Noise Prediction of NASA SR2 Propeller in Transonic Conditions

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Abstract. In this paper we propose a numerical approach for noise prediction of high-speed propellers for Turboprop applications. It is based on a RANS approach for aerodynamic simulation coupled with Ffowcs Williams-Hawkings (FW-H) Acoustic Analogy for propeller noise prediction. The test-case geometry adopted for this study is the 8-bladed NASA SR2 transonic cruise propeller, and simulated Sound Pressure Levels (SPL) have been compared with experimental data available from Wind Tunnel and Flight Tests for different microphone locations in a range of Mach numbers between 0.78 and 0.85 and rotational velocities between 7000 and 9000 rpm. Results show the ability of this approach to predict noise to within a few dB of experimental data. Moreover corrections are provided to be applied to acoustic numerical results in order for them to be compared with Wind Tunnel and Flight Test experimental data, as well computational grid requirements and guidelines in order to perform complete aerodynamic and aeroacoustic calculations with highly competitive computational cost.

Keywords: CFD, Aeroacoustics, Ffowcs Williams-Hawkings Acoustic Analogy, Transonic Cruise Propeller, NASA-SR2

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INTRODUCTION

Low noise design process receives increasing attention in highly industrialized countries, and consequently control of noise emission challenges a growing community of engineers. In a growing market of turboprop aircraft, noise reduction is a big issue, therefore the development of quick and efficient numerical tools is a key point for the design-to-noise approach for high-speed propellers. Despite the great progresses made by Computational Fluid Dynamics that has benefited from the exponential growth in computational resources over the last few decades, aerodynamically generated noise is still very demanding in terms of processing power when using approaches such as Detached Eddies Simulation (DES) and Large Eddies Simulation (LES). In this paper we propose an approach based on Moving Reference Frame (MRF) RANS simulation of aerodynamic flow field combined with the Ffowcs Williams-Hawkings (FW-H) acoustic analogy for propeller noise prediction. The test case geometry adopted is the transonic cruise 8-bladed propeller NASA SR2, chosen for the huge amount of experimental data available in the literature for wind tunnel and flight test conditions. Blade Passing Frequency - Sound Pressure Levels (BPF-SPL) have been computed for different microphone locations for transonic Mach numbers close to cruise condition for the adopted geometry. A detailed description of the computational grid and simulation settings are provided in order to achieve fully converged simulations with a low computational cost compatible with industrial CFD requirements. Calculations have been performed with the commercial software ANSYS-FLUENT.
GEOMETRY AND EXPERIMENTAL DATA SET

NASA-SR2 8-bladed propeller geometry provided in [1,2] has been adopted as test-case for the simulations. It is a straight blade propeller constructed from the NACA 65 2D aerofoil section from root to 37% of its span extension, and from the NACA 16 2D aerofoil section from 44% to tip. The mid region from 37% to 44% of span is made by a transition zone where airfoils do not lie in any standard family. Propeller diameter is 0.622 m (24.5 inches) and geometrical details are given in figure 1 where blade-width ratio (b/D), ideal lift coefficient (C_{Ld}), design angle (\Delta\beta) and blade-thickness ratio (t/b) are given as function of blade fractional radius (r/R). A picture of CAD model of propeller is given in figure 1 as well.

![CAD model of NASA-SR2 8-Blades Propeller](image)

Geometrical data are provided from 24% to 100% of span and the blade root is assumed to be mounted on a cylindrical shaped body while the blade tip is assumed to be smooth. The blade angle is given by the reference design angle (measured at ¾ of span) added or subtracted to the \Delta\beta curve of figure 1. The SR2 propeller was tested with the design angle \beta_{3/4} equal to 60 degrees in NASA Lewis 8-by-6 foot wind tunnel [3,4] and mounted on the NASA Jetstar aircraft with a design angle equal to 58 degrees [3,5].

The propeller was operated at different nominal advance ratio \(J=V/nD\), where \(V\) is the asymptotic velocity in m/sec, \(n\) the rotational speed in rps (root per second) and \(D\) the diameter in meters. For wind tunnel tests 2 microphones were located on the tunnel ceiling, while for flight-test 6 microphones were located on aircraft fuselage. Microphone positions are given in table 1 and they are only identified by the visual angle \(\theta\) [11]. The distance between the propeller tip and the tunnel ceiling and between the propeller tip and the fuselage is the same and it is equal to 0.8 diameters (0.498 m). In order to compare similar microphone locations, only M4-FT, M5-FT and M6-FT were taken into account for flight test data. This choice was made because the microphones located approximately 20 degrees behind the propeller plane are assumed to be the most accurate in the experimental campaign as well as the least affected by repeatability error according to the NASA references [3,6].

<table>
<thead>
<tr>
<th>TABLE 1. Microphone Locations.</th>
<th>Wind Tunnel Locations (Tunnel Ceiling 0.8 D far from Prop. Tip)</th>
<th>Flight Test Locations (Fuselage 0.8 D far from Prop. Tip)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Microphone ID</td>
<td>M1-WT</td>
<td>M2-WT</td>
</tr>
<tr>
<td>Visual Angle (\theta) [deg]</td>
<td>110</td>
<td>130</td>
</tr>
</tbody>
</table>

AERODYNAMIC AND AEROACOUSTICS MODELLING

The propeller geometry was constructed from 6 aerofoil sections, of the NACA 65 series family for the lower part and 14 of the NACA 16 series family for the upper part. They were located with a constant spacing up to 90% of span, while a decreasing spacing was adopted up to the tip to follow the increasing chord gradient. A triangular surface mesh was generated in ANSYS GAMBIT on the blade and spinner, while a hybrid volume mesh was then built in ANSYS TGRID consisting of 40 prism layers and tetrahedral cells in the remaining computational domain. Prism layers were designed in order to have not less than 20 layers within the physical boundary layer and the \(y^+\) value was less than 1 on the whole blade surface for all test conditions. The total cell count was approximately 10.5M per sliced periodic domain. Aerodynamic simulations were performed with RANS pressure based coupled
solver with periodic rotational conditions, Multiple Reference Frame (MRF) and $k$-$\omega$ SST turbulence model [10]. The aerodynamic solution was evaluated by monitor of the power coefficient $C_{P} = \frac{P}{\rho_{0} n^{3/4} D^{5}}$, where $P$ is the power in W, $\rho_{0}$ the density in Kg/m$^3$, $n$ the rotational speed in rps and $D$ the propeller diameter in meters. The acoustic Sound Pressure Level (SPL) at the microphone locations was estimated applying the Farassat & Brentner FW-H acoustic analogy formulation for moving surfaces [7, 8]. This formulation allowed us to estimate an unsteady pressure time signal at microphone locations from a steady RANS simulation. For comparisons between simulation and experiments only the maximum of the SPL spectra, corresponding to the Blade Passing Frequency (BPF), was taken into account. The optimized simulation strategy adopted consisted of 2 main parts: the first one was the initialization of the flow field, reaching fully converged calculations in approximately 500/600 iterations. More details are provided in reference [11].

RESULTS AND CONCLUSIONS

Aerodynamic simulations for transonic Mach numbers equal to 0.85 for wind tunnel tests and 0.787 for flight test were performed, and the $\beta_{\text{ind}}$ design angle was changed in order to match computational and experimental $C_{P}$.

This calibration is a common procedure in propeller aerodynamic tests as reported by NASA [13]. The calibration was achieved for both conditions with a design angle equal to 62 deg. In Table 2 a summary is provided of the correlated aerodynamic results for the tested conditions. Note that ambient pressure has been assumed equal to 76.7KPa for wind tunnel test taking account of the pressure losses into the wind tunnel test-chamber, and equal to 30KPa for flight test performed at 35.000 ft of altitude [3,6]. Moreover note that the propeller was operated with comparable advance ratio, very close to its nominal cruise condition [14].

Noise predictions were made for the two aerodynamic conditions for the near-field microphone locations provided in Table 1 with the Farassat & Brentner FW-H acoustic analogy formulation for moving surfaces. The considered microphones are M1-WT and M2-WT for Wind Tunnel Tests and M4-FT, M5-FT and M6-FT for Flight Tests and only the first peak of the noise spectrum, corresponding to Blade Passing Frequency (BPF), was considered for comparison to experimental data. Moreover noise predictions were corrected in order to extend the FW-H acoustic analogy to near-field microphones, where “near-field” is the region of space affected by pseudo-noise. In this case SPL spectra were estimated for equivalent visual angle microphones located at a distance of 16 diameters far from the propeller, and then scaled to 0.8 diameters with the correction provided in [3,11]. Moreover 1.5 dB were added to computational SPL values in order to take into account the quadrupole contribution related to transonic flow-field and shock wave formation on the blade surface [4] while 6dB were subtracted from experimental Flight Test data in order to take into account the fuselage interference [4]. These corrections may be avoidable if the effects concerned are taken into account directly by introducing more complex simulation approaches (e.g. sliding-mesh, non periodicity, porous FW-H formulation and direct CAA), albeit with a significant increase of computational cost of simulation. Noise results for the mentioned microphone locations are presented in figure 2. A very good agreement was achieved for noise prediction in microphone locations M1-WT, M4-FT and M5-FT, with a discrepancy between predicted and experimental SPL of less than 2 dB. On the other hand, for the microphones M2-WT and M6-FT the discrepancy magnitude increases, and this deviation could be ascribed to the lack of accuracy of experimental data, as mentioned above. However the simulation results remain within 5 dB of the test data. In this paper we present a deep investigation into the high-speed transonic-cruise propeller noise simulation for industrial applications.

In conclusion aerodynamic simulations were performed on NASA SR2 propeller with steady RANS approach, coupled with multiple reference frame and periodic conditions to take into account of rotation. Description of mesh requirements and guidelines are provided, reaching a computational grid of 10.5M hybrid cells with 40 layers of prisms on blade surface. Optimal simulation strategy was achieved performing the simulation with the full multigrid initialization, reaching fully converged calculations in approximately 500/600 iterations. Aeroacoustic simulations were performed with FW-H acoustic analogy for different microphone locations for both wind tunnel and flight test experimental data, in a range of Mach numbers and rotational velocities close to the cruise condition for the adopted
test-case geometry. Results show that this approach is able to predict propeller near-field noise with an error of less than 2 dB for the microphones located approximately 20 degrees behind the propeller plane. An increasing discrepancy between predicted and experimental data was achieved for rear locations, ascribed to the lack of accuracy of experimental data for these microphones, as stated by NASA in references [3,6].

FIGURE 2. Acoustic Experimental VS Computational Data, Blade Passing Frequency SPL. Wind Tunnel Test (left) – Flight Test (right)

A short discussion about corrections to apply in order to take into account experimental devices interference, near-field and non-linear effects is provided. Moreover a more detailed discussion is given in reference [11].

REFERENCES