EIGHTEENTH EUROPEAN ROTORCRAFT FORUM

A - 07

Paper No 58

THEORETICAL AND EXPERIMENTAL COMPARISONS FOR HIGH-SPEED AND BLADE-VORTEX INTERACTION NOISE

S. IANNIELLO
C.I.R.A., ITALY

P. DI FRANCESCANTONIO
AGUSTA, ITALY

D. TARICA, E. DE BERNARDIS
C.I.R.A., ITALY

September 15 - 18, 1992

AVIGNON, FRANCE

ASSOCIATION AERONAUTIQUE ET ASTRONAUTIQUE DE FRANCE

THEORETICAL AND EXPERIMENTAL COMPARISONS FOR HIGH-SPEED AND BLADE-VORTEX INTERACTION NOISE

S. Ianniello
CIRA, Italian Aerospace Research Center
81043 Capua, Italy

P. di Francescantonio
Agusta SpA
21017 Cascina Costa di Samarate, Italy

D. Tarica, E. De Bernardis
CIRA, Italian Aerospace Research Center
81043 Capua, Italy

Abstract

Some tests for the validation of two aeroacoustic codes are presented in this paper. The numerical tools have been developed at Agusta and C.I.R.A., respectively, during a joint effort within a project sponsored by the EEC. Comparisons are established with previous numerical results, as well as experimental data, available from the literature.

1. Introduction

In this paper some experiences in helicopter rotor noise calculation are presented. Two numerical codes, currently being developed at C.I.R.A. and Agusta, have been tested under several flight conditions in order to check their ability to represent different qualitative aspects of acoustic emission phenomena.

Mathematical basis for both prediction procedures is the Ffowcs Williams-Hawkings equation [1]:

$$\begin{aligned}\frac{\partial \tilde{\rho}}{\partial t^2} - c_0^2 \frac{\partial \tilde{\rho}}{\partial x_i^2} &= \frac{\partial}{\partial t}\left[\rho_0 v_n \delta(f)\right] \\ &- \frac{\partial}{\partial x_i}\left[\tilde{P}_{ij}\hat{n}_j \delta(f)\right] \\ &+ \frac{\partial^2}{\partial x_i \partial x_j}\left[T_{ij} H(f)\right] \qquad (1)\end{aligned}$$

where $T_{ij} = \rho u_i u_j + \tilde{P}_{ij} - c_0^2 \tilde{\rho} \delta_{ij}$. This equation describes the generation and propagation of sound from a body moving in a fluid flow; using the free-space Green function for the wave equation yields the following integral expression for the acoustic disturbance:

$$
\begin{aligned}
4\pi c_0^2\tilde{\rho}(\mathrm{x},t) &= \frac{\partial}{\partial t}\iint_S \left[\frac{\rho_0 v_n}{r|1-m_r|}\right]_{\mathrm{ret}} dS \\
&- \frac{\partial}{\partial x_i}\iint_S \left[\frac{\tilde{P}_{ij}\hat{n}_j}{r|1-m_r|}\right]_{\mathrm{ret}} dS \\
&+ \frac{\partial^2}{\partial x_i \partial x_j}\iiint \left[\frac{T_{ij}}{r|1-m_r|}\right]_{\mathrm{ret}} dV
\end{aligned} \tag{2}
$$

In the above formulas, standard symbols are used to denote physical quantities involved in the fluid dynamics phenomena responsible for the generation of noise by moving bodies. Equation (2) is the most immediate form to represent the solution of the Ffowcs Williams-Hawkings equation (1). Over the last two decades, a great deal of theoretical work has been done to derive from this formula different representations, in order to improve the attitude of this solution to be implemented for numerical calculations.

According to Farassat [2], the second term — loading noise contribution — on the right-hand side of equation (2) is modified as follows:

$$
\frac{\partial}{\partial x_i}\iint_S \left[\frac{\tilde{P}_{ij}\hat{n}_j}{r|1-m_r|}\right]_{\mathrm{ret}} dS = -\frac{1}{c_0}\frac{\partial}{\partial t}\iint_S \left[\frac{\tilde{P}_{ij}\hat{n}_j\hat{r}_i}{r|1-m_r|}\right]_{\mathrm{ret}} dS - \iint_S \left[\frac{\tilde{P}_{ij}\hat{n}_j\hat{r}_i}{r^2|1-m_r|}\right]_{\mathrm{ret}} dS \tag{3}
$$

so that the divergence of a vector integral, which is computationally expensive, is changed into two scalar integrals (one involving a simpler time derivative). They represent a far field (r^{-1} dependence) and a near field (r^{-2}), respectively, and exhibit the unit vector $\hat{r}_i$ in the source-observer direction: it accounts for the directivity of the dipole source, clearly appearing in the form of the left-hand side.

The same transformation involved in equation (3) can be applied twice to the third term on the right-hand side of equation (2), so that the following expression has been obtained by Farassat and Brentner [3] for the quadrupole noise contribution:

$$
\begin{aligned}
\frac{\partial^2}{\partial x_i \partial x_j}\iiint \left[\frac{T_{ij}}{r|1-m_r|}\right]_{\mathrm{ret}} dV &= \frac{1}{c_0^2}\frac{\partial^2}{\partial t^2}\iiint \left[\frac{T_{ij}\hat{r}_j\hat{r}_i}{r|1-m_r|}\right]_{\mathrm{ret}} dV \\
&+ \frac{1}{c_0}\frac{\partial}{\partial t}\iiint \left[\frac{3T_{ij}\hat{r}_j\hat{r}_i - T_{ii}}{r^2|1-m_r|}\right]_{\mathrm{ret}} dV + \iiint \left[\frac{3T_{ij}\hat{r}_j\hat{r}_i - T_{ii}}{r^3|1-m_r|}\right]_{\mathrm{ret}} dV
\end{aligned} \tag{4}
$$

In the above formula, the spatial complexity of the quadrupole source — shown by the double divergence on the left-hand side — is accounted for by the dependence of the three integrands on increasing powers of $1/r$.

Expressions (3) and (4) represent key features of the time domain formula implemented by the codes presented in this paper: further developments due to the authors are pointed out in the following. Four series of tests are designed for the validation of these procedures: several numerical and experimental results available from the literature are exploited. Different kinds of comparisons are established: they all refer to previous fundamental contributions to the study of helicopter rotor noise.

In section 2, following Schultz and Splettstoesser [4], test cases relating to two different flight conditions were conducted by di Francescantonio with his BENP code (developed at Agusta). Results for high-speed impulsive noise are illustrated for helicopter in forward flight up to very high advancing blade tip Mach number.

Three series of test cases are presented for HERNOP code (developed at C.I.R.A.). Results referring to comparisons with WOPWOP code calculations [5] (this was developed by Brentner based on the so-called Farassat's formulation 1-A [6]) are shown in section 3; computational results are also compared with experimental data reported in [5].

The tests reported in section 4, refer to high-speed problems, again involving the accuracy of quadrupole noise prediction methods. These are devoted to the evaluation of transonic effects for hovering rotors, and the basis for the comparisons with HERNOP results is provided by frequency domain calculations proposed by Prieur [7].

Finally, section 5 shows a series of tests concerning comparisons of numerical results with acoustic pressure signatures from flight tests measurement, reported by Schmitz and Yu [8]; HERNOP has been tested on a level flight condition, highlighting the importance of source-observer relative placement.

2. Comparing BENP calculations with previous results

The accurate prediction of the noise radiated by high speed rotors requires the evaluation of integrals not only on the blade surface, but also in the volume around the blade itself, as shown by equation (2). This causes the computing time to dramatically increase while, on the other hand, a large amount of aerodynamic data is required. However, some researchers (Caradonna [9], Schultz and Splettstoesser [4]) have shown that, using suitable approximations, the required aerodynamic data and the computing time can both be reduced. In this section, starting with the approximation proposed by Schultz and Splettstoesser, a new method is introduced to estimate the quadrupole contribution, and an analysis is conducted in order to assess its capability in the prediction of High Speed rotor noise.

The numerical experiments were carried out using the aeroacoustic code BENP developed by di Francescantonio: it allows the evaluation of all the terms (surface and volume) of the FW-H equation for rotors in hovering and forward flight. In the quadrupole calculation proposed by Schultz and Splettstoesser, only the chordwise component of the fluid perturbation velocity is retained: it is integrated along the normal to the blade surface, and a momentum thickness is obtained. Then, in the acoustic calculation the volume integrals are replaced by surface intergrals of the momentum thickness.

In the present formulation, the value of the momentum thickness is redestributed in the direction perpendicular to the blade surface, so that a description of the velocity disturbance in a volume around the blade is obtained. The quadrupole terms are then evaluated in a portion of the volume around the blade: the size of this region depends on the way the redestribution is performed. In order to validate the present method, BENP calculations were compared with results from an experimental campaign conducted in 1982 at DNW [10,11] on the AH-1/OLS rotor.

The first case refers to a forward flight condition with 0.843 Mach number at the advancing blade tip. Figure 1 shows the results obtained using BENP, those obtained by Schultz and Splettstoesser [4], and the experimental data corresponding to three microphones placed in the rotor plane, the same distance (1.72 times the tip radius) from the shaft, and at three different azimuth locations: upstream direction, 30° from upstream direction on the advancing side, and 30° on the retreating side, respectively. The results were obtained using the momentum thickness calculations performed by Yu, Caradonna, and Schmitz [9], referring to two-dimensional flow around NACA 0012 airfoil section at zero incidence. The redestribution was then made on a very small volume around the blade (the extention in the direction perpendicular to the blade surface was less then 1% of the blade chord); further approximations were neglecting volume contribution in the outer blade tip region, and assuming a two-dimensional flow through the blade sections.

In figure 1, pressure signatures from BENP exhibit good agreement with experimental data, when the contribuition of the volume quadrupole is added to the thickness term. The main advantage of this approximation is the need of a limited amount of aerodynamic data, since only the knowledge of the momentum thickness as a function of the Mach number is required (the momentum thickness is in fact assumed to be constant along the chord). On the other hand, the number of points used for the volume integration is very small, due to the size of the region where the redistribution is performed. In this case, in fact, only one layer of volume elements is considered, so that the computing time is nearly that required by simple thickness-loading calculation. It is interesting to note that good agreement can be obtained at this Mach number in spite of the crude approximations used.

The results are no longer satisfactory when the Mach number increases, as it can be seen from figure 2, showing comparisons for a test case with advancing tip Mach number of 0.893. Although the agreement is quite good for the first microphone position, the peak amplitude is overpredicted at the advancing side and underpredicted at the retreating side.

A first attempt to improve the method, was to change the momentum thickness redistribution. The noise signature, however, exhibits low sensitivity to the size of the volume considered, and to the distribution law inside the volume itself. Further improvement was to relax the assumption of constant momentum thickness along the chord. Figure 3 reports the results for the advancing side, center, and retreating side microphones, respectively. As it can be seen, the noise signature seems to be sensitive to the chorwise distribution, but the accuracy does not increase. At this stage of the analysis it seems that when the Mach number is lower than a certain value (approximately 0.85), the method introduced here yields good results, while at higher Mach number there is need for a more detailed knowledge of the aerodynamic data. For example, it might be helpful to evaluate the momentum thickness with a 3D aerodynamic code, and to describe also the outer blade tip region. The method proposed by di Francescantonio can be seen as an easy tool that, using a small amount of aerodinamic data and low computing time, allows an accurate noise prediction when the Mach number is not too large.

3. HERNOP versus WOPWOP comparisons

This section shows some results obtained using HERNOP code, developed at C.I.R.A. by Ianniello, Tarica and De Bernardis. An attempt is made to check the ability of this new code of reproducing the main features of noise signature characteristics as calculated by similar procedures, for which some results have already been published. WOPWOP code, developed by Brentner at Langley Research Center [12], is particularly well suited to this validation task. Though based on the earlier formulation 1, HERNOP code exploits most of the experience gained at Langley in building aeroacoustic codes. Besides, some results of WOPWOP calculations (including only thickness and loading terms) were published by Brentner [5]: comparisons were established with experimental data presented by Conner and Hoad [13].

Concerning the test cases presented in the following, some remarks are in order. Linear calculations from HERNOP are presented, along with results containing quadrupole contribution. Linear calculations do only include thickness term effect, since it was not possible to use the same loading inputs provided WOPWOP by C81 code. On the other hand, since calculations of transonic aerodynamics for the UH-1 rotor in nonlifting mode could be performed at C.I.R.A., these results were used to tentatively assess the quadrupole contribution — calculated following Schultz and Splettstoesser — and comparison of this overall signature (thickness and quadrupole) is established with measured acoustic pressure.

Figure 4 shows results for a test case with advancing tip Mach number of 0.828; microphones were both located 40° from the upstream direction, on the advancing and the retreating side, respectively. Thickness signature from HERNOP is very close to WOPWOP prediction: at the Mach number considered, the loading noise contribution mostly affects the size of the two positive peaks of the overall signature, while the large negative peak is almost completely determined by the thickness effect. When the quadrupole contribution is added to the thickness term, good agreement is obtained with the main peak of the experimental noise data reported by Brentner. Similar results are obtained at a larger value of the forward speed. Figure 5 shows the comparisons referring to a test case with 0.866 advancing tip Mach number. Microphone locations are the same as in figure 4.

Note that numerical calculations are unable to correctly predict the positive peaks of the experimental waveforms. In fact, they are generally determined by two different causes: blade-vortex interaction effects and shock waves and delocalization (not appearing, presumably, in the cases considered in this section). Concerning the first phenomenon, the linear loading component of WOPWOP, as well as HERNOP, should be able to account for this occurrence, provided that unsteady aerodynamic loading on the blade surface are supplied. In order to account for strong shock waves effects, a different procedure will be implemented by HERNOP, following an approach proposed by Farassat and Brentner [2].

4. Comparisons with frequency domain results for hovering flight

A test case has been selected from an extensive study conducted by Prieur [7]. He developed a frequency domain method and performed a valuable investigation on the quadrupole radiation from hovering UH-1H model rotor with tip Mach number in the transonic range. The comparison considered here refers to a test with tip Mach number of 0.88, at which no delocalization effect is present. Results from HERNOP exhibit good agreement with the peak value of quadrupolar component, although some differences appear in the waveform shape.

5. Comparisons with flight tests measurements

Among the large amount of different results shown by Schmitz and Yu [8], some flight test data have been selected in order to check the ability of HERNOP code to predict the acoustic behaviour of UH-1H rotor in forward flight. In particular, comparisons with in-flight measured data are established, relating to the lateral directivity in level flight at an indicated airspeed of 115 knots, leading to an advancing tip Mach number of 0.9. Observer locations are near the tip path plane, 7° below the flight level. Good agreement is obtained for the peak value of the acoustic pressure at the microphone positions 53° and 72° from upstream direction. At the more critical position, only 29° from upstream direction, peak pressure is significantly overpredicted.

Acknowledgements

This work was partially supported by the European Economic Community under the BRITE/EURAM contract No. AERO-0010-C (MB) "Helicopter and Tilt-rotor Aircraft Exterior Noise Research", acronym HELINOISE.

References

1. J.E. Ffowcs Williams and D.L. Hawkings, Sound Generation by Turbulence and Surfaces in Arbitrary Motion, Phil. Trans. of the Royal Society, A264, pp. 321–342, 1969.

2. F. Farassat, Theory of Noise Generation from Moving Bodies with an Application to Helicopter Rotors, NASA TR R-451, December 1975.

3. F. Farassat and K.S. Brentner, The Uses and Abuses of the Acoustic Analogy in Helicopter Rotor Noise Prediction, Journal of the American Helicopter Society, 33, pp. 29–36, January 1988.

4. K.-J. Schultz and W.R. Splettstoesser, Prediction of Helicopter Rotor Impulsive Noise Using Measured Blade Pressures, 43rd Annual Forum and Technology Display of AHS, St. Louis, MO, May 1987.

5. K.S. Brentner, Prediction of Helicopter Rotor Discrete Frequency Noise for Three Scale Models, Journal of Aircraft 25, pp. 420–427, May 1988.

6. F. Farassat and G.P. Succi, The Prediction of Helicopter Rotor Discrete Frequency Noise, Vertica 7, pp. 309–320, April 1983.

7. J. Prieur, Calculation of Transonic Rotor Noise Using a Frequency Domain Formulation, AIAA Journal 26, pp. 156–162, February 1988.

8. F.H. Schmitz and Y.H. Yu, Helicopter Impulsive Noise — Theoretical and Experimental Status, Journal of Sound and Vibration, 109, pp. 361–422, 1986.

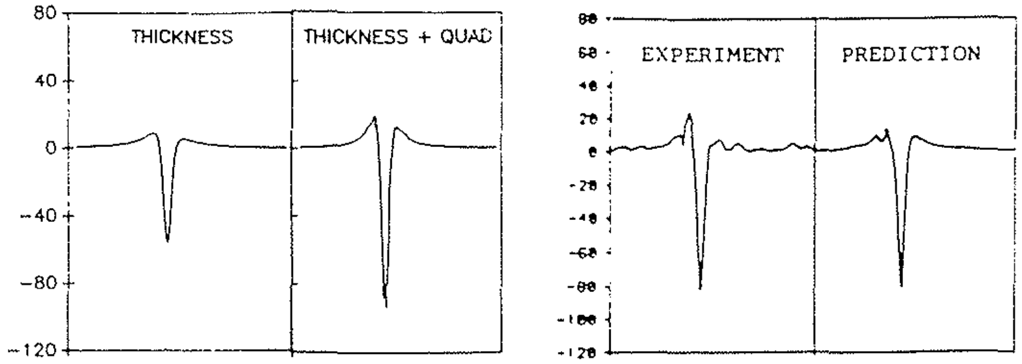
9. Y.H. Yu, F.X. Caradonna and F.H. Schmitz, The influence of the transonic flow field on high speed helicopter implulsive noise, 4th European Rotorcraft and Powered Lift Aircraft Forum, Paper 58, Italy, 1978.

10. W.R. Splettstoesser, K.-J. Schultz, D.A. Boxwell and F.H. Schmitz, Helicopter Model Rotor Blade-Vortex Interaction Impulsive Noise: Scalability and Parametric Variations, 10th European Rotorcraft Forum, Paper 18, The Hague, The Netherlands, August 1984.

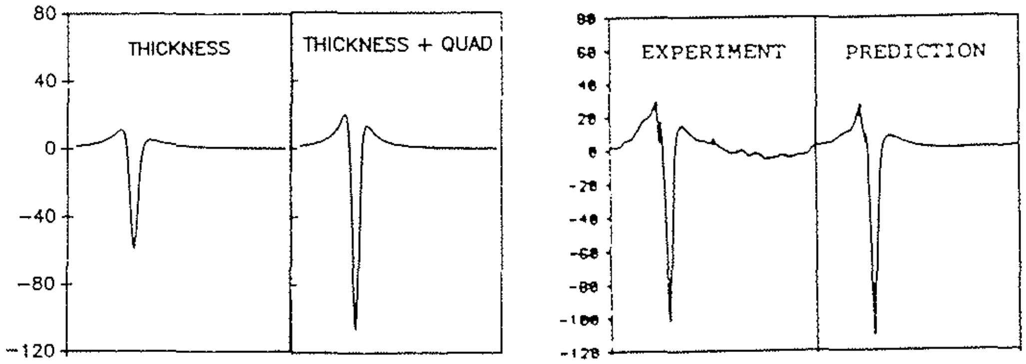
11. D.A. Boxwell, F.H. Schmitz, W.R. Splettstoesser and K.-J. Schultz, Model Helicopter Rotor High Speed Impulsive Noise — Measured Acoustic and Blade Pressures, NASA Technical Memorandum 85850 and USAAVRADCOM Technical Report–83–A–14, September 1983.

12. K.S. Brentner, Prediction of Helicopter Rotor Discrete Frequency Noise, NASA Technical Memorandum 87721, October 1986.

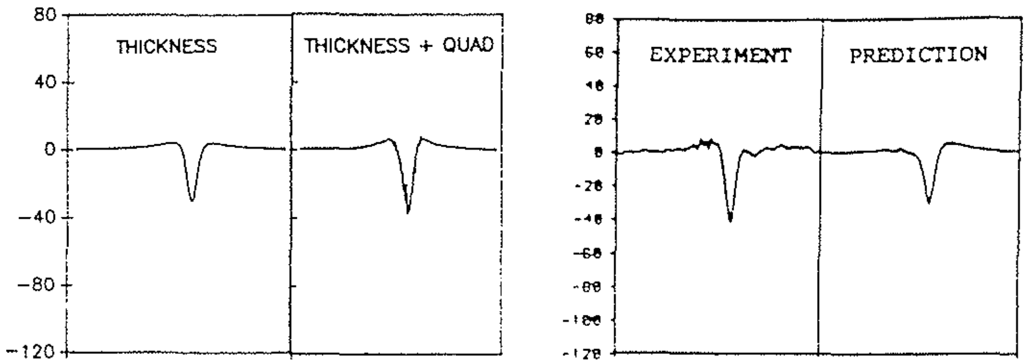
13. D.A. Conner and D.R. Hoad, Reduction of High-Speed Impulsive Noise by Blade Planform Modification of a Model Helicopter Rotor, NASA TM 84553, AVRADCOM TR 82–B–6, 1982.



a) Microphone position: upstream direction

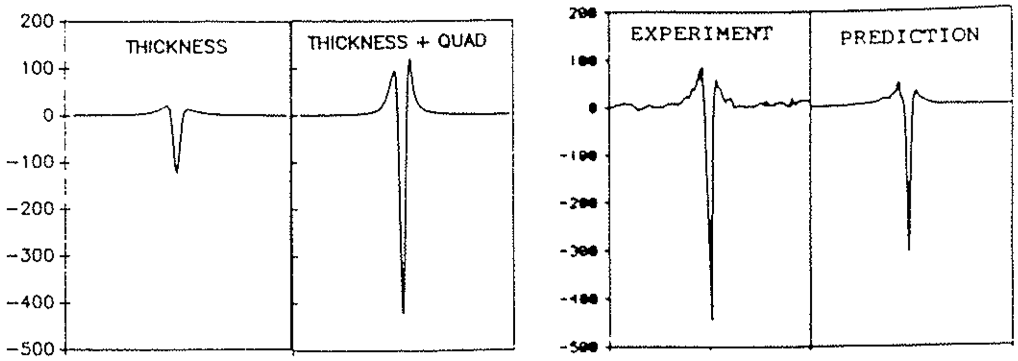


b) Microphone position: 30° from upstream direction, advancing side

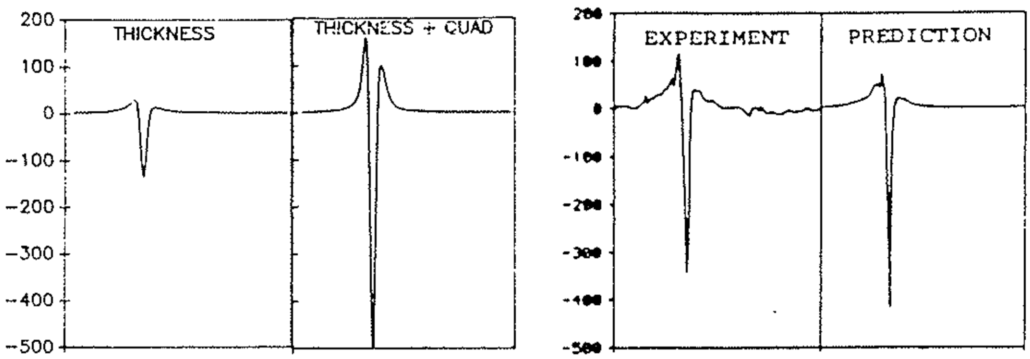


c) Microphone position: 30° from upstream direction, retreating side

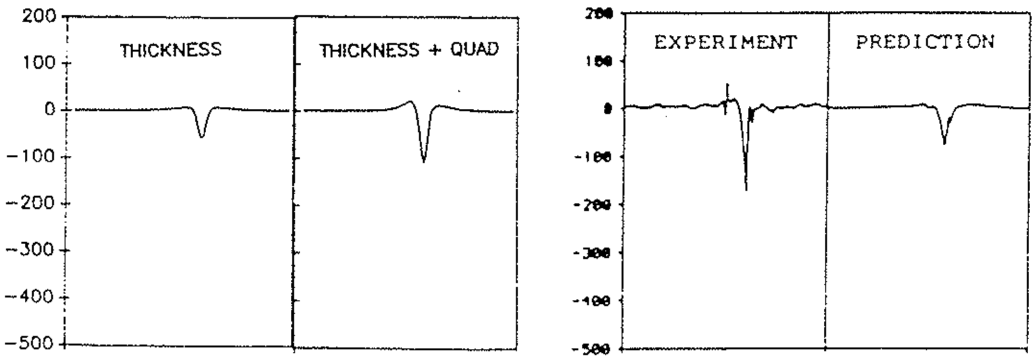
Figure 1: BENP calculations (left pictures) and results from reference [4] (right pictures) at three different micriphone locations, with 0.843 advancing blade tip Mach number.



a) Microphone position: upstream direction

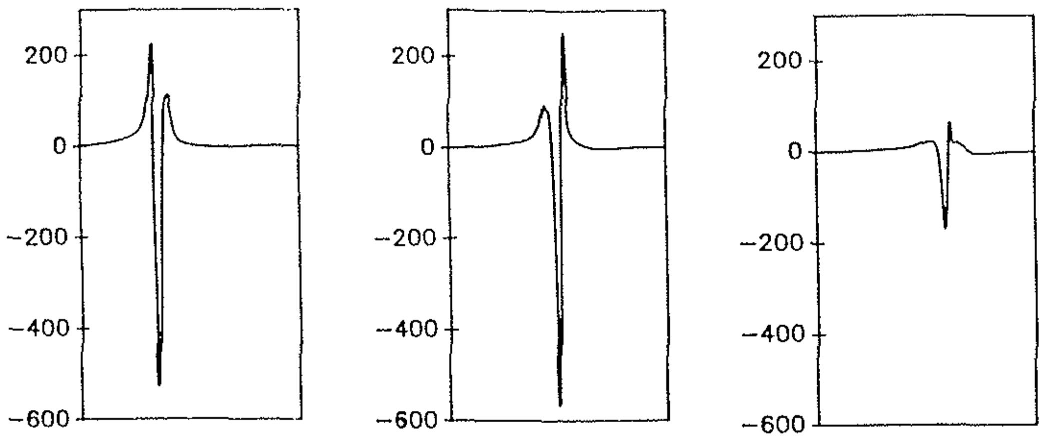


b) Microphone position: 30° from upstream direction, advancing side



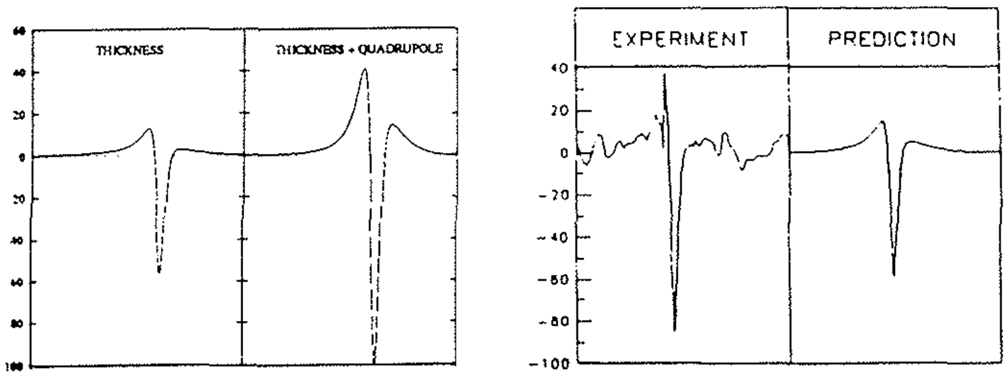
c) Microphone position: 30° from upstream direction, retreating side

Figure 2: BENP calculations (left pictures) and results from reference [4] (right pictures) at three different miciphone locations, with 0.893 advancing blade tip Mach number.

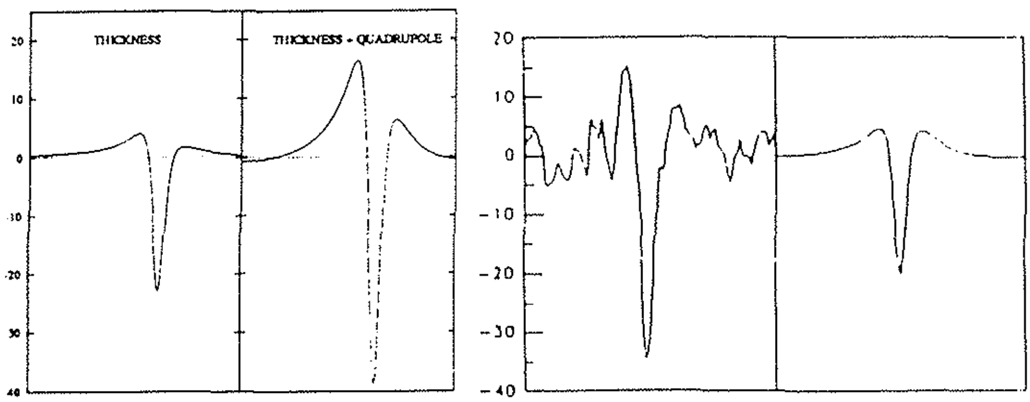


a) Advancing side b) Center c) Retreating side

Figure 3: Improved pressure signatures from BENP for test cases in figure 2.

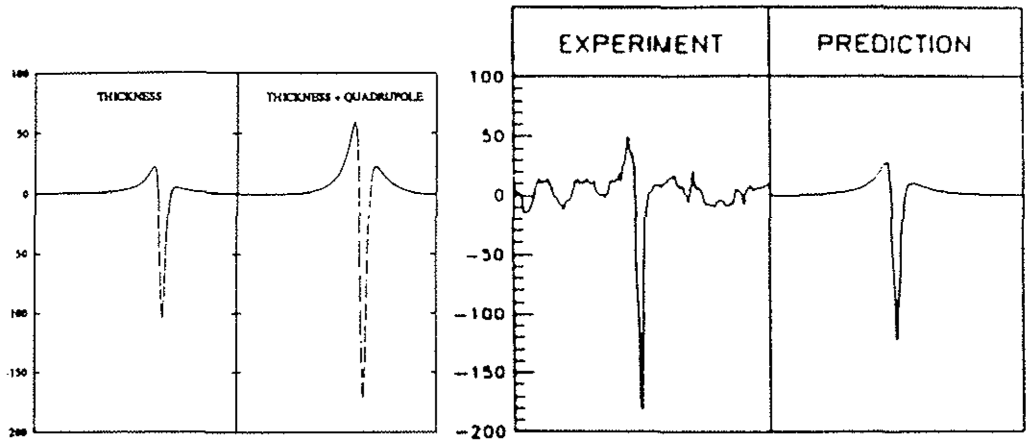


a) Microphone position: 40° from upstream direction, advancing side

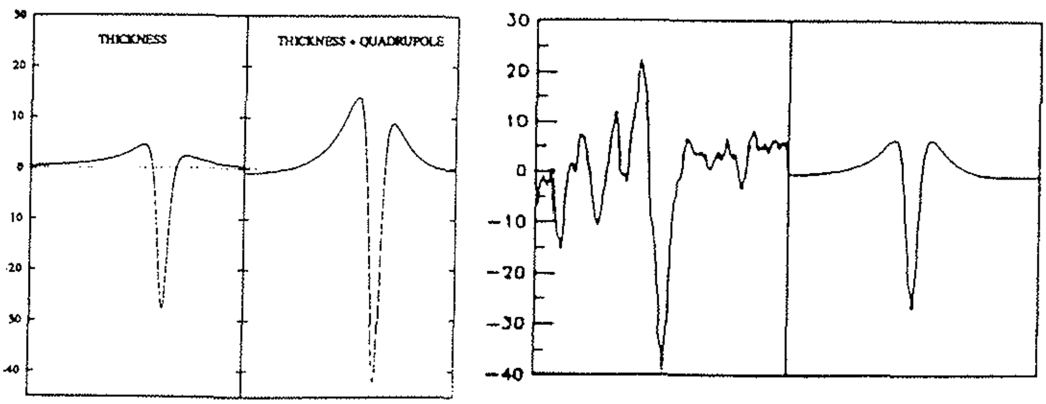


b) Microphone position: 40° from upstream direction, retreating side

Figure 4: HERNOP calculations (left pictures) and results from reference [5] (right pictures) at two different microphone locations, with 0.827 advancing blade tip Mach number.



a) Microphone position: 40° from upstream direction, advancing side



b) Microphone position: 40° from upstream direction, retreating side

Figure 5: HERNOP calculations (left pictures) and results from reference [5] (right pictures) at two different microphone locations, with 0.866 advancing blade tip Mach number.

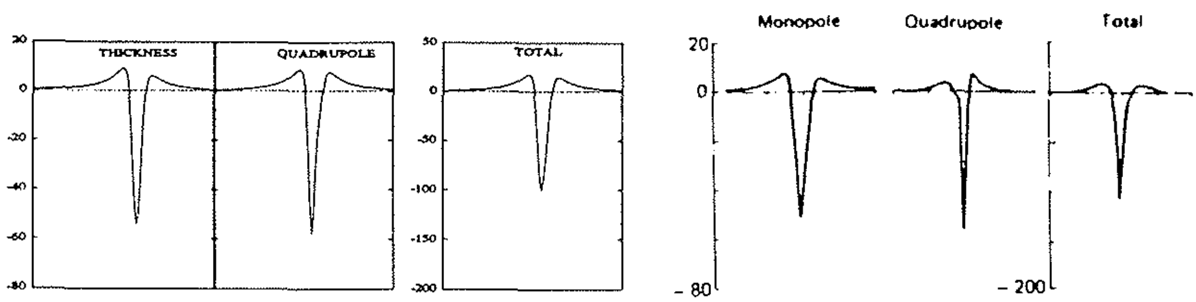
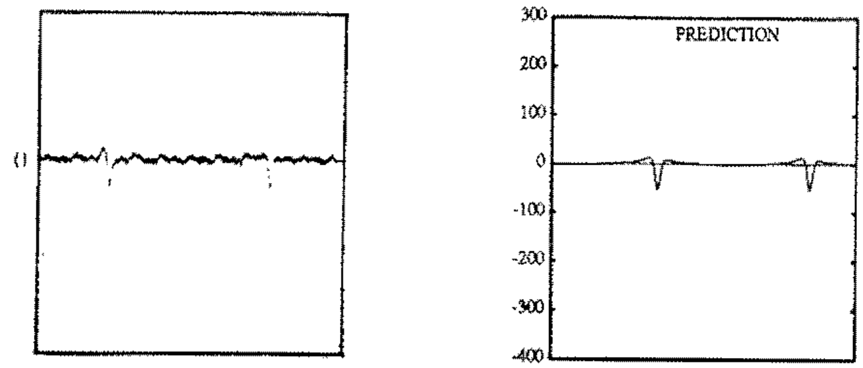
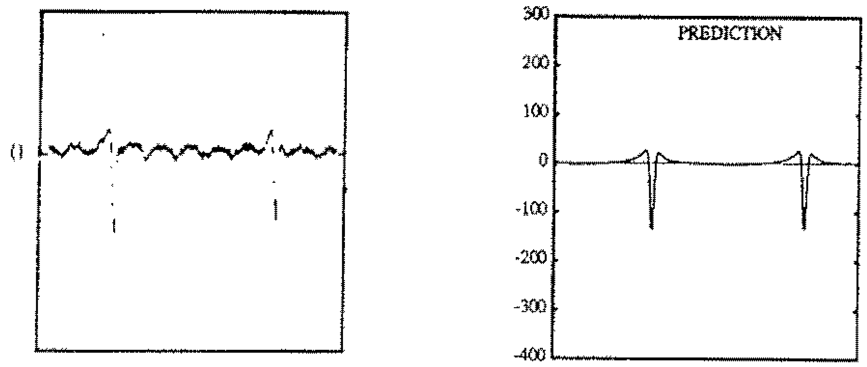


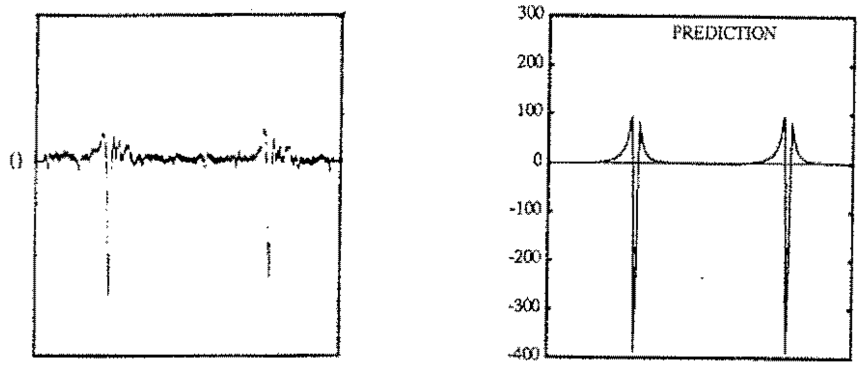
Figure 6: HERNOP calculations (left pictures) and results from reference [7] (right pictures) for hovering rotor, with 0.88 blade tip Mach number.



a) Microphone position: 29° from upstream direction, advancing side



b) Microphone position: 53° from upstream direction, advancing side



c) Microphone position: 72° from upstream direction, advancing side

Figure 7: HERNOP calculations (right pictures) compared with in flight measurements reported in reference [8] (left pictures), at three different (moving) micriphone locations.