Acoustical Methods Towards Accurate Prediction of Rotorcraft Fuselage Scattering

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Abstract

Main and tail rotors are major sources of noise for helicopters and contribute significantly to ground noise footprint. The main research effort in the past was concentrated on the noise generation mechanism and its reduction. Even though the scattering of noise generated by helicopter rotors has been recognized to deeply affect noise spectrum and directivity of the isolated rotary-wing system, there has not been an extensive research effort towards the comprehension of the phenomenon. This is particularly important in dealing with tail rotor noise, for which the wavelength of the harmonics is comparable or smaller than the characteristic dimension of the fuselage. In order to boost research activities on noise propagation in presence of the fuselage, a specific Action Group (AG24) has been constituted in the Helicopter Group of *Responsables* framework of the Group for Aeronautical Research and Technology in EURope (GARTEUR). The focus is on the development and validation of numerical prediction methods, addressed within the WP1 of the AG. The experimental activities carried out in the second WP of the action are described in a separate paper presented at this forum. Accurately predicting the effective helicopter external noise under the influence of the fuselage requires the use of advanced analysis tools overcoming limitations of classical acoustic analogy methods. The evaluation of the scattered acoustic field allows the interior noise prediction and the evaluation of fuselage vibro-acoustical feauters. One of the aim of the WP1 is to expand the limits of current noise prediction tools, enabling the development of new vehicles exploiting shielding effects and controlled surface impedance thus reducing the environmental impact of helicopters and increasing public acceptance. From a scientific point of view, this objective is addressed through a validation of the different prediction design tools developed within the participants' institutions. Most of the codes solve the Helmholtz equation, using a Boundary Element Method for addressing the discretized Green's function integral formulation of the solution.

1. INTRODUCTION

Fuselage scattering of the rotor noise was first addressed using a ray tracing method applied to a, generic fuselage model with ellipsoidal shape [1]. The Main Rotor (MR) BVI noise was modelled as a rotating impulsive point source. Their research indicated that the scattering effects involving rotating source cannot be ignored especially for sideline noise. An analysis of the scattering of tail rotor noise by the fuselage has been addressed in [2,3]. The studies were conducted with a simple geometric model without including tail boom and empennage which may impose significant modification on both the aerodynamics and acoustics of the tail rotor. Noise sources from tail rotor and main rotor were defined using either simplified low fidelity model (blade element momentum theory) for low frequency source or a rotating point impulsive source for resembling MR BVI noise for the mid- and high-frequency components of the rotor noise. In addition, the flight conditions were limited to hover, only. These studies showed that TR noise is more likely to be changed significantly because of the higher frequency. A successful attempt to study helicopter noise generation, fuselage scattering, and propagation in an urban environment was conducted in [4] by coupling a time domain FW-H rotor noise generation model with a frequency domain FEM propagation approach. Some scattering effects have been identified within the Helinovi European project test [5][6], but the focus of this project was only on the tail rotor noise generation mechanism. In commonly used methods for solving scattering problems the noise field is divided into incident and scattered components [1,2,3,4]. Under an assumption that the source of the incident field is fluid–dynamically independent of the presence of the scattering surfaces, the incident pressure field may be first determined through a prior aerodynamic-aeroacoustic analysis of the isolated rotary-wing device by using the Ffowcs Williams and Hawkings (FW-H) equation. The rest of the configuration (*i.e.*, the scatterer surface) may be included in the second step of the process, dealing with the scattering analysis solving an integral equation through a boundary element method (BEM), typically in frequency domain. In order to avoid limitations of the frequency domain methods, as the requirement of periodicity and the need of solving only a single frequency *per* computation, a time domain approach is proposed in [3] to analyze acoustic scattering problem of helicopter tail rotor. Furthermore it is the only way to investigate non-periodic or transient events during transient rotorcraft maneuvers. Although computational aeroacoustic (CAA) methods are designed to accurately capture the unsteady flow and noise radiation including scattering and non-uniform flow effects, nowadays they are too expensive from a computational standpoint to solve 3D rotor acoustic problems with respect to acoustic analogy-based approaches that, in turns, are widely applied in practical applications.

1.3 Objectives

The present research work will address noise propagation in presence of the fuselage. The focus is on the development and validation of numerical prediction methods. A crucial objective of the AG is to define a unique experimental database for acoustic scattering using a generic configuration, including sound pressure data in the field as well as clearly prescribed noise sources. At now, such database is not available. The database will be used in the future as benchmark for codes validation. The effect of acoustic scattering is likely to be more significant for tail rotor noise because the wavelength of the tail rotor harmonics is comparable with or smaller than the characteristic dimension of the fuselage. The noise shielding and refraction effect can significantly alter the tail rotor noise directivity in the far field. Therefore, the AG will give more focus on the scattering problem of the tail rotor.

For cabin noise studies, the present AG research work will also provide a reliable estimation of the acoustic pressure on the helicopter fuselage. Furthermore, passive technology installed on fuselage for noise reduction will be investigated.

From a scientific point of view, the main innovation of the AG comprises:

1. unique quality database - for unsteady scattered acoustic pressure on the fuselage and in the far field as well as mean-flow convective effects;
2. validated prediction design tools for main and tail rotor noise under the influence of fuselage - including main/tail rotor interactions;
3. Proof of rotor noise reduction through acoustic absorbing liners on the fuselage.

This AG will expand the limits of current noise prediction tools. The tools will enable the development of new helicopter generations which exploit shielding effects and controlled surface impedance to further reduce the noise emission on the ground. Thus reducing the environmental impact of helicopters and increasing public acceptance.

This paper compares the acoustic scattering predictions from different codes available within the AG with the analytical solution for the simple test-case of the rigid sphere, described below for the sake of completeness. The aim is the cross-validation and a review of the accuracy of the different methods and implementations developed. The configuration concerns the solid spheres that have been tested at the DLR AWB test facility.

2. Test Case

Figure 1 depicts the characteristics of the different rigid spheres, sources and observer positions used in the present analysis. As described below, the measuring points have been distributed on a circle with a radius $R_M = 0.6\ m$ for all the analyzed configurations.

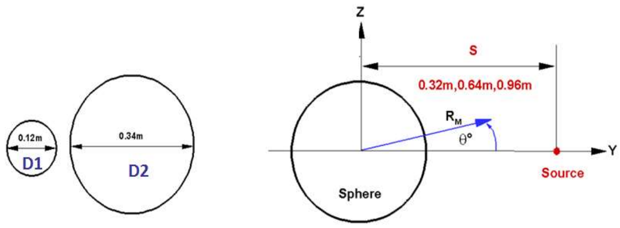


Figure 1: (left) Spheres used for calculating the scattering of the acoustic signal; (right) Observer positions and the different monopole source positions.

The sphere grid dimensions, reported in Table 1, have been selected depending on the frequency of the scattering waves. A spatial sampling rate of $f = 1/7$ has been chosen; the calculations have been repeated using $f' = f/2$ and $f'' = f/4$, for those case in which the dimension of the corresponding problem has been handable from a computational point of view.

Table 1: Grid dimensions according to the selected spatial sampling rate, PPW (Point Per Wave).

PPW	F=2500(Hz)	5000(Hz)	7500(Hz)
7	ΔX=0.01943m	0.00971m	0.00648m
14	0.00971m	0.00486m	0.00324m
28	0.00486m	0.00243m	0.00162m

3. Theoretical Models

In this section, the analytical solution of the scattering caused by a nonmoving rigid sphere impinged by the sound due to a monopole source is presented. In addition, a brief description of the scattering formulations used by the AG partners is presented too.

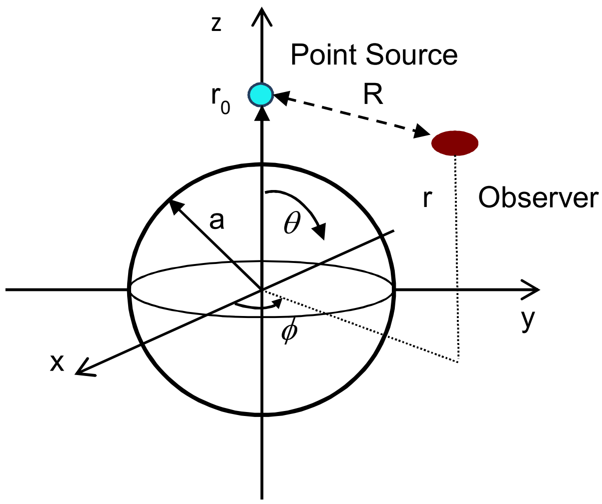


Figure 2: Scheme of acoustic scattering of a point monopole source by a sphere.

Consider the acoustic scattering of a point monopole source by a rigid sphere of radius *a*, with microphones located at the spherical coordinates *(r, θ, ϕ)* and a source located at a distance r_0 positioned on the z axis at $\theta = 0°$, $\phi = 0°$ (see Figure 2). The analytical solution of the total pressure reads [7]:

$$P_{tot}(r,\theta) = \begin{cases} \dfrac{i\,k}{4\pi}\displaystyle\sum_{m=0}^{\infty}(2m+1)\left[j_m(kr)\,h_m^{(1)}(kr_0) - \dfrac{j_m'(ka)}{h_m^{(1)}{}'(ka)} h_m^{(1)}(kr_0) h_m^{(1)}(kr) \right] P_m(\cos\theta)\,, & r \le r_0 \\ \dfrac{i\,k}{4\pi}\displaystyle\sum_{m=0}^{\infty}(2m+1)\left[j_m(kr_0)\,h_m^{(1)}(kr) - \dfrac{j_m'(ka)}{h_m^{(1)}{}'(ka)} h_m^{(1)}(kr_0) h_m^{(1)}(kr) \right] P_m(\cos\theta)\,, & r > r_0 \end{cases}$$

(4)

where $P_m(z)$ is the zeroth degree Legendre function of first kind of order m, $j_m(z)$ and $h_m^{(1)}(z)$ are the spherical Bessel and Henkel functions of the first kind and order *m*, whereas $j_m'(z)$ and $h_m^{(1)}{}'(z)$ denote their derivatives.

The CIRA BEM code, OptydB-BEM [8][9], has the possibility to include the effect of the fluid velocity, solving the convected Helmholtz equation formulated either in pressure (Lighthill's analogy) or in terms of the velocity scalar potential (Howe/Pierce analogy). The integral equations are treated using the collocation approach and the Combined Helmholtz Integral Equation Formulation (CHIEF) for removing the spurious frequencies. The discrete set of equations associated then with the boundary problem is solved with an iterative approach. The code can manage unstructured grids with triangular and quadrilateral elements and different type of boundary conditions. At last a black-box directional Fast Multipole Method (FMM) is implemented for dealing with large scattering problems.

DLR is using Fast Multipole Boundary Element Method (FMBEM) code [10][11] which solves for the scattered pressure field. FMBEM code solves the exterior Helmholtz problem (scattering problem). It is a BEM method and the fast multipole method (FMM) for triangulated surfaces FMBEM uses an iterative solver and thus the fast evaluation of matrix-vector Products and No storage of matrix required. In addition, Burton-Miller approach is used to guarantee uniqueness of solution.

ONERA is using two different acoustic scattering codes. The goal is to identify the limitation of the first using the later as a reference. The simplest method is based on the assumption of a locally flat surface with single reflection. This methodology is implemented in the FW-H ONERA code named KIM [12]. The second approach used at ONERA is the BEM code named BEMUSE [13] solving the boundary integral problem with the Brakhage-Werner approach [14]. Even if convection effect are not taken into account in BEMUSE, a post-processing can be used following [15] to deal with potential flow effect. The code handle parallel computations with up to 0.5 Million points thank to the ACA (Adaptative cross approximation) compression matrix compression method. Figure 3 summarized the computational methodology used when a BEM code is employed. The analytical solution of a monopole source is as an incident pressure field (including pressure gradient) on the scattering surfaces and as a direct pressure field at the microphone. The total pressure is obtained by adding the scattering filed provided by the BEM code and the direct pressure field. On the other hand, a slightly different approach is used with the KIM code for which the incident and direct field are computed by solving a Kirchhoff or a Ffowcs-williams Hawkings integral. The main advantage is that the incident pressure field created by a rotor can be directly obtained by solving one of those equations. Consequently, in this particular case, the analytical solution of the monopole is stored on a double layered spherical surface composed of twice 360·180=64800 points with a radius of 0.001 m that is used as a Kirchhoff surfaces. Two layers are considered to compute pressure gradient. One can note that no pressure gradient on the scattering surface is needed in this case. This methodology is illustrated in Figure 4.

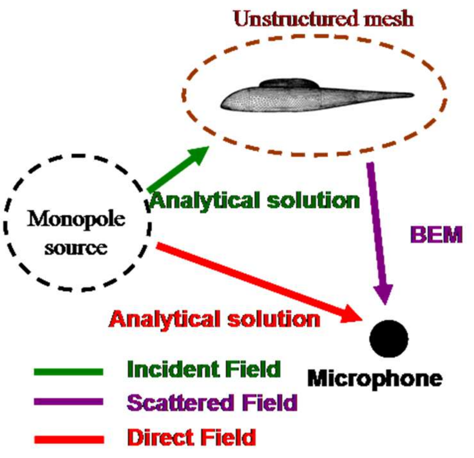


Figure 3: Computational methodology using BEM

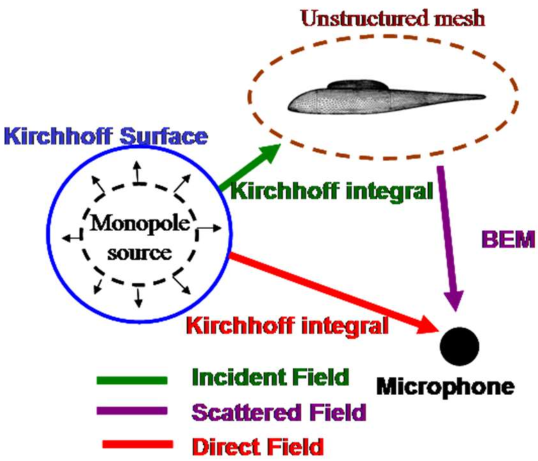


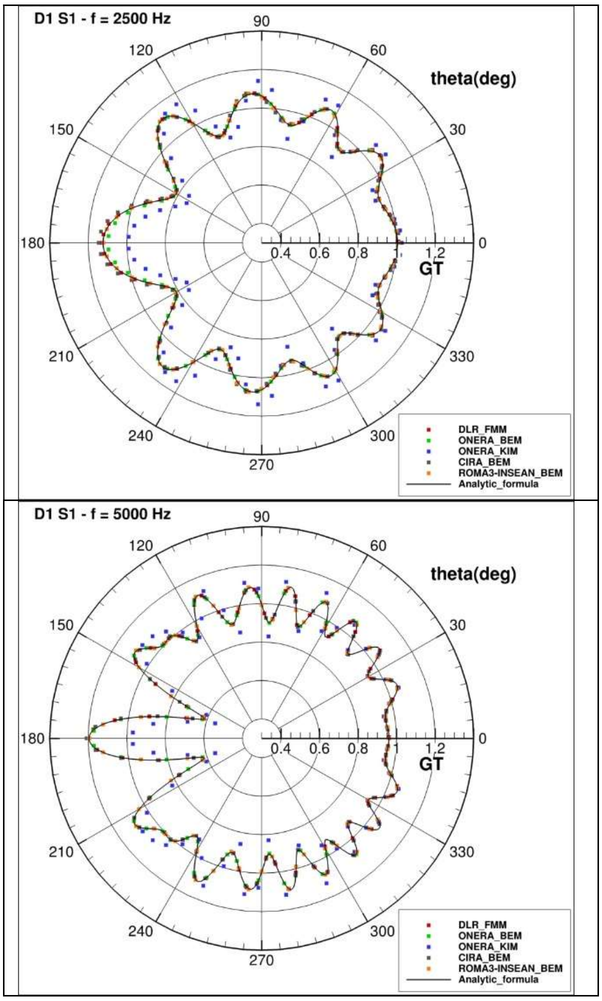
Figure 4: Computational methodology using KIM code

Differently, the University of Roma Tre and CNR-INSEAN have developed a non-standard tool, in the frequency domain, based on the boundary integral solution of the permeable Ffowcs-Williams and Hawkings Equation for the scattering analysis of moving/elastic bodies [16]. This formulation yields the transfer functions matrix between the impinging pressure field and the scattered pressure on the wall of the scattering body and, for elastic bodies, it allows the prediction of scattering effects due to wall vibrations, too. Beside this pressure-based approach, the Helmholtz equation for the velocity potential is also proposed to compute the scattered pressure field. This formulation has been recently extended to include non-linear volume terms [17]. Both acoustic methodologies are solved by a the *zero-th* order panel method and the issue of spurious frequencies occurrence (if any) is overcome through the CHIEF regularization technique.

4. Numerical Results and Analysis

The variable used to compare the different results is the total attenuation factor *Gamma Total*, GT defined as $\gamma_T(f) = \langle p_T(f) \rangle / \langle p_I(f) \rangle$, with $\langle \cdot \rangle$ indicating the ensemble average operator and p_T, p_I, respectively, the total and incident pressure field fluctuations. Results for point source placed at 0.32m (noted S1) are presented in

Table 2 and **Table 3** respectively for spheres D1 and D2, with solid line representing the analytical solutions. All methods give similar trends which are in good agreement with analytical results. This is especially true when considering the BEM results, which are very close and collapse on the analytical solution. Finally, poorer results are provided by the flat approximation method of the KIM code. Results are improved in high frequency but the area between approximately 120° and 240° (shadow zone) is always of poor accuracy. This method only predicts reflection (by supposing a surface locally flat), ignores refraction. Consequently, the sphere test case is particularly hard for this approach.



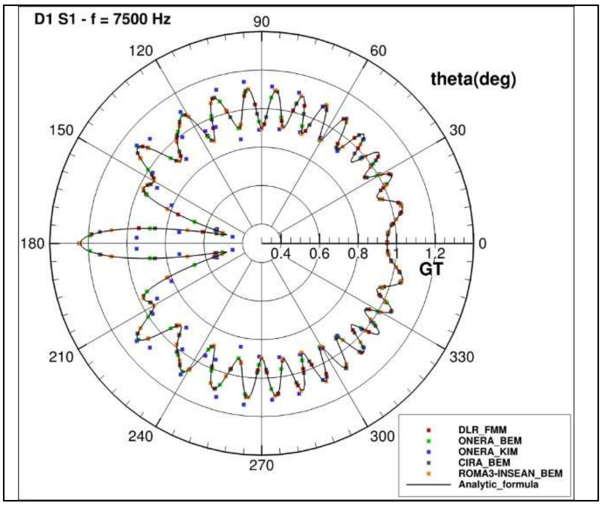
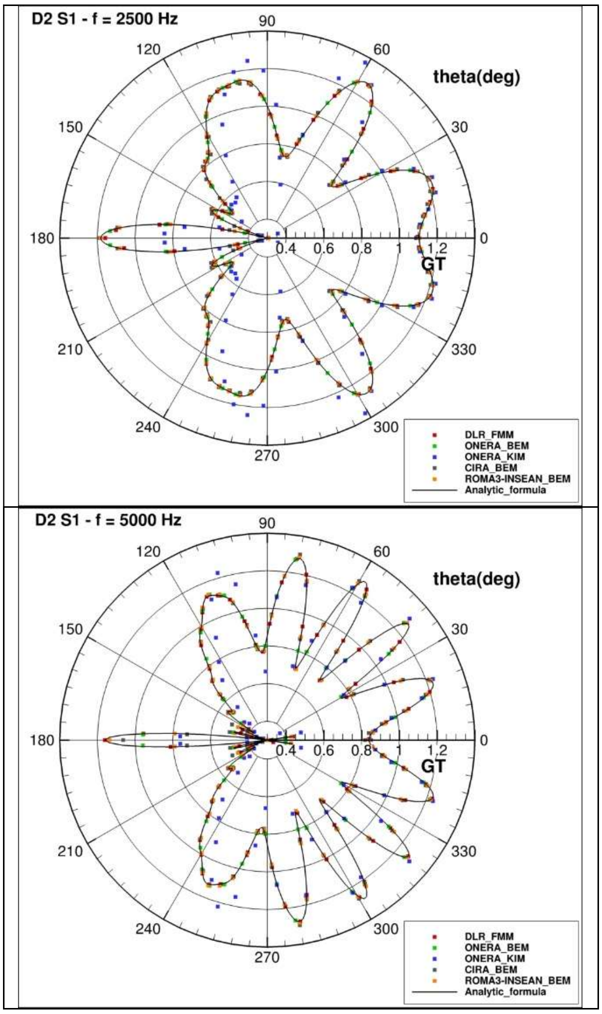


Table 2: Comparison of the scattering directivity from the sphere D1 impinged by sound from the source S1, at three different frequencies.



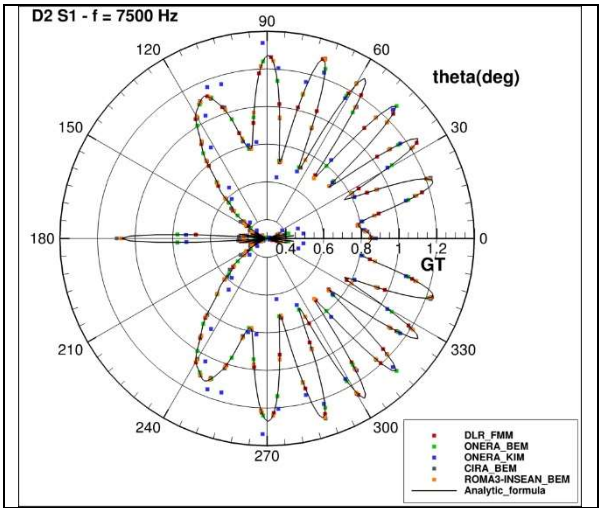


Table 3: Comparison of the scattering directivity from the sphere D2 impinged by sound from the source S1, at three different frequencies.

5. Conclusions

In this paper a numerical comparison among the acoustic scattering predictions carried out by different solvers available within the Action Group AG24 is presented. The baseline configuration, herein investigated, is a rigid nonmoving sphere, impinged by the sound waves emitted by a monopole; the analysis concerns with spheres with different radius, at three frequencies of the pulsating source of noise, simulating the high frequency of the tail-rotor noise emission. This case-study highlights the general high level of accuracy of the acoustic scattering models in capturing the analytical solution in terms of magnitude and directivity. This fact is a valuable starting point towards the analysis of more complex configurations (in motion or at rest) in view of the future comparisons with experiments planned within the framework of the GARTEUR AG24.

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