of the volume integral related to the Lighthill tensor into a surface one, through the use of an integral in a direction normal to the blade surface (the so-called momentum thickness); the latter integral is then replaced by an empirical and very simple relation so the complexity of numerical approach and the requested CPU time are strongly reduced. However this method may be adopted only for particular observer positions and the determination of momentum thickness cannot leave apart an accurate knowledge of perturbation velocity upon the blade surface. Unfortunately, at typical Mach number range where the quadrupole sources contribution becomes significant the availability of aerodynamic data is rather rare, and the development of numerical codes working for aerodynamic calculations of transonic rotor blades is still a research subject, especially for forward flight. A first attempt to apply a three-dimensional integration for the determination of the non linear term contribution has been implemented by HERNOP code, exploiting the results from C.I.R.A. aerodynamic code UTAH; this is based on a potential formulation and performs the calculation of perturbation velocity field on a prescribed three-dimensional grid around the blade (Figure 4). No data fitting is requested, since HERNOP directly works on the external grid for the three-dimensional calculations, so the results produced by different aerodynamic codes may be used. However some limitations are present in the actual version of code; in particular only hover condition can be examined. The comparison between the two solution methods for quadrupole treatment refers to a non lifting blade of a hovering rotor with a uniform distribution of NACA 0012 profile along span and considers a tip Mach number of 0.8; the agreement between the predicted quadrupole signatures is generally good, although a pronounced difference appears in the second positive peak pressure (Figure 5).

A very interesting description of quadrupole source term has been developed by Farassat in 1987 (Ref 12): exploiting some results from the theory of generalized functions and concepts of differential geometry, the differential expression of quadrupole is split up into four different groups, each related to a particular generating noise mechanism. Following this analysis a new solution method is being developing, considering at the moment the blade surface as the only discontinuity present in the flow field.

4. Boundary Element Noise Prediction

A code for the prediction of noise radiated by helicopter rotors that could be used for realistic configurations, and able to model complex noise generation mechanisms such as BVI and HS noise has been developed by Agusta during the Helinoise project. The adopted formulation is based on the FWH. equation, that requires the knowledge of a certain number of aerodynamic quantities (i.e. loads on the blade, and Lighthill stress tensor around it). this approach permits a great flexibility, since, depending on the accuracy desired, different methods and approximations can be used to compute the aerodynamic quantities. During the formulation great attention has been paid in writing a modular code, in such a way that further extension or improvement could be easily added. The code developed, called BENP (Boundary Element Noise Predictor), permits, at the current stage of development, to compute thickness, loading, and quadrupole terms, using for the last term two different kinds of approximations. The code is able to handle complex geometries and motions; for example modern rotor blades with complex tips can be easily modelled, and also the flapping, feathering, and lagging motions, typical of forward flight helicopter blades can be described. Besides also the blade elastic deformation can be introduced if required. The code accept input in a wide range of formats, in particular the aerodynamic data, can be provided with different degree of accuracy in relation to the kind of calculation to be performed.

Theoretical Approach

The code BENP permits to obtain the solution of the FWH. equation using two different approaches, the first one is the classical Farassat's formulation (Ref 13), in which the integration is executed on the physical surface of the source, while the second one permits, with a numerical formulation developed in Agusta, the integration on the acoustic surface of the radiating source. The solution for the thickness ad loading terms are so written in the following two ways:

Physical Surface (S)

$$4\pi p' = \frac{\partial}{\partial t}\int_S \frac{[\rho_0 v_n]_{ret}}{[r|1-M_r|]_{ret}} dS + \frac{1}{c_0}\frac{\partial}{\partial t}\int_S \frac{[P'_{nr}]_{ret}}{[r|1-M_r|]_{ret}} dS + \int_S \frac{[P'_{nr}]_{ret}}{[r^2|1-M_r|]_{ret}} dS$$

Acoustic Surface (Σ)

$$4\pi p' = \frac{\partial}{\partial t}\int_\Sigma \frac{[\rho_0 v_n]_{ret}}{r\Lambda} d\Sigma + \frac{1}{c_0}\frac{\partial}{\partial t}\int_\Sigma \frac{[P'_{nr}]_{ret}}{r\Lambda} d\Sigma + \int_\Sigma \frac{[P'_{nr}]_{ret}}{r^2\Lambda} d\Sigma$$

where $\Lambda = 1 - M_n^2 - 2M_n\cos(\theta)$, being θ the angle between the surface normal ñ and the radiation direction r. It is clear that the second method presents the advantage that the occurrence of the transonic singularity is greatly reduced.

Quadrupole Approximations

The evaluation of the quadrupole term plays an important role in HS conditions and is a very demanding task due to the need to evaluate volume integrals, that requires great computational resources, and due to the large amount of input data required. Two approximations have so been introduced that aim to reduce both computational time and required input data. The first one is an evolution of the so called momentum thickness approximation that was introduced by Caradonna, and firstly used fo rotor noise evaluation by Schultz and Splettstoesser (Ref 11). The second one is usually known as Farassat's shock wave formalism, or quadrupole decomposition.

The central point in the momentum thickness approximation is to suppose that the volume around the blades that give a meaningful contribution to the quadrupole term can be considered very small, and so its extension in the direction perpendicular to the blade surface can be neglected. In this way it is possible to replace the volume integrals with more simple surface integrals, and it is possible to write:

$$4\pi p' = \frac{1}{c_0^2}\frac{\partial^2}{\partial t^2}\int_S \frac{[\delta'_{2r}]_{ret}}{[r|1-M_r|]_{ret}} dS + \frac{1}{c_0}\frac{\partial}{\partial t}\int_S \frac{[3\delta'_{2r} - \delta'_2]_{ret}}{[r^2|1-M_r|]_{ret}} dS + \int_S \frac{[3\delta'_{2r} - \delta_2]_{ret}}{[r^3|1-M_r|]_{ret}} dS$$

where $\delta'_{2i} = \int_n u_i^2 \, dn$ has to be provided as an input to the acoustic code. Obviously depending on the approximations introduced for the evaluation of this term different degrees of accuracy can be obtained. In particular it is interesting to note that using a very simple 2D transonic code for evaluating d it is possible to obtain good results for Mach number up to 0.85 for rectangular blades (Ref 8).

The other approximation introduced in BENP is the direct evaluation of the surface quadrupole terms introduced by Farassat (Ref 12). Following his work it is possible to show that the volume quadrupole terms can be manipulated in such a way that it includes also some surfaces terms, and it is possible to write:

$$\frac{\bar{\partial}^2 T_{ij}}{\partial x_i \partial x_j} = \frac{\partial^2 T_{ij}}{\partial x_i \partial x_j} + \Delta\left(\frac{\partial T_{ij}}{\partial x_i}\right) n_i |\nabla f| \delta(f) + \frac{\bar{\partial}}{\delta x_i}\left[\Delta T_{m} |\nabla f| \delta(f)\right]$$

Due to the Dirac delta the second and third terms on the right member are surface terms, that have to be evaluated for all the surfaces f = O, for which the Lighthill stress tensor is discontinuous, that are shock waves, the wake, and the body surface. The approximation proposed by Farassat consists in considering only these surface terms, and neglecting the remaining volume term. The code in the current version permits the evaluation of the surface quadrupole term using a numerical technique that permits an efficient evaluation of integrals on deformable surfaces such as shock waves (Ref 14). Further theoretical studies are however required in order to provide a better understanding on the noise generation mechanisms of shock waves, and to assess the real applicability of this approach.

Results

The validation of the code is now in progress using all the available experimental data. The results here presented refer to an experimental campaign held in 1982 in DNW where blade pressure and acoustic signature were measured at the same time on an OLS rotor model. Figure 6 gives the computed and experimental noise signature in BVI condition for a microphone placed below the rotor disk; due to the few sensors for which the blade pressures were available an interpolation was introduced that permitted the phase information to be preserved. Figure 7 refers to a HS condition with the tip Mach number equal to 0.843 and the observer placed in three different positions in the plane of the rotor. The quadrupole term was computed using the momentum thickness approximation, and the required input data were computed using a 2D approximation (Ref 8). In each figure the first plot is the computed thickness, the second is the sum of thickness and loading, and the third is the experimental results. It is possible to see that, in spite of the very simple quadrupole approximation adopted, the results are very encouraging.

5. **Vortex-Lattice Method for Rotor Blade Pressur Distribution**

An algorithm, developed at the Bundeswher-Hochschule, Munchen, has been extended by ECD to predict the pressure distribution of a subsonic, rotor blade of a forward flying helicopter, particularly for the very strong and annoying noise source of blade/vortex interaction. There have been made the assumption of incompressible, frictionless and non-rotating (with the exception of the rotating blade and its wake) flows, thin blades represented by plates or plate segments, no vortex bursting, and flow directions at the method's control points tangential to the local blade area (no penetration through the blade at these points). The theory takes into account; twist and arbitrary blade planform, blade feathering by cyclic control, blade flapping and airfoil camber.

The constraints of the method described are besides the required neglect of incompressibility: the blades' finite thickness, the fulfilling of the boundary conditions only at the control points and the availability of only the pressure difference D*p* between the upper and lower sides of the blade. Nevertheless, D*p* can be used as input (source term) of an aeroacoustic noise prediction code.

For the solution of such problems, a time dependant, discrete method, based on a zero order doublet or dipole distribution is applied. The doublet elements are discretely distributed along the blade, representing its geometric (solid) and aerodynamic discontinuity surfaces. They are of constant strength m equivalent to vortex rings with G = m. These vortex rings are - starting with an impulsive motion of helicopter and blade rotation - displaced and geometrically deformed by the local resulting velocity implying; helicopter cruise speed, blade rotational velocity, induced velocity and blade flapping velocity. They generate hereby in a quasisteady procedure a free vortex sheet up to the attainment of a steady wake configuration. With the exception fo the kinematic incident flow condition of no flow penetration through the blade surface all boundary conditions are satisfied implicitly at the control points, so that no iterative solution methods are required.

In order to save computing time, the first wake determination process is effectuated by a constrained number of doublets, say 1 in chordwise and 10 in spanwise direction. Having attained steady wake conditions the number of doublets in chordwise direction is increased, say to 10 to 20, so that a realistic pressure distribution for one rotor revolution (necessary for a forward flight case) can be established. In general, the number of revolutions necessary for steady aerodynamic blade conditions is depending on the flight velocity. The lower the flight speed, the larger the required rotor revolutions. The resulting wake is shown in Figure 8.

The method is just now in the process of being validated by the results of the HELINOISE tests performed in December 1992 in the DNW. As an example, Figure 9 illustrates the experimental and theoretical development of the pressure difference D*p* of lower minus upper side for a slight descent flight case with $v_{\tilde{N}}$ = 33 m/s (m = 0,151) versus azimuth angle PSI. D*p* is shown for different outer radial stations (where blade vortex interaction occurs) at a blade chord position of 3%. The strong pressure gradients at PSI = 90^o can be explained by the corresponding local wake geometry in Fig 8. At the outer region of the blade pointing to PSI = 90^o a deformation of the wake stemming from the preceding blade pointing to 180^o can be identified. It is originated by interference between wake and blade. The strong pressure gradient gives rise to significant impulsive noise levels.

ECD will continue the work described by refining the analytical model in cooperation with European partners. In a follow-on research programme, finite blade thickness and reverse flow will be introduced for more realistic flow description.

6. Scattering of Rotor Noise

A separate study has been made at IST Lisbon on the scattering of rotor noise by the turbulent wake of the rotor. The aerodynamic and aeroacoustic computer codes are most effective in the calculation of the impulsive component of helicopter rotor noise, i.e. they predict the sound intensity I_n for each rotor tone w_n. This uses information to predict the complete spectrum, including broadband noise, using the formula:

$$E(w) = E_o + \sum_{n=1}^{N} I_n \exp(-b(w-w_n)^2 - a\, w_n^2),$$

where there are three parameters: (i) the background noise E_o; (ii) the attenuation a, which affects more the higher frequency tones; (iii) the correlation b, which spreads the energy in each tone over a Gaussian band. The attenuation and correlation can be calculated from the properties of the sound and flow fields, e.g. turbulence spectra Ref 15). If this information is not available, then the parameters can be determined by fitting to experimental noise spectra. An example is the set of Bell UH-18 rotor noise spectra measured by Cox & Lynn (Ref 16), and illustrated on the r.h.s. of the figure, in comparison with the prediction of our formula on the l.h.s. The comparison is satisfactory over a range of frequencies of 400 Hz, which includes many tones.

Conclusions

A series of theoretical studies attacking different elements of the rotor noise field have been undertaken by participants in the HELINOISE programme. These have given rise to a variety of new results, and encouraging comparisons with experiment. The work is now being further developed in the HELISHAPE programme under EC funding.

Acknowledgements

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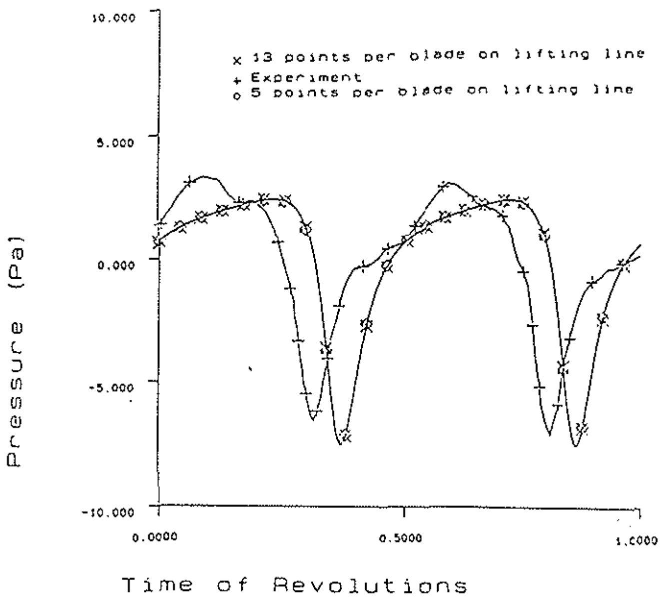

Figure 1 Experimental vs Theoretical Noise Waveforms

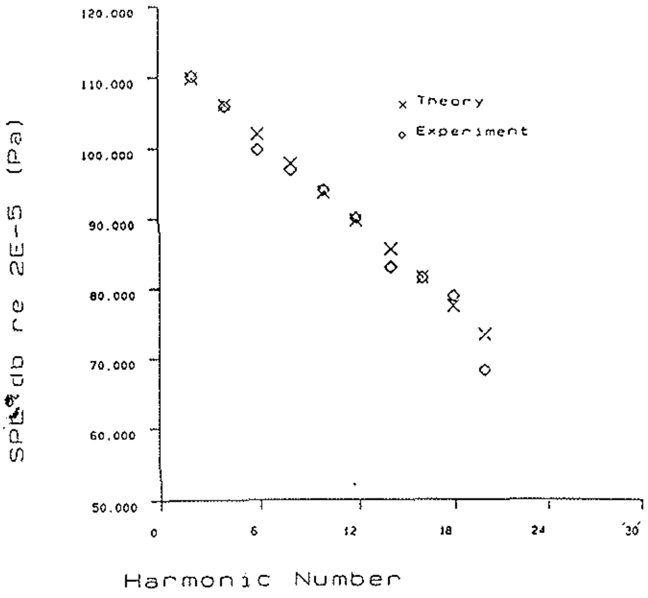

Figure 2 Experimental vs Theoretical Noise Spectra

In the right figure the acoustic pressure refers to a hovering rotor; in the left figure results for forward flight are shown. These test cases have been extracted from Ref 10.

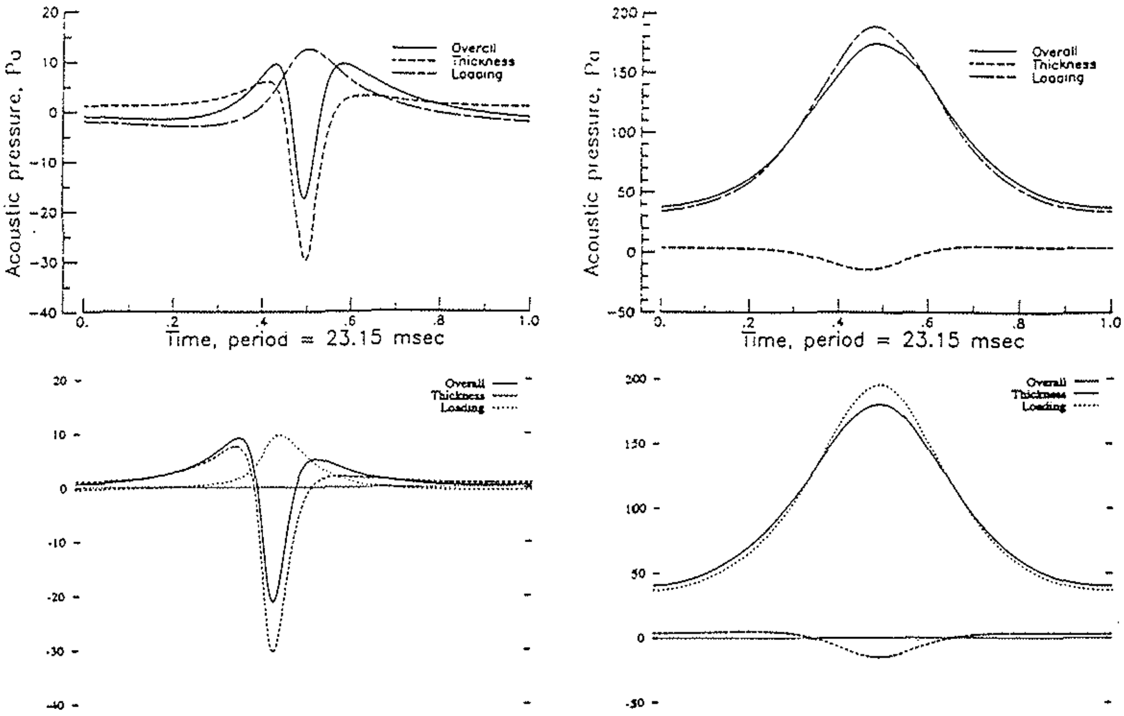

Figure 3 Comparison between HERNOP and WOPWOP results.

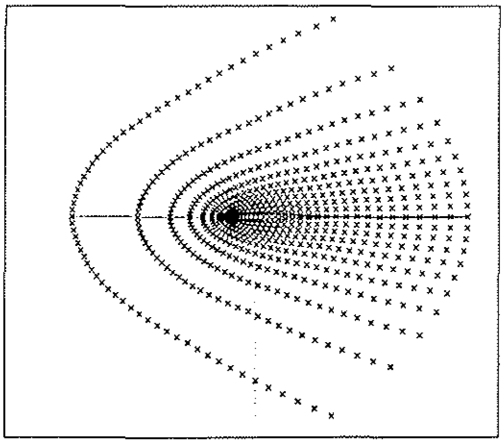

Figure 4 Two-dimensional view of UTAH grid used for HERNOP quadrupole term calculation.

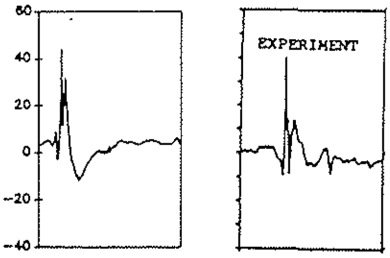

Figure 6 BVI - Observer 30° below rotor disk

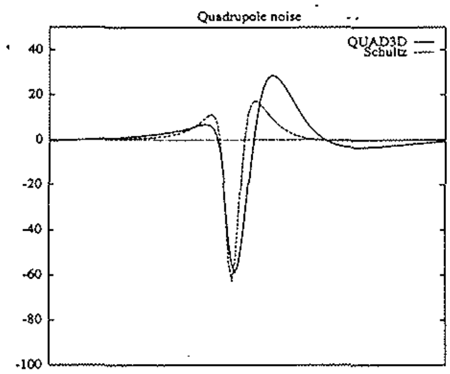

Figure 5 Comparison between quadrupole noise signatures calculated by Schultz approximation and the Volume integration.

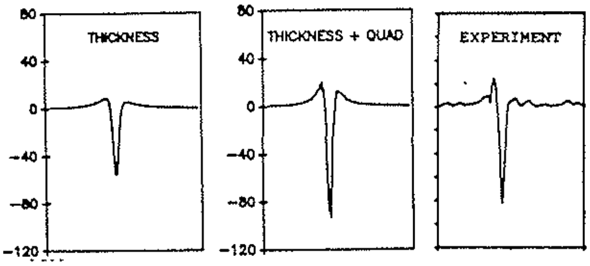

Figure 7a HS - Observer in rotor disk, Centerline

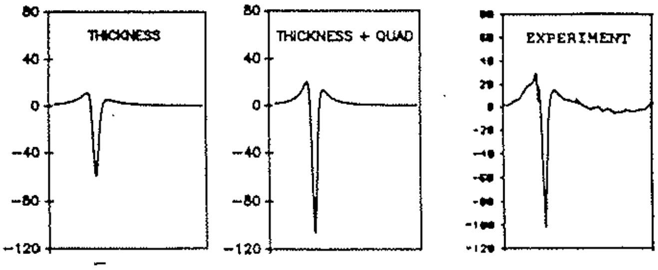

Figure 7b HS - Observer in rotor disk, Advancing Side

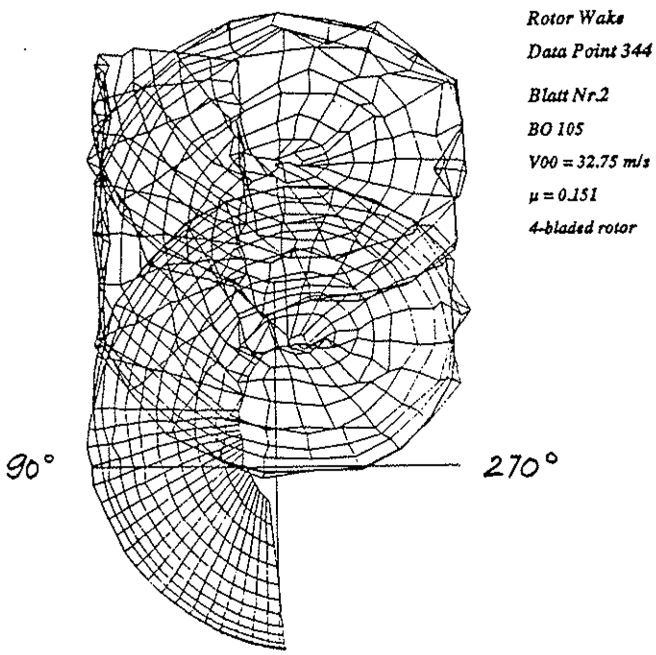

Figure 8 Predicted Wake Geometry

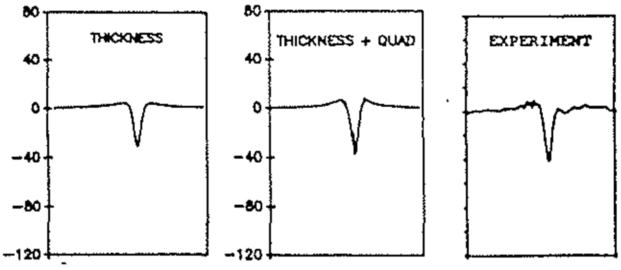

Figure 7c HS - Observer in rotor disk, Retreating Side

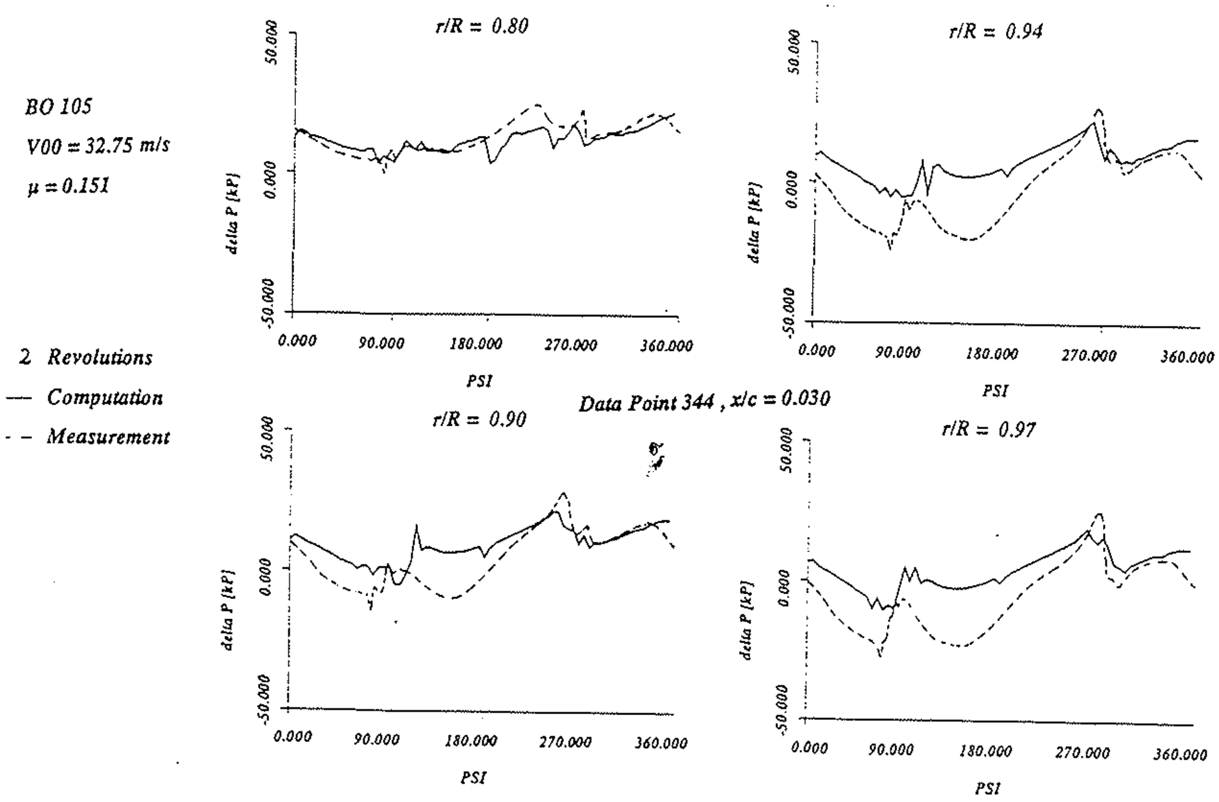

Figure 9 Experiment vs Theory for DNW Test

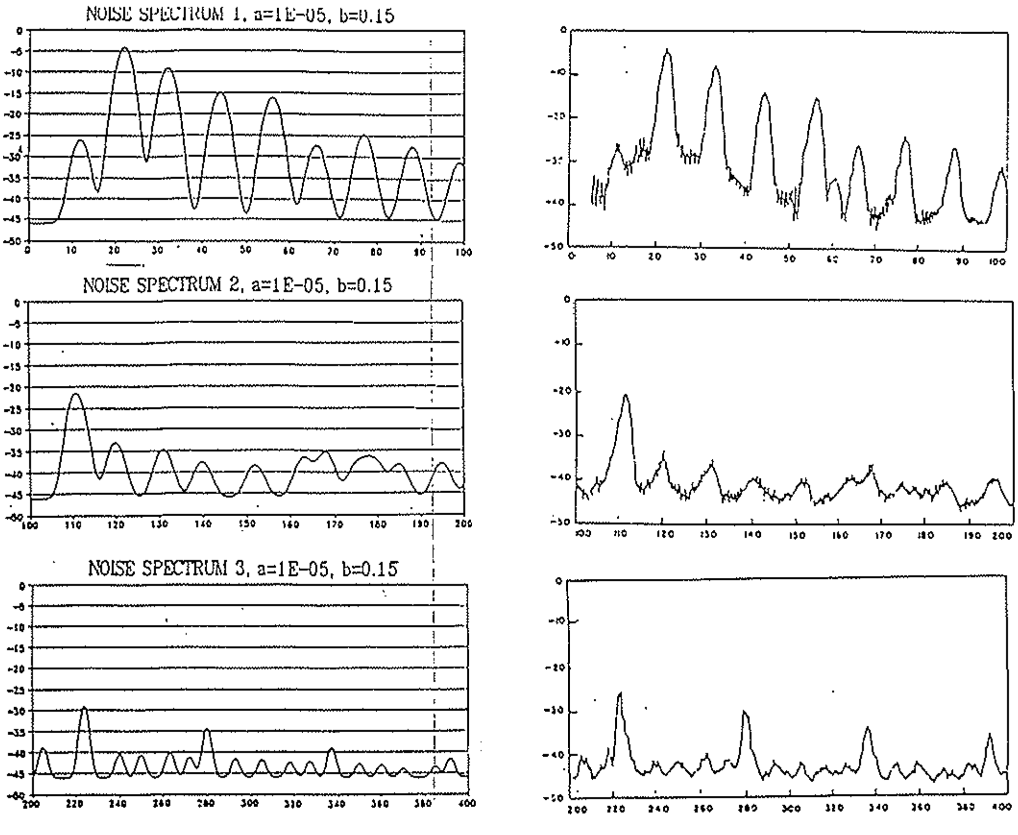

Figure 10 Comparison of Theory and Experiment for Spectral Broadening