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Abstract

In this paper some results from HERNOP code are presented. The code is designed for the prediction of helicopter rotor noise, in subsonic and transonic regime; it has been developed at C.I.R.A., during the **Helinoise** project, sponsored by the EEC. A number of comparisons are shown with previous numerical results and experimental data, available from literature.

1. Introduction

HERNOP (HElicopter Rotor NOise Prediction) has been conceived to provide a powerful investigation tool for the prediction of helicopter rotor noise. Based on the well-known Farassat time domain formulations 1 and 1-A, the code allows to examine subsonic and transonic problems, evaluating the quadrupole sources contribution following two different ways. The current version of the program considers only rigid rotor blades; it may be run with different blade models and implements realistic blade motions, considering variations of flapping, feathering and lead-lag angles, during the revolution period. The knowledge of blade geometry and kinematics is requested to thickness noise evaluation, while the determination of loading noise strongly depends on the availability of reliable aerodynamic data. For loading noise prediction the code requires the blade pressure distribution; it is also able (for blades with NACA airfoil sections) to asses this distribution from the knowledge of lift coefficient at different stations along span, using a semplified method. The numerical calculations of the quadrupole noise, necessary for high tip speed blades, can be performed following two different approaches, on the grounds of available aerodynamic data. The possible availability of the *momentum thickness* distribution upon the blade allows the evaluation of quadrupole noise through a surface integral, applying the *Schultz approximation*, for in-plane and far-field positions. Otherwise, only for hovering rotors, it is possible to apply a full three-dimensional integration; this exploits the perturbation velocity distribution around the blade, supplied by an aerodynamic code. To check HERNOP ability to represent various qualitative aspects of rotor acoustic phenomena, several tests have been conducted, for hover as well as forward flight conditions.

2. Theoretical background

As a theoretical basis for the analysis of sound generated by a body moving in a fluid, the Ffowcs Williams-Hawkings (FW-H) equation [1] has been adopted:

$$\frac{\bar{\partial}\tilde{p}}{\partial t^2} - c_0^2\bar{\nabla}^2\tilde{p} = \frac{\bar{\partial}}{\partial t}\left[\rho_0 v_i \hat{n}_i \delta(f)\right] - \frac{\bar{\partial}}{\partial x_i}\left[\tilde{P}_{ij}\hat{n}_i \delta(f)\right] + \frac{\bar{\partial}^2}{\partial x_i \partial x_j}\left[T_{ij}H(f)\right] \tag{1}$$

where $T_{ij} = \rho u_i u_j + (\tilde{P}_{ij} - c_0^2\tilde{\rho}\delta_{ij})$ is the Lighthill stress tensor and standard symbols are used.

By neglecting the quadrupole source term, several forms of solution to equation (1) have been developed, that are valid for subsonic and supersonic blade motions. Following a standard Green's function approach, equation (1) is transformed into an integral expression for acoustic pressure $p(\mathbf{x}, t)$, with the body surface as the integration domain:

$$4\pi p(\mathbf{x}, t) = \frac{1}{c_0}\frac{\partial}{\partial t}\iint_S \left[\frac{\rho_0 v_n c_0 + l_r}{r\,|1 - m_r|}\right]_{\text{ret}} dS + \iint_S \left[\frac{l_r}{r^2\,|1 - m_r|}\right]_{\text{ret}} dS \tag{2}$$

Here $l_r = \mathbf{l}\cdot\hat{\mathbf{r}}$, with $\mathbf{l}$ the vector of components $l_i = \tilde{P}_{ij}\hat{n}_j$ and $\hat{\mathbf{r}}$ the unit vector along the source-observer direction. Equation (2), known as *formulation 1*, has been proposed by Farassat in 1975 [2]: it allows to determine the acoustic pressure generated by a subsonic tip speed blade. The two integrals correspond to a possible decomposition of acoustic signature into *far field* and *near field*, based on the dependence of the integrands on $1/r$ and $1/r^2$ respectively. All the kernels appearing in equation (2) are characterized by the subscript *ret*: it denotes the emission time $\tau^* = t - |\mathbf{x} - \mathbf{y}|/c_0$, corresponding to the current observer time t, at which all the quantities involved in the integrals on (and around) the body surface have to be evaluated. Note here that for the resolution of the FW-H equation other approaches consider as integration domain the so-called *retarted surface*. At any observer time, it represents the surface drawn by the source points at correspondent emission time; then the informations about the delay between the observer time and the emission time are included inside the integration domain (Figure 1).

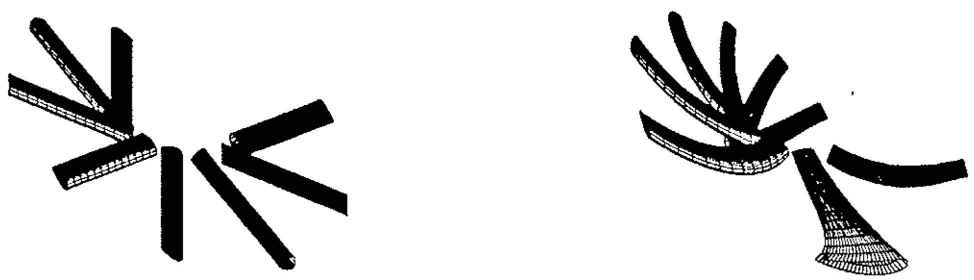


Figure 1 - *Plot of eight successive positions of a rotor blade in forward flight and the corresponding retarted surface, as calculated by HERNOP.*

The time derivative outside the first integral makes the equation (2) not very suitable for numerical use. The accuracy of predicted noise signatures may be increased by taking the time derivative into the integral [3], thus obtaining the so-called *formulation 1-A*:

$$\begin{aligned}4\pi p(\mathbf{x},t) &= \iint_S \left[\frac{\rho\dot{v}_n}{r|1-m_r|^2}\right]_{\rm ret} dS + \iint_S \left[\frac{\rho v_n\left(r\dot{m}_i\hat{r}_i + c_0 m_r - c_0 m^2\right)}{r^2|1-m_r|^3}\right]_{\rm ret} dS \\ &+ \frac{1}{c_0}\iint_S \left[\frac{\dot{l}_i\hat{r}_i}{r|1-m_r|^2}\right]_{\rm ret} dS + \iint_S \left[\frac{l_r - l_i m_i}{r^2|1-m_r|^2}\right]_{\rm ret} dS \\ &+ \frac{1}{c_0}\iint_S \left[\frac{l_r\left(r\dot{m}_i\hat{r}_i + c_0 m_r - c_0 m^2\right)}{r^2|1-m_r|^3}\right]_{\rm ret} dS\end{aligned} \tag{3}$$

The time derivatives appearing in equation (3) may be analytically calculated once the blade motion is known: then the errors due to numerical differentiation and the CPU time requested to convergence may be significantly reduced. Note that the decomposition into *far field* and *near field* components holds for both thickness and loading noise: the latter differs from that proposed by Formulation 1.

Following the same procedure for equation (2), the contribution of quadrupole source term to the acoustic pressure field may be represented by the integral expression:

$$4\pi p_Q(\mathbf{x},t) = \frac{\partial^2}{\partial x_i \partial x_j}\iiint_{\mathcal{V}} \left[\frac{T_{ij}}{r|1-m_r|}\right]_{\rm ret} dV \tag{4}$$

where the integration domain $\mathcal{V}$ is intended to be the whole space outside the body. The main problem in dealing with expression (4) is that a volume integral is to be evaluated, requiring a complete knowledge of the flow field around the blade; so, the complexity of the numerical procedure and the requested CPU time become considerable. Upon transforming the space derivatives into time derivatives, equation (4) becomes:

$$\begin{aligned}4\pi p_Q(\mathbf{x},t) &= \frac{1}{c_0^2}\frac{\partial^2}{\partial t^2}\iiint_{\mathcal{V}} \left[\frac{T_{ij}\hat{r}_j\hat{r}_i}{r|1-m_r|}\right]_{\rm ret} dV \\ &+ \frac{1}{c_0}\frac{\partial}{\partial t}\iiint_{\mathcal{V}} \left[\frac{3T_{ij}\hat{r}_j\hat{r}_i - T_{ii}}{r^2|1-m_r|}\right]_{\rm ret} dV \\ &+ \iiint_{\mathcal{V}} \left[\frac{3T_{ij}\hat{r}_j\hat{r}_i - T_{ii}}{r^3|1-m_r|}\right]_{\rm ret} dV\end{aligned} \tag{5}$$

Many theoretical studies have been conducted upon equation (5), trying to understand the complex noise generating mechanisms hidden inside the non-linear source term of FW-H equation. At the same time, several kinds of approximation have been implemented in aeroacoustic codes in the attempt of turning the volume integration into a sequence of simpler operations. The method proposed by Yu, Caradonna and Schmitz [4] allows to study cases with in-plane far-field observer positions and only refers to the first term on the right-hand side of equation (5). First an integration along the direction normal to the blade is carried out yelding the so called *momentum thickness* distribution, then a two-dimensional integration is performed on the blade surface. The quadrupole noise may thus be written in the form:

$$4\pi p_Q(\mathbf{x},t) = \frac{\partial^2}{\partial t^2}\iint_S \left\{\frac{\rho m_0^2}{r|1-m_r|}\left(1+\frac{\gamma-1}{2}m_0^2\right)\left[\int_n \left(\frac{u_r}{u_0}\right)^2 dn\right]\right\}_{ret} dS \tag{6}$$

where m_0 is the instantaneous blade section Mach number. Starting with equation (6), a further simplification has been adopted by Schultz and Splettstoesser [5]: on the ground of numerical results, they have related the unknown momentum thickness distribution with the maximum streamwise perturbation velocity, exploiting the simple empirical expression:

$$\delta_2 = \int_n \left(\frac{u}{u_0}\right)^2 dn \approx A \left(\frac{u_{max}}{u_0}\right)^3 \tag{7}$$

where A depends on the tip Mach number. On the grounds of available data, HERNOP calculates the quadrupole sources contribution by following two different approaches; if the spanwise distribution of momentum thickness is known, the pressure $p_Q(\mathbf{x}, t)$ is determined exploiting expressions (6) and (7), both for hover and forward flight conditions. Otherwise the complete expression (5) may be evaluated (currently only for hovering rotors) using a three-dimensional integration in a prescribed volume around the blade. This can be attained using the perturbation velocity distribution in the flow field, provided by an aerodynamic code.

3. Thickness and Loading noise calculations

An assessement of HERNOP results for subsonic conditions and their comparison with an analogous acoustic code is presented in this section; in particular, WOPWOP code, developed by K.S. Brentner at NASA Langley Research Center, is considered [6]. This code is well suited for our validation task: in fact it is based on Farassat time domain formulation 1-A and its results have proved to be in good agreement with experimental data.

The test cases are referred to a 1/4-scale UH-1 main rotor, with a rectangular blade, linear twist distribution and uniform NACA 0012 airfoil sections. Figure 2 shows the comparison between the acoustic noise signatures (and in particular thickness and loading noise components) for an hovering rotor. The steady aerodynamic load is obtained with a simple superposition method, described by Abbott and Von Doenhoff [7], exploiting data for incompressible velocity distribution on wing section. 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. A comparison between HERNOP results obtained with the two different formulations for this hovering case is presented in Figure 3, showing excellent agreement.

Two examples referring to forward flight have been analysed and compared with WOPWOP results (Figure 4). In the first one the observer location is near the rotor tip path plane, where the contribution of thickness noise is dominant; in the second example the observer is placed just below the rotor blade and noise signature is dominated by the loading noise near-field component. The unsteady aerodynamic load is provided by the computer code C81 (the AGAJ77 version): from the knowledge of the lift coefficient upon some stations along span and for different azimuthal positions, the pressure distribution on the blade surface is reconstructed and its time derivative is calculated. The method adopted for this pressure calculation is the same for both examples, but the code exhibits a noticeably different behaviour in the two cases. When the observer position is on the tip path plane, an accurate prediction of loading noise is strongly dependent on pressure distribution along blade leading edge; so, if the density of blade source points is not increased in the vicinity of leading edge, loading noise signatures may result very inaccurate. On the other hand, an exceeding density of points may introduce numerical errors in the subsequent time derivative. These problems do not appear in the other case, referring to an observer position far from tip path plane, where the signatures *smoothness* is independent of stretching parameters. The very good agreement between

HERNOP and WOPWOP results, confirm the ability of the new code in the prediction of linear terms contribution to the acoustic field.

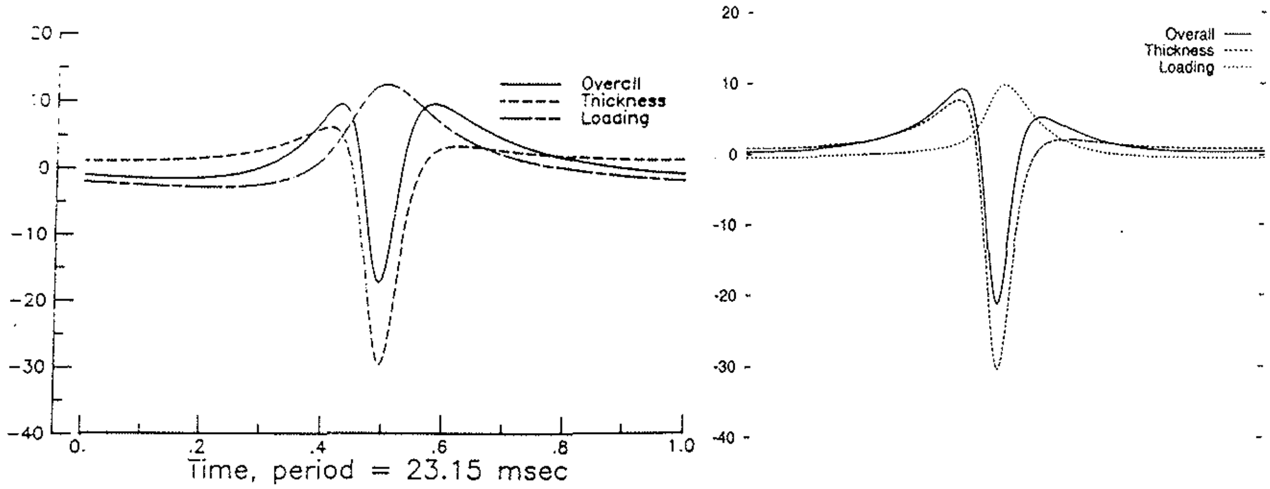


Figure 2 - *Overall acoustic pressure for hovering rotor. Comparison between HERNOP and WOPWOP results* [6] .

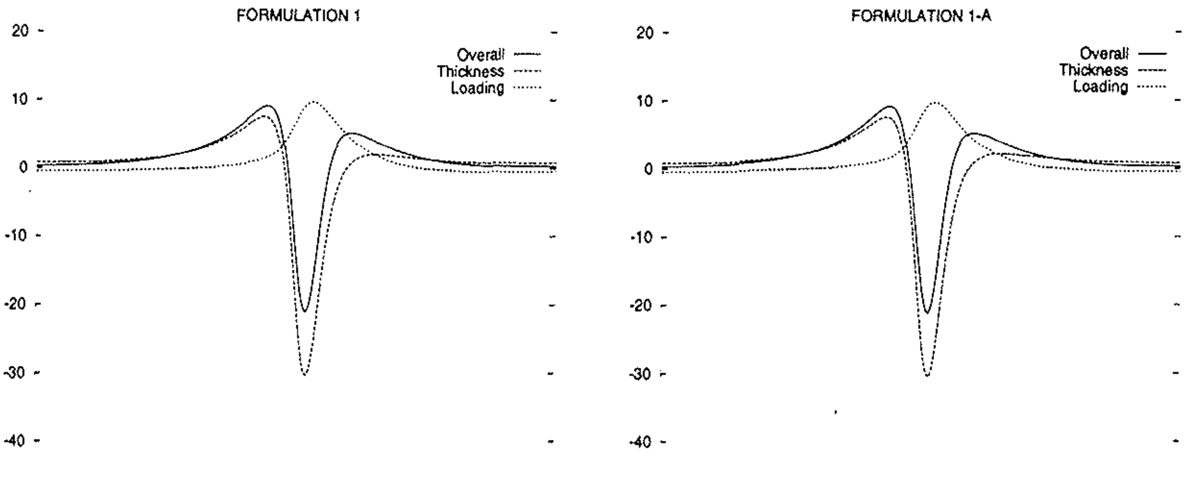


Figure 3 - *Comparison between HERNOP acoustic pressure signatures, calculated by Farassat formulations 1 and 1-A, for an hovering rotor.*

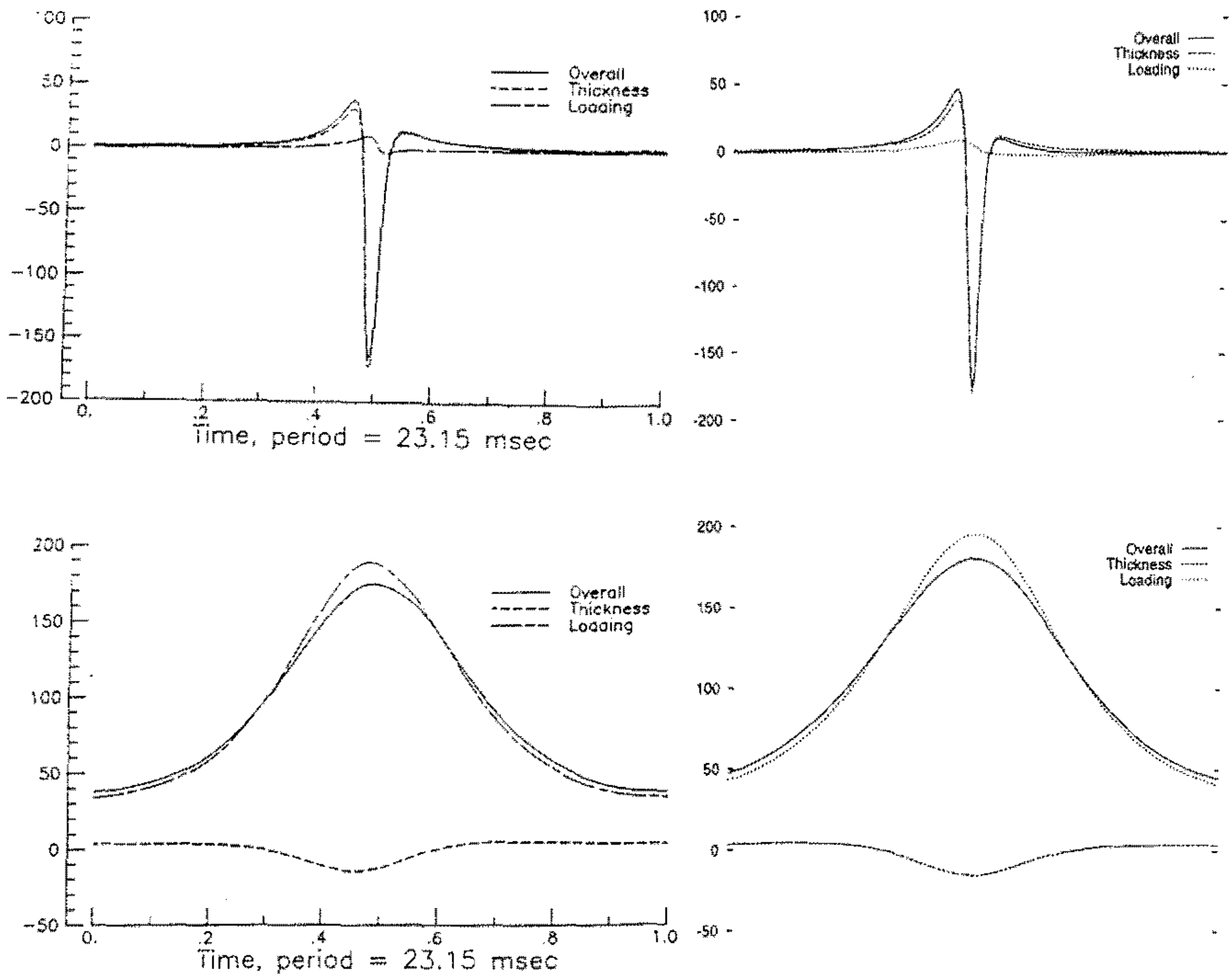


Figure 4 - *Comparison between HERNOP and WOPWOP predicted acoustic pressure for rotor in forward flight. The upper figure refers to an observer position in the rotor tip path plane: the thickness noise contribution is predominant. The lower one concerns an observer position below the rotor plane: the acoustic pressure is dominated by loading noise.*

4. Quadrupole noise calculations

The determination of quadrupole source terms contribution to the acoustic pressure field is essential for the analysis of high tip speed blades; the main difficulty in solving this problem is the lack of aerodynamic data. Experimental results providing the perturbation velocity field in a volume around the blade can hardly be found; on the other hand, numerical codes for helicopter rotor blades in the transonic range are still at a research stage, especially those dealing with forward flight.

As already mentioned, if the spanwise distribution of momentum thickness is available, HERNOP performs the quadrupole noise evaluation exploiting the Schultz approximation: then only a surface integral is to be calculated, and the requested CPU time is strongly reduced. Unfortunately this approximation proves to be effective only for in-plane and far-field observer positions; furthermore a calculation of momentum thickness distribution upon the blade surface is not immediate and generally requires an heavy interpolation work (unless a proper aerodynamic grid is available). The development of a code performing three-dimensional integration code is the last enhancement of HERNOP; the evaluation of quadrupole noise makes use of the grid, providing by the aerodynamic code. No interpolation is requested: given the geometry and motion of rotor blade, HERNOP exploits the three-dimensional field of perturbation velocity and evaluates the contribution of quadrupole source terms directly applying equation (5).

To check HERNOP ability in the prediction of quadrupole noise, some tests have been conducted for non-lifting hovering rotors. Figure 5 shows the acoustic pressure signatures (sum of thickness and quadrupole contributions, calculated through the Schultz approximation) at tip Mach numbers of 0.8,0.88 and 0.9, compared with the experimental results, extracted from [8]. We note here that a rigorous comparison may be realized only if an "exact" value for constant A in the equation (7) is determined; on the ground of information contained in [8], A has been chosen equal to 1.0, 1.2 and 1.4 for tip Mach number 0.8, 0.88 and 0.9, respectively. Furthermore, on the right of each figure, the notation "*Theory*" refers to only monopole term calculations, performed with originary acoustic codes. The agreement at the lowest tip Mach number looks quite good, both for signal shape and negative peak pressure; but increasing M_{tip}, the localized transonic effects progressively change the symmetrical character of the acoustic signature. Then the Schultz approximation becomes unable to describe the very complex phenomena taking place in the flow field around the blade, and even though reasonable values are obtained for negative peak pressure, the agreement between the predicted acoustic signature and experimental data is not good. This is true especially for $M_{tip} > 0.88$, when the shock delocalization takes place.

For HERNOP tests concerning quadrupole treatment through a volume integration, results from the C.I.R.A. aerodynamic code UTAH have been used; this code is based on a non-conservative full-potential formulation, and provides the perturbation velocity distributions in a prescribed three-dimensional grid around the rotor blade [9]. UTAH grid extends off the blade tip so that a more detailed flow field description may be obtained; for HERNOP validation tests, a mesh of 20790 nodes has been considered, with a region extending outside the body of about 30% of blade span (Figure 6). Figure 7 shows a comparison of two quadrupole noise signatures, calculated with Schultz approximation and the three-dimensional integration, for $M_{tip} = 0.8$: the agreement is quite good, especially for the predicted negative peak pressure.

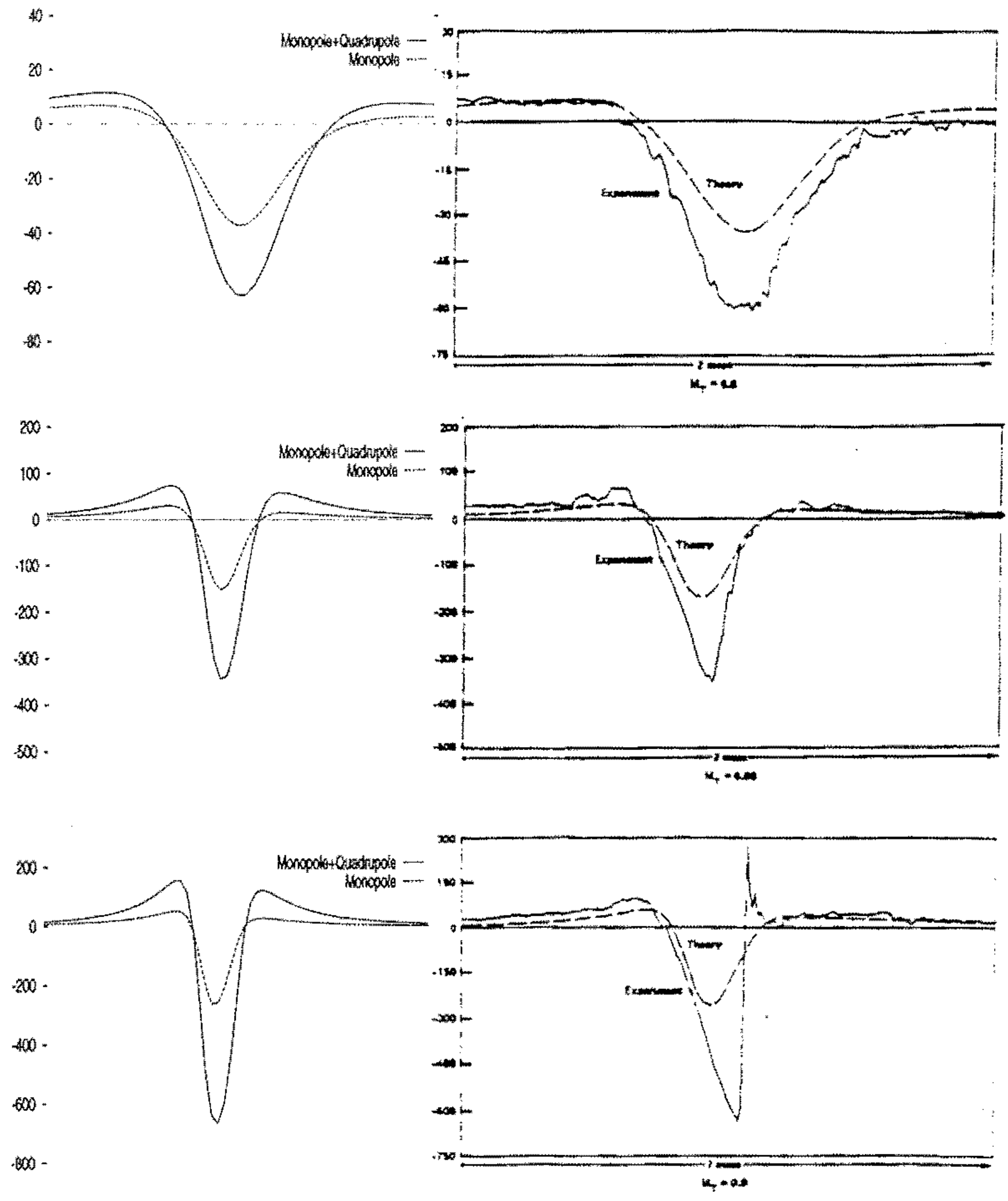
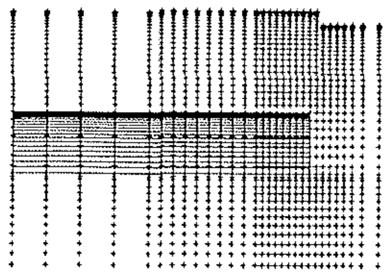


Figure 5 - *Comparison of HERNOP predicted acoustic signatures with experimental pressure time histories, in-plane, $r/D = 1.5$, $M_{tip} = 0.8, 0.88$ and 0.9. The figures on the right have been extracted from* [8]*; the notation* Theory *refers to only monopole term calculation.*



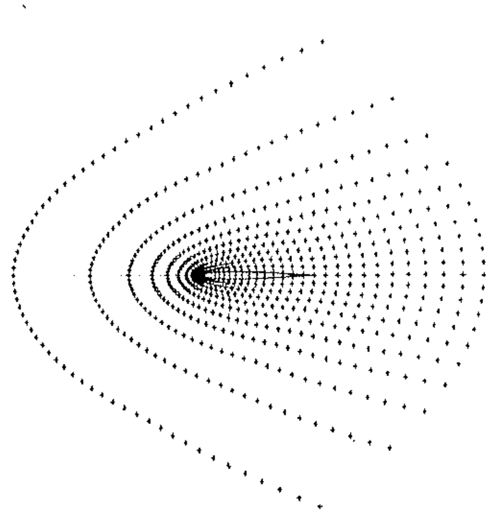


Figure 6 - *Planform and side view of UTAH mesh for HERNOP validation tests.*

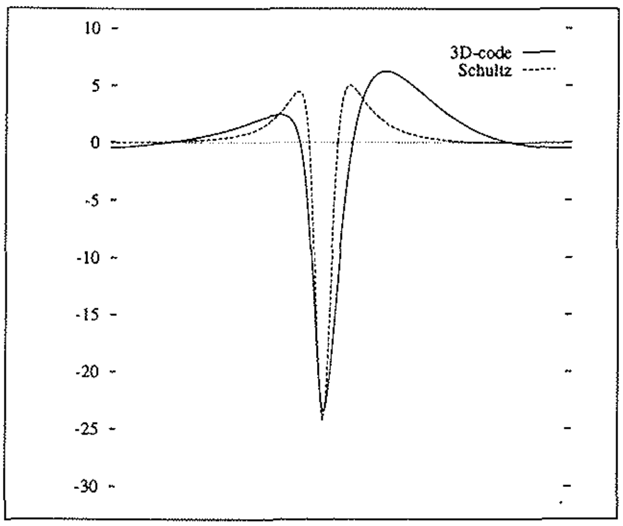


Figure 7 - *Comparison between the predicted quadrupole noise signatures, from Schultz method and the volume integration (*3D-code*); the example refers to an hovering rotor at* $M_{tip} = 0.8$ *and an observer position with* $r/R = 3.09$.

Recently, aerodynamic and aeroacoustic calculations of transonic hovering rotors have been presented by J. Prieur, M. Costes and J.D. Baeder [10]. In this paper a comparison between the aerodynamic results from an Euler code [11] and a conservative, full-potential code were presented; then, to check the ability of ONERA acoustic code for high speed impulsive noise prediction, these aerodynamic data were exploited. We point out here that the acoustic pressure signature was obtained by Baeder, directly using the Euler code too; exploiting a wide grid around the blade, the

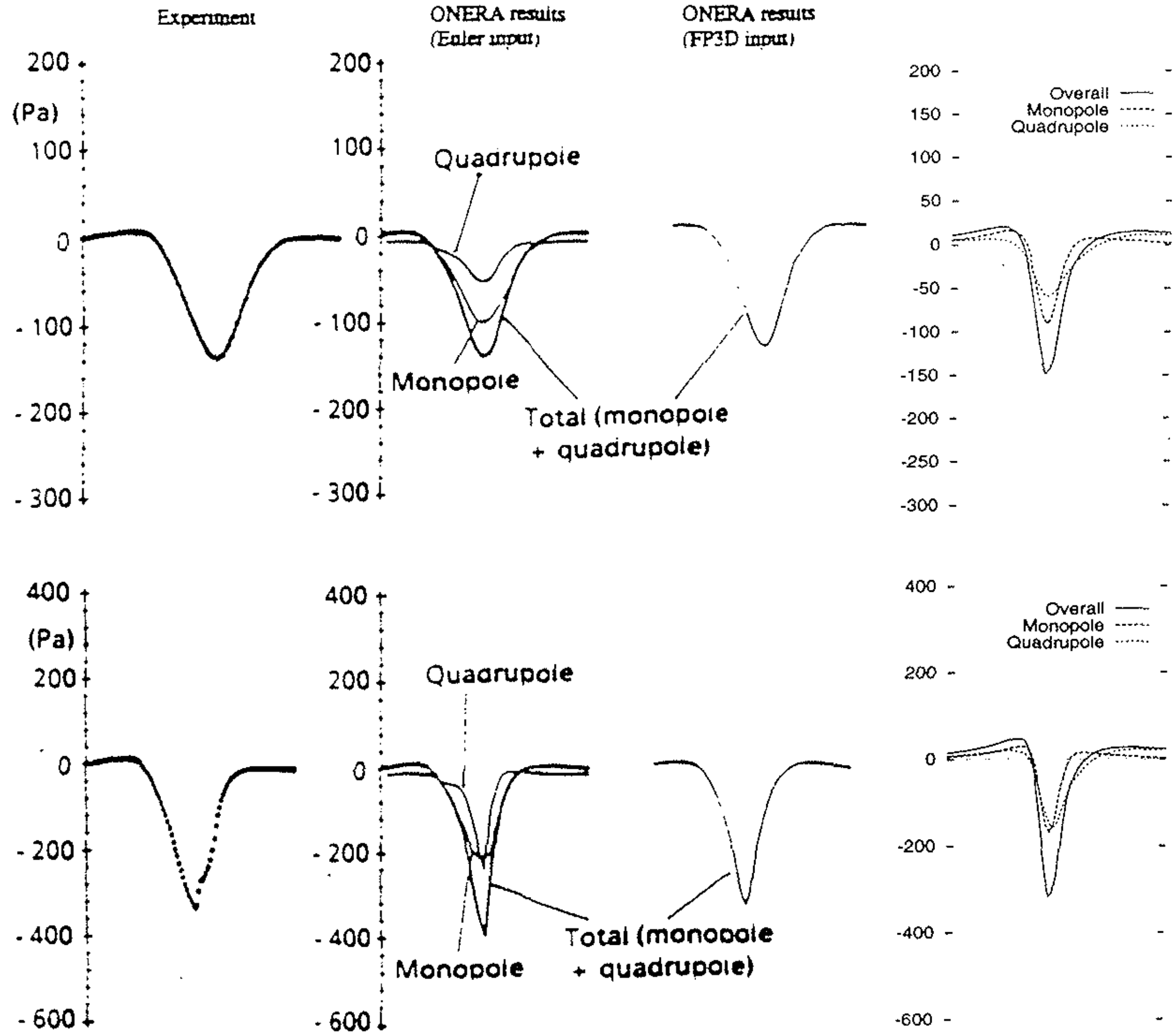


Figure 8 - *Results for nonlifting, hovering rotor, at M_{tip} equal to* 0.85, 0.88 *are reported on the right. The observer position is at $r/R = 3.09$*

Figure 8 presents the comparison between ONERA and HERNOP results: the latter are obtained using UTAH aerodynamic input and the three-dimensional integration. At M_{tip} equal to 0.85 and 0.88 the agreement with the experimental pressure time histories is very good: the symmetrical shape of resulting signatures is confirmed and the numerical comparison for negative peak pressure is excellent. But at $M_{tip} = 0.9$ (Figure 9) the agreement is not so good: despite a pronounced asymmetrical character of quadrupole noise signature, the resulting acoustics pressure is underpredicted. This is more pronounced at higher tip Mach numbers. Probably this underprediction is related to aerodynamic input. Even though, from a qualitative point of view, the volume integration is able to account for the shock (obtaining an asymmetrical quadrupole signature), the perturbation velocity determined through a non-conservative, full-potential code like UTAH, is certainly underestimated. This is especially true in the region outside the blade surface, where the shock delocalization occurs; so, the most important contribution of quadrupole sources, in the region from blade tip to sonic circle, is underestimated.

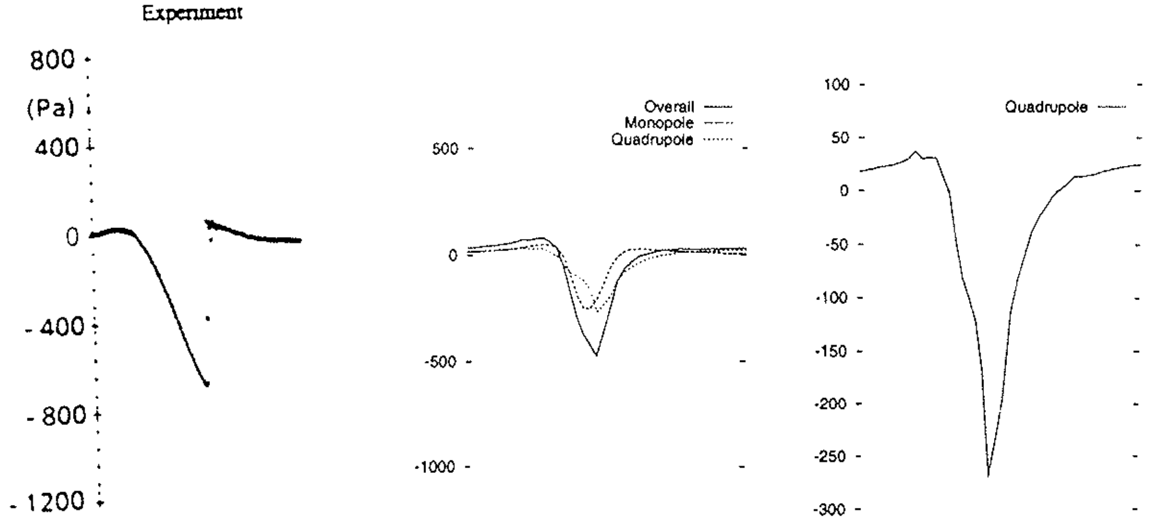


Figure 9 - *HERNOP results for nonlifting, hovering rotor, at* M_{tip} *equal to* 0.9. *The flow field description given by aerodynamic input succeeds in breaking the symmetrical shape of quadrupole signature, but the resulting acoustic pressure is undervalued, with respect to the experimental results.*

5. Conclusions

Some results from HERNOP code have been presented in this paper. Thickness and loading noise calculations have been successfully compared with numerical results from acoustic NASA code WOP-WOP, for hover and forward flight at subsonic conditions. For hovering rotors the non-linear term in the FW-H equation has been accounted for, following two different solution forms; the agreement between the predicted acoustic pressure signatures and experimental results is good as far as the aerodynamic input data are able to represent the transonic effects in the flow field. Over $M_{tip} = 0.88$, the need for more accurate aerodynamic data is stringent, so that acoustic calculations exhibit qualitative and quantitative deviation from experimental data.

References

[1] J.E. Ffowcs Williams and D.L. Hawkings 1969 Sound Generation by Turbulence and Surfaces in Arbitrary Motion, *Philosophical Transactions of the Royal Society* **A264**, 321–342.

[2] F. Farassat 1975 Theory of Noise Generation from Moving Bodies with an Application to Helicopter Rotors, *NASA Technical Report* **R-451**.

[3] F. Farassat 1981 Linear Acoustic Formulas for Calculation of Rotating Blade Noise, *AIAA Journal* 19, 1122–1130.

[4] Y.H. Yu, F.X. Caradonna and F.H Schmitz 1978 The Influence of the Transonic Flow Field on High-Speed Helicopter Impulsive Noise, *4th European Rotorcraft and Powered Lift Aircraft Forum, Paper No. 58.*

[5] K.J. SCHULTZ and W.R. SPLETTSTOESSER 1988 Prediction of Helicopter Rotor *Impulsive* Noise Using Measured Blade Pressures, *43rd Annual Forum and Technology Display of AHS, St. Louis, MO.*

[6] K.S. BRENTNER 1986 Prediction of Helicopter Rotor Discrete Frequency Noise, *NASA Technical Memorandum* **87721**.

[7] I.H. ABBOTT and A.E. VON DOENHOFF 1959 *Theory of Wing Sections*, Dover Publications Inc., New York.

[8] D.A. BOXWELL,Y.H. YU and F.H. SCHMITZ, Hovering Impulsive Noise: Some Measured and Calculated Results, *Vertica*, Vol.3, pp.35-45, 1979.

[9] A. PAGANO 1993 UTAH Unsteady Transonic Aerodynamics of Helicopters - Calcoli per pale *non portanti*, C.I.R.A. **DILC-EST-TR-278** Capua, Italy.

[10] J. PRIEUR, M. COSTES and J.D. BAEDER 1991 Aerodynamic and Acoustic calculations of Transonic Nonlifting Hovering Rotors.

[11] J.D. BAEDER 1990 Euler Solutions to Nonlinear Acoustics of Non-Lifting Hovering Rotor Blades, *16th European Rotorcraft Forum, Sept. 18-21, Glasgow, Scotland and NASA* **TM-103837**. *58.*