Numerical simulation of aeroacoustical noise from a wing-flap configuration

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Abstract. A noise-free volumetric synthetic turbulence generator has been applied for Embedded LES of the flow over the wing-flap configuration experimentally studied by Lemonie et al. Good agreement of CFD results with experimental data provides some evidence for the correctness of the chosen computational strategy, which includes a noise-free volumetric synthetic turbulence generator to create turbulent content, “sponge layers” to avoid the reflection of pressure waves from the external boundaries and the Ffowes Williams, Hawking acoustic model for calculating far-field noise.

1. Introduction
Prediction of noise generated by flow over the airframe elements, in particular, noise from a wing-flap configuration, is one of the most important aeroacoustic tasks. Since in this case the noise is caused by turbulent vortices reacting with each other and with solid surfaces, it is necessary to use methods which resolve at least a part of the turbulence structures. However, the use of scale resolving simulation (even LES with near-wall RANS modelling) for attached boundary layers at high Reynolds numbers is too costly. Therefore a zonal method, combining RANS and LES, such as Embedded LES (ELES), is a more preferable approach. ELES assumes using more accurate WMLES only in a restricted flow region where resolved turbulence is essential, whereas the rest of the flow is treated with economical RANS.

ELES of attached flow requires generation of turbulent content at the RANS-LES interface to ensure transition from the RANS zone where the whole turbulence is modeled to the LES zone where it is partly resolved. For aeroacoustic tasks the quality of artificial turbulent content has a crucial effect since the creation of artificial vortices can lead to the generation of spurious noise. A noise-free Volumetric Synthetic Turbulence Generator has been developed by NTS [1] specifically to use in aeroacoustic applications. NTS VSTG has been modified to implement it in ANSYS Fluent and tested by the example of compressible boundary layer with zero pressure gradient [2], however its efficiency for aeroacoustic tasks has not been estimated yet.

The goal of this work is application of the modified VSTG in the framework of ELES of flow over a wing-flap configuration in Fluent. The results of the ELES solution are compared with experimental data to assess the efficiency of the considered generator.
2. Brief description of Volumetric Synthetic Turbulence Generator

In the frame of VSTG, synthetic velocity fluctuations are introduced within a 3D forcing zone (VSTG on Figure 1) by means of an additional volume source term into the momentum equations:

$$ f_i = \frac{C_{BF} \cdot U_0 \cdot \rho \cdot u^i(r, t)}{L_{VSTG}} $$

Here $U_0$ is the maximum of velocity over the interface updated every time step, $L_{VSTG}$ - the length of the forcing zone in the streamwise direction, $u^i(r, t)$ - synthetic fluctuations of the velocity field and $C_{BF}$ - empirical constant. The field of velocity fluctuations $u^i(r, t)$ is defined by means of NTS STG [3] and based on the RANS solution at the interface. Due to smooth introducing turbulent fluctuations inside the forcing zone the appearance of spurious noise is avoided and VSTG can be applied for simulation of an aeroacoustic task.

![Figure 1. ELES with VSTG.](image)

3. Problem definition

The wing-flap configuration consists of two aligned airfoils: the wing is a long plate with a sharp trailing edge and the flap is a NACA0012 airfoil. Based on the free-stream velocity ($U_0 = 50$ m/s) and the flap chord ($c = 0.1$ m) the Reynolds number of a compressible flow over the wing-flap configuration is $Re_{flap} = 3.3 \cdot 10^5$, and the Mach number is $M = 0.15$.

![Figure 2. Wing-flap configuration.](image)

4. Computational strategy

Aeroacoustical noise simulation was carried out in two stages: in the first stage turbulence simulation was performed by means of ELES and in the second stage far-field noise was calculated with the use of Ffowcs Williams, Hawking's acoustic model [4].

4.1. Embedded LES

In the frame of ELES of the flow over the wing-flap configuration, turbulence in the RANS sub-domain is modelled by means of $k-\omega$ SST model and algebraic WMLES is applied in LES zone. The
RANS-WMLES interface is located 0.2 m upstream of the wing trailing edge. The boundary layer thickness at the RANS-WMLES interface is \( \delta_0 = 6 \cdot 10^{-3} \) m. Simulation of the considered flow is performed in a computational domain with the size \( L_x = 11c, L_y = 12c, \) and \( L_z = 0.18c \) in the streamwise, wall-normal and spanwise directions respectively.

The grid in the WMLES sub-domain is designed in accordance with the guidelines of wall-modeled LES. Particularly, the near-wall step is \( \Delta y^+ = 8 \cdot 10^4 \) m, which ensures \( \Delta y^+ = 1.2 \) in wall coordinates everywhere in the domain. The computational grid is uniform in the X and Z directions with grid steps \( \Delta x = 0.1\delta_0, \Delta z = 0.05\delta_0, \) which translate into \( \Delta x^+ = 90 \) and \( \Delta z^+ = 45 \) in wall coordinates. The total grid count is around 12 million cells.

Developed velocity and turbulent characteristics profiles are specified at the inlet boundary. The top and bottom boundaries are slip walls. Constant static pressure is set at the outlet. On the wall, a no-slip condition is assumed. Periodic boundary conditions are used in the Z direction. VSTG is employed for creation of the turbulent content. The volume source is activated at the RANS-WMLES interface \( (x = -0.2 \text{ m}) \) and the length of the volume forcing zone is equal \( L_{VSTG} = 3\delta_0 \). In order to avoid the reflection of pressure waves from the external boundaries a procedure using “sponge layers” [3] near the boundaries is implemented in Fluent via UDF. Inside these layers at each time step a current WMLES density field is defined by “weighting” it with the constant RANS density.

The transient pressure based solver of Fluent using the SIMPLEC algorithm is employed. Time integration is performed using a second order accurate scheme. The dimensional time step is \( \Delta t = 6 \cdot 10^{-3} \) s, ensuring that the CFL number is less than unity in the entire computational domain. For the approximation of convective terms in the momentum equations, the weak bounded central differencing scheme (WBCD scheme) combining central differencing and bounded central differencing scheme is used for both sub-zones (RANS and WMLES). For the turbulence equations the second order upwind scheme (SOU scheme) is utilized. The interpolation of variables on faces is performed by the Green-Gauss cell based method and the Standard scheme is used for the pressure interpolation scheme.

4.2. *Flowcs Williams, Hawkings acoustic model*

The far-field noise in Fluent is calculated by means of Flowcs Williams, Hawkings acoustic model. In the frame of the FWH method the far-field noise is calculated as a superposition of point sources enclosed by the control FWH surfaces. Two FWH control surfaces (Figure 3) for the noise calculations are considered:

- Solid wall surface \( S_0 \), including the whole flap surface and the part of the wing surface starting at \( x = x_{\text{inflow}} \).
- Permeable surface \( S_1 \) starting at \( x = x_{\text{inflow}} \) and ending at \( x = x_{\text{outflow}} \).

![Figure 3. FWH surfaces.](image)

Since the simulations are carried out using a computational domain which is narrow compared to the domain studied in the experiment, a “long span body” correction [5] is employed in order to take into account the contribution of noise caused by the whole span. This correction assumes that the inputs of separate spanwise patches of length \( L_z \) into the total noise are non-correlated.
5. Results

5.1. Flow structure
Shown is a typical flow pattern obtained by means of an eddy-resolving simulation in Figure 4. The use of the WBCD scheme with a fine mesh permits to resolution of rather small turbulent structures inside the boundary layer. Turbulent structures generated by VSTG are similar to those which are observed downstream of the forcing zone. This means that the turbulent content generated by VSTG is similar to the turbulence which occurs in reality.

![Figure 4. Q-criterion colored by streamwise velocity.](image)

Figure 4. Q-criterion colored by streamwise velocity.

Figure 5 shows that there is no spurious noise caused by the synthetic turbulence generation thus confirming the efficiency of the VSTG method for aeroacoustic applications. As seen from the acoustic pressure fields, the noise is radiated from the both elements of the airframe evenly and the source of the noise is the vortices populating the boundary layer.

![Figure 5. Snapshots of pressure time-derivative in the acoustic range.](image)

Figure 5. Snapshots of pressure time-derivative in the acoustic range.

5.2. Comparison of CFD results with the experimental data
The wing-flap configuration has been experimentally studied by Lemonie et al [6]. A comparison of computational spectra with the experimental data has been carried out for 15 control points distributed over the wing and flap surfaces. For all of them fairly good agreement of Fluent results with the experiment is observed. Figure 6 shows the comparison of spectra for some of probes where it can be seen that the simulation correctly reproduces the variation of both the spectral shapes and levels over the main wing and flap surfaces.
Far-field noise in Fluent is calculated by means of FWH model with the use of two types of control FWH surfaces. Considering solid surface $s_0$ as a control FWH surface, the noise sources populating the boundary layer are taken into account partially: monopole and dipole noise are accounted for while quadrupole noise is not considered. Due to accounting for quadrupole noise, the use of permeable surface $s_1$ enables estimation of whole noise spectrum and significantly improves the agreement of Fluent results with measurements in the high-frequency range (Figure 7). The remaining part of the spectrum is predicted quite accurately using as the control surface ether the solid or the porous surface.

Figure 7. A comparison of far-field noise obtained by integration over solid and porous FWH surfaces.

Figure 7 shows that two closely-located low frequency peaks observed on the experimental distribution are reproduced in the computations. The difference between CFD and experimental data in the low frequency range is caused by background wind-tunnel noise existing in the experiment [3].

6. Conclusions
The VSTG has been successfully applied for simulation of an aeroacoustic task concerning the flow over the wing-flap configuration. The good agreement of CFD results with the experimental results confirms the efficiency of the computational tools used, including a volumetric noise-free synthetic turbulence generator, “sponge layers” and the Ffowcs Williams, Hawkings acoustic model.

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