

Aeroacoustical Investigation of NACA 0012 Airfoil Using CFD

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Abstract

This paper presents an investigation of a two-dimensional approach to numerical prediction of aerodynamical noise generated by NACA 0012 airfoil. The aim of this paper is to investigate this approach as a simple prediction method for aerodynamical noise generated by two-dimensional bodies. The numerical simulation was performed by the commercial software (Ansys Fluent) using unsteady Reynolds-averaged Navier-Stokes (URANS) equations for a flow solution and Ffowcs-Williams and Hawkings (FW-H) analogy for an acoustic solution. The obtained results were compared to available published experimental results.

Key-words: aerodynamic noise, aeroacoustic, CFD, FW-H, NACA 0012

1. Introduction

The aerodynamically generated noise is one of the most demanded topics of aerodynamics. Unfortunately, the aeroacoustic measurement are very expensive and hard to get compared to aerodynamic measurement, so does the computer simulation. For aeroacoustic computation an unsteady simulation is required with very small time-step. For simulating aerodynamic noise up to 20 kHz the time step at least $2,5 \cdot 10^{-5}$ s is needed. The acoustic disturbances are the small pressure fluctuations in order $10^{-4} - 10^1$ Pa.

One of the most reliable aeroacoustic simulation is still direct numerical simulation, which extremely computational expensive. The most used computational simulation is large-eddy simulation for the aerodynamic solution with Ffowcs-Williams and Hawkings analogy for the aeroacoustic part of the solution.

This paper investigates two-dimensional approach using Unsteady Reynolds-Averaged Navier-Stokes equations with k- ω turbulence model.

Since the aeroacoustic properties of NACA 0012 airfoil is well-known from experimental measurements [1], this airfoil was chosen for a test-case with using 2D URANS for aeroacoustic simulation.

The motivation for evaluating this approach is to find a simple approach for rough aerodynamically generated noise prediction.

2. Aerodynamic calculation

For the first, the aerodynamic solution of the test-case must be found. Since the simulation is required to be unsteady, turbulent and two-dimensional, the URANS equations solver was chosen. Since the low Reynolds number, the flow was solved as an incompressible gas with constant density.

The URANS equations were solved with non-iterative time-advancement, which means there was only one iterative step for a time step.

The aerodynamic simulation must reach quasi-stationary state. In this state the lift and drag force must be statistically steady.

2.1. Turbulence model

According to [2] the k- ω SST model is the most appropriate for simulation flow around NACA 0012.

3. Aeroacoustic Theory

In Ansys Fluent are implemented Ffowcs-Williams and Hawkings analogy [3] which is extension to Lighthill analogy [4] to predict the aerodynamically generated noise in present of moving surfaces.

For evaluation of acoustic pressure at some point sound pressure level is usually used, which is defined as:

$$SPL = 10 \log \frac{p'_{rms}}{p_{ref}}$$

Where the reference sound pressure is usually:

$$p_{ref} = 2 \cdot 10^{-5} \text{ Pa}$$

3.1. Ffowcs-Williams and Hawkings analogy

In Fluent there is implemented the solution of the next equation FW-H equations [5]:

$$\begin{aligned} \frac{1}{a_0^2} \frac{\partial^2 p'}{\partial t^2} - \nabla^2 p' &= \frac{\partial^2}{\partial x_i \partial x_j} \{T_{ij} H(f)\} \\ &- \frac{\partial}{\partial x_i} \{[P_{ij} n_j + \rho u_i (u_n - v_n)] \delta(f)\} \\ &+ \frac{\partial}{\partial t} \{[\rho_0 v_n + \rho (u_n - v_n)] \delta(f)\} \end{aligned} \quad (1)$$

Where T_{ij} is the Lighthill stress tensor:

$$T_{ij} = \rho u_i u_j + P_{ij} - a_0^2 (\rho - \rho_0) \delta_{ij} \quad (2)$$

And P_{ij} is the compressive stress tensor:

$$P_{ij} = \rho \delta_{ij} + \mu \left[\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \frac{2}{3} \frac{\partial u_k}{\partial x_k} \delta_{ij} \right] \quad (2)$$

Heaviside function $H(f)$ is integral of Dirac delta function $\delta(f)$.

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The solution of these equations can be obtained using Green's function. The solution consists of surface and volume integrals. The volume integral, which represents a quadrupole source of noise, is neglected for small Reynolds numbers.

3.2. Source Correlation Length

Since the solution of equation 1 is obtained by means of surface integrals of the source surface (in this case the surface of the airfoil). In the two-dimensional simulation the source correlation length parameter is required. This parameter substitutes the third dimension.

For this simulation the source correlation length was set to 1 m. It is evident that the source correlation length has a significant impact on the magnitude of acoustic pressure fluctuations around the airfoil.

4. Mesh Grid

The mesh of the computational domain was created by a custom 2D mesh generator which was created for MathWorks Matlab.

The mesh grid generator creates a structured grid consisting of quadrilaterals between the airfoil and the outer boundary of the computational domain.

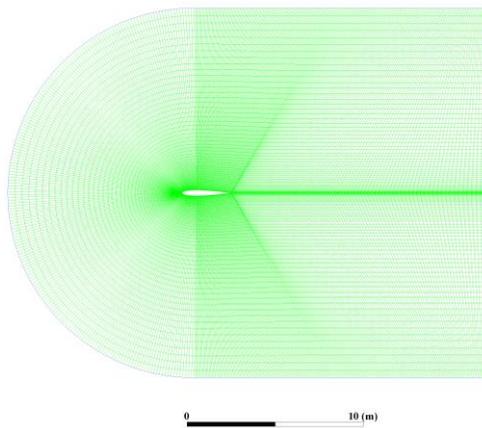


Fig. 1. Meshed computational domain

The computational domain for this aeroacoustical investigation consists of 35 282 quadrilateral cells. The boundary conditions are velocity components at the inlet and zero pressure at the outlet.

In Fig. 2 is the mesh grid near the airfoil in detail. The chord of the airfoil is 2.5 m and the longest cell wall near the airfoil is $2 \cdot 10^{-2}$ m long. If at least 15 cells per wavelength at the source surface is considered, the maximal obtained frequency of acoustic waves is 1100 Hz.

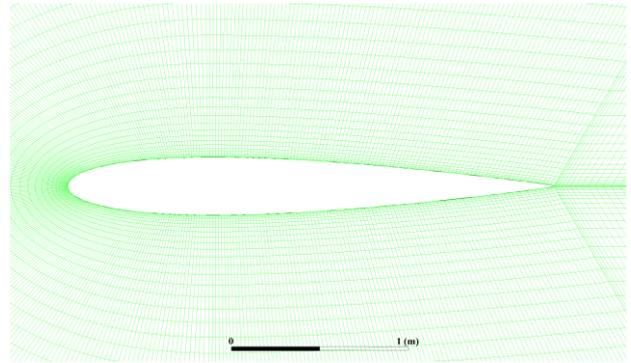


Fig. 2. Detailed grid around the airfoil

5. Results and discussion

5.1. Verification of aerodynamic parameters

After the simulation reaches the quasi-stationary state, the verification of the aerodynamic results is required. Since the monitors of the simulation were lift and drag forces, they were also used for the validation.

In Fig. 3 and Fig. 4 there are computed lift and drag coefficients for various angles of attack compared to the ones computed using XFOIL [6].

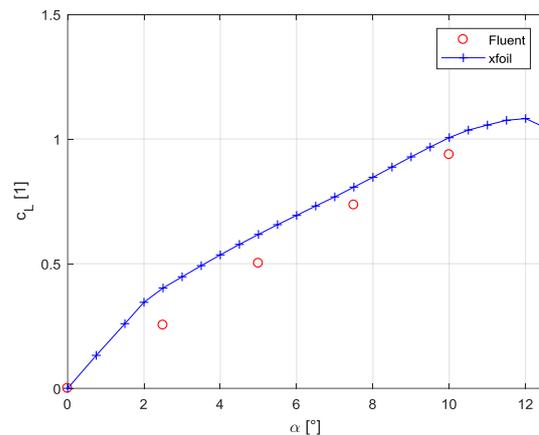


Fig. 3. Lift coefficients of NACA 0012 at $Re = 171\ 232$

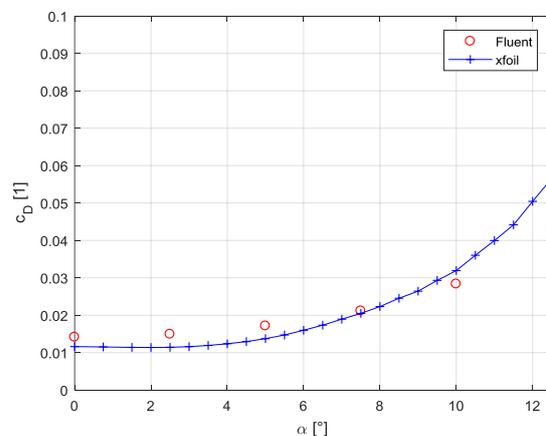


Fig. 4. Drag coefficients of NACA 0012 at $Re = 171\ 232$

The difference between Xfoil and Fluent results are expected, and they should not impact the aeroacoustic investigation.

5.2. Investigation of aeroacoustic parameters

In the aeroacoustic part of the simulation the sound pressure levels at one point were evaluated. The evaluated SPL for frequencies below 200 Hz are negative, so they are not shown in the next graphs.

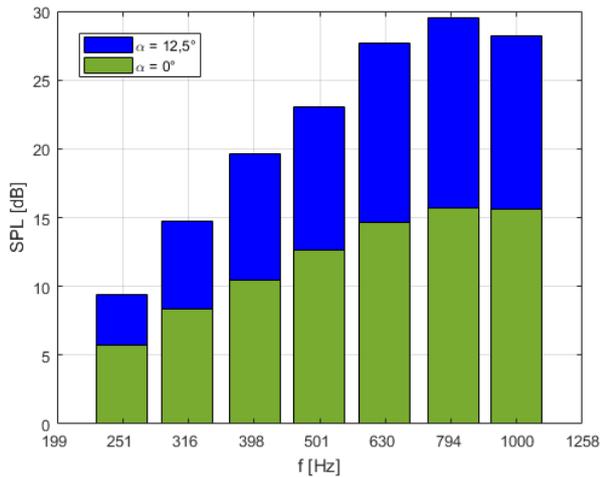


Fig. 5. SPL at the point above NACA 0012 airfoil at the distance 7,5 m for two various angles of attack at Re = 171 232

The sound pressure level is supposed to grow with the growing angle of attack. In the figure 5 there are sound pressure levels in 1/3 octave spectrum for angle of attacks at Reynolds number 171 232. In the figure 6 there are sound pressure levels for two Reynolds number 171 232 and 1 712 320. The sound pressure levels are evaluated at the point above the airfoil at the distance 7.5 m – the spatial coordinates (0; 7.5). The origin of the axes is at the ¼ of the chord of the airfoil.

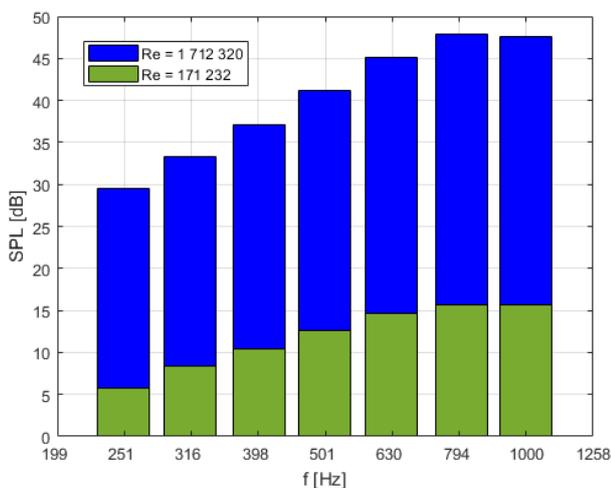


Fig. 6. SPL at the point above NACA 0012 airfoil at the distance 7,5 m with the angle of attack α = 0°

In the figure 7 there is comparison of the results obtained from this CFD simulation and the Brooks' experiment. The CFD simulation was for the correlation length 3.75 m and Reynolds number 1 712 320. The Brooks' experiment was measured with Reynolds number 1 487 760 and the ratio between the airfoil chord and the span wise length was 1.5. So, the change of the correlation length in simulation cause the same ratio between the airfoil chord and the length in the third dimension. Also, the position of the point, where the SPL is evaluated, is changed according to Brooks' experiment.

This comparison shows that this CFD simulation gets lower sound pressure than the experimental measurement. This difference can be caused by missing vortex structures and the noise sources in the wake in the CFD simulation.

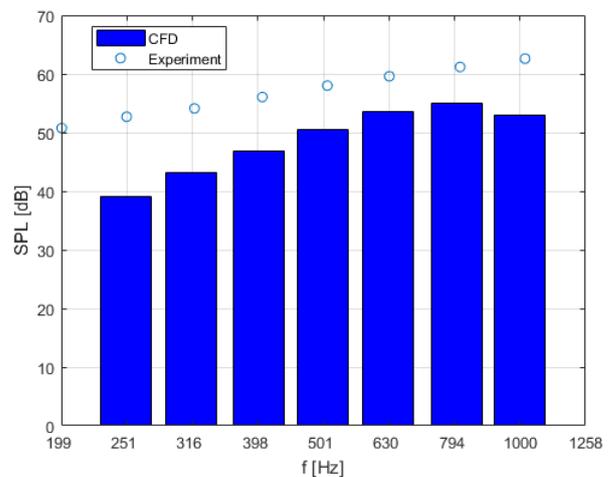


Fig. 7. Comparison of the CFD and experimental results by Brooks [1].

6. Conclusion

The basic numerical evaluation of the usage two-dimensional Unsteady Reynolds Averaged Navier-Stokes equations for aerouacoustical computations was provided.

For the wider range of evaluated frequencies in acoustic spectra the finer mesh near the airfoil is required. Although the structured quadrilateral mesh is very convenient for numerical calculation, an unstructured mesh should be considered due to creating finer mesh near the airfoil and more coarse mesh at the outer boundary of the computational domain.

This 2D approach can be used for fast estimation of the aerodynamically generated noise by the airfoil. However, the most important kind of noise – tonal noise can be missing due to lack of 3D vortex structures. For more accurate results is better to use the Large-Eddy Simulation, but the fine grid on the surface of the airfoil is still necessary.

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Nomenclature

CFD computer fluid dynamics
 RMS root mean square
 SPL sound pressure level
 SST shear stress transport

a_0 sound speed in the far field ($\text{m}\cdot\text{s}^{-1}$)
 ρ_0 fluid density in the far field ($\text{kg}\cdot\text{m}^{-3}$)
 ρ fluid density in the far field ($\text{kg}\cdot\text{m}^{-3}$)
 μ dynamic viscosity ($\text{Pa}\cdot\text{s}$)

p' acoustic pressure fluctuations (Pa)
 p'_{RMS} RMS of acoustic pressure fluctuations (Pa)

c chord length (m)
 f frequency (Hz)
 n_i normal vector (m)
 Re Reynolds number (1)
 t time (s)
 u_i flow velocity ($\text{m}\cdot\text{s}^{-1}$)
 v_i surface velocity ($\text{m}\cdot\text{s}^{-1}$)
 x_i spatial coordinate (m)

δ_{ij} Kronecker delta (1)
 $\delta(f)$ Dirac delta function (1)
 $H(f)$ Heaviside function (1)
 α angle of attack (rad)

T_{ij} Lighthill stress tensor
 P_{ij} compressive stress tensor

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