Overset-LES with Stochastic Forcing for Sound Source Simulation

P. Bernicke, R.A.D. Akkermans, R. Ewert and J. Dierke

Abstract An application of a hybrid RANS/LES method to trailing-edge noise, is presented in this contribution. The numerical framework of the CAA-code PIANO offers a basis for extending the Non-Linear Perturbation equations with viscous terms. As a result, a full Navier-Stokes equations perturbation analysis, denoted with "Overset", can be performed on top of a steady background flow. With such a scale-resolving simulation tool, consisting of optimized higher-order numerical schemes for aeroacoustics, the investigation of sound source mechanism on first principals become feasible. An issue of such hybrid zonal approaches, namely the seeding of proper inflow turbulence, is solved with the Fast Random Particle-Mesh method in combination with the Eddy-Relaxation source term. The overall process chain of the intended Overset-LES usage is illustrated by means of NACA0012 trailing-edge noise computations at moderate Reynolds number and zero angle-of-attack.

1 Introduction

PIANO (Perturbation Investigation of Aerodynamic NOise, [6]) is a Computational Aeroacoustics (CAA) code, which solves appropriate linearised perturbation equations over a time-averaged background flow. Viscous effects are normally disregarded in CAA as they play a negligible role when sound propagation is considered over small distances. Furthermore, non-linear effects are often neglected when small acoustic perturbations are considered. Therefore, the implemented perturbation equations in PIANO consist of the Linearised Euler Equations and Acoustic Perturbation Equations [8], but also non-linear Euler Equations (the latter case when the linearity assumption is relaxed).

P. Bernicke · R.A.D. Akkermans (✉)
Institute of Fluid Mechanics, TU Braunschweig, 38108 Braunschweig, Germany
e-mail: r.akkermans@tu-braunschweig.de

R. Ewert · J. Dierke
German Aerospace Center (DLR), Institute of Aerodynamics and Flow Technology, 38108 Braunschweig, Germany

A. Dillmann et al. (eds.), *New Results in Numerical and Experimental Fluid Mechanics XI*, Notes on Numerical Fluid Mechanics and Multidisciplinary Design 136, https://doi.org/10.1007/978-3-319-64519-3_54

As is common in CAA, PIANO is a hybrid approach, meaning the noise generation and propagation are treated separately. The governing equations are explicitly formatted in perturbation form, to avoid numerical errors in the flow calculation that possibly mask the smaller acoustic signal. In the majority of cases, the background flow is obtained from a Reynolds Averaged Navier-Stokes (RANS) simulation (i.e., a steady mean-flow). Besides this, PIANO encompasses many common CAA features such as block-structured, high-order, low dispersive and dissipative characteristics [6].

If the above mentioned (non-linear) Euler equations are extended with the corresponding viscous terms, the complete non-linear Navier-Stokes equations expressed in perturbation form over a given base flow is obtained. As such, the code is applicable as a Direct Numerical Simulation (DNS) tool besides the traditional CAA application. To stress this difference, the code is referred to viscous-PIANO when the CFD tool is meant. A further alleviation of computational demands can be obtained by modelling the small scales (i.e. applying an LES).

In the above described simulation approach, viscous-PIANO is applicable as a hybrid zonal tool. As opposed to the so-called embedded approach (see, e.g., [13]), the here proposed method is denoted as Overset-DNS to emphasise that a perturbation analysis is performed on top of a background flow (see, Fig. 1).

In this contribution, we concisely present the governing equation of the Overset approach together with the numerical method. Furthermore, the application of this hybrid Overset-LES tool to trailing-edge noise is presented. In this context, seeding of inflow turbulence at upstream boundaries is elucidated. This inflow turbulence is stochastically generated with the Fast Random Particle-Mesh (FRPM) method and injected into the viscous-PIANO code with the eddy-relaxation source term (see, e.g., [9, 11]). In a subsequent step, the computed turbulent sound sources could

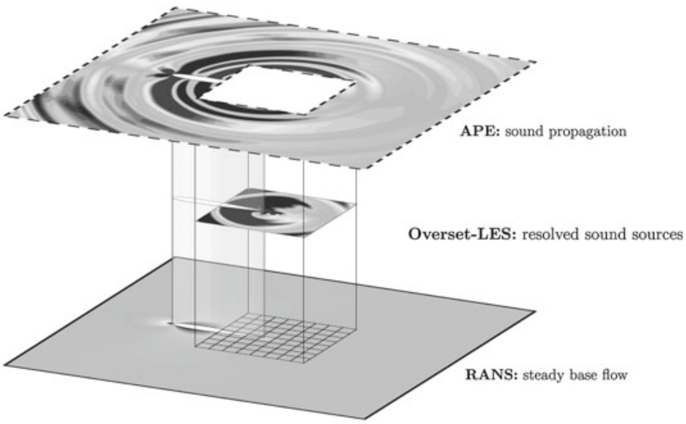

Fig. 1 Schematic of Overset-LES computation of trailing-edge noise, illustrating the perturbation analysis on top of a RANS background flow (the middle and bottom level, respectively). Furthermore, the subsequent CAA propagation is illustrated with the third level

then be propagated with PIANO as a CAA-code (in the above airframe noise example, sound is generated by the interaction of a turbulent flow with the trailing edge of the airfoil). Noise directivity shows the dipolar-like radiation characteristic from trailing-edge noise.

This proceeding is organised as follows. In the next section, the derivation of the governing equations is concisely presented, followed by details concerning the numerical method. In Sect. 4, results related to how well stochastically generated turbulence matches the target turbulence are presented as well as its subsequent injection in the Overset-LES simulation. This is followed by results from NACA0012 trailing-edge computations obtained with the Overset approach. Finally, the conclusion are presented in Sect. 5.

2 Governing Equations

The here used equations are based on the Non-Linear Perturbation Equations (NLPE) extended with viscous terms. They are derived from the compressible Navier-Stokes equations in primitive formulation. The variables are decomposed into a base flow and fluctuating part (e.g., density ρ becomes $\rho^0 + \rho'$, respectively). After substitution of such decompositions for density ρ, velocity $\boldsymbol{v}$ and pressure p into the Navier-Stokes equations, terms only containing base flow contributions are grouped together on the right-hand side. The interested reader is referred to Ewert et al. [10] and Akkermans et al. [1, 2] for a more detailed derivation.

$$
\begin{aligned}
&\frac{\partial \rho'}{\partial t} + \boldsymbol{v} \cdot \nabla \rho' + \boldsymbol{v}' \cdot \nabla \rho^0 + \rho \nabla \cdot \boldsymbol{v}' + \rho' \nabla \cdot \boldsymbol{v}^0 = r_1^0, \\
&\frac{\partial \boldsymbol{v}'}{\partial t} + (\boldsymbol{v} \cdot \nabla)\, \boldsymbol{v}' + \left(\boldsymbol{v}' \cdot \nabla\right) \boldsymbol{v}^0 + \frac{\rho'}{\rho} \left(\boldsymbol{v}^0 \cdot \nabla\right) \boldsymbol{v}^0 + \frac{\nabla p'}{\rho} - \frac{\nabla \cdot \tau'}{\rho} = \frac{\rho^0}{\rho} \boldsymbol{r}_2^0, \\
&\frac{\partial p'}{\partial t} + \boldsymbol{v} \cdot \nabla p' + \boldsymbol{v}' \cdot \nabla p^0 + \gamma p \nabla \cdot \boldsymbol{v}' + \gamma p' \nabla \cdot \boldsymbol{v}^0 + (1-\gamma) \left[\left(\tau' \cdot \nabla\right) \cdot \boldsymbol{v} + \right. \\
&\qquad\qquad \left. + \left(\tau^0 \cdot \nabla\right) \cdot \boldsymbol{v}' - \nabla \cdot \boldsymbol{q}'\right] = r_3^0.
\end{aligned}
\tag{1}
$$

Here, the viscous stress tensor and heat fluxes are denoted by τ and $\boldsymbol{q}$, respectively. Note that τ' represents the fluctuating part of the stress tensor, i.e., the viscous fluctuations. Turbulent stresses from the base flow are indicated in Eq. (2) by τ^{t0} (similar for the turbulent heat fluxes q^{t0}). Furthermore, γ represents the specific heat ratio. In the above equations, variables without superscript are total variables, and when multiplied with primed variables produce non-linear terms. Note that the above equations reduce to the original Navier-Stokes formulation when the base flow is set to zero. Equation (1) is reformulated for storage reasons. When using a time invariant mean flow (e.g., RANS), the RANS momentum equation can be used to replace $\nabla \cdot \tau^0$ and therefore, its permanent storage is prevented (see [4, 10]).

The right hand side terms r_1^0, $\boldsymbol{r}_2^0$, and r_3^0 contain only base flow contributions. In general, this base flow is supposed to satisfy the mean-flow condition applied to the Navier-Stokes equations, which leads to the following definition of the residual right-hand source terms

$$\begin{aligned} r_1^0 &= 0, \\ \boldsymbol{r}_2^0 &= -\frac{\nabla \cdot \tau^{t0}}{\rho^0}, \\ r_3^0 &= -(\gamma - 1)\left[\left(\tau^{t0} \cdot \nabla\right) \cdot v^0 - \nabla \cdot q^{t0}\right]. \end{aligned} \tag{2}$$

The right-hand terms in Eq. (1) represent the residual turbulent viscous stresses and heat fluxes, whose definition depends on the base flow. The above equations constitutes a hybrid RANS/DNS approach similar to what Terracol [17] proposed, however, formulated in primitive variables. It is known that numerical codes based on a non-conservative formulation have a disadvantage with respect to shock capturing [3]. However, this might not be too problematic as an Overset (perturbation) analysis is performed on top of a background flow, where the latter is often obtained from the strongly conservative RANS-code TAU (see, e.g., [18]).

The primed variables in Eq. (1) need not have zero mean, e.g., as is common for the Reynolds decomposition in the RANS framework. Any mean contributions here must be subtracted from the pressure fluctuations as this would mask the acoustic content, i.e.,

$$p'_{\text{acoustic}} = p' - \overline{p'}, \tag{3}$$

where the latter bar indicates time averaging. A non-vanishing mean provides information over the correctness of the used background flow.

To alleviate the computational demand of a DNS simulation, only the large energetic scales could be resolved and the smaller universal ones modelled. This modelling leads to the Large-Eddy Simulation approach, where in the current work a classical Smagorinsky model is used. For more information the reader is referred to Ref. [4].

3 Numerical Method

As mentioned earlier, viscous-PIANO takes advantage of the high-order numerics of the CAA-code PIANO. For a detailed description the reader is referred to Ref. [6]. Spatial gradients are approximated by the Dispersion Relation Preserving (DRP) scheme, as proposed by Tam and Webb [16]. The temporal integration is achieved with the 4th-order low-dispersion Runge-Kutta (LDDRK) algorithm proposed by Hu et al. [15]. Furthermore the possibility of filtering of contaminating short wave components of the wave spectrum is provided by artificial selective damping.

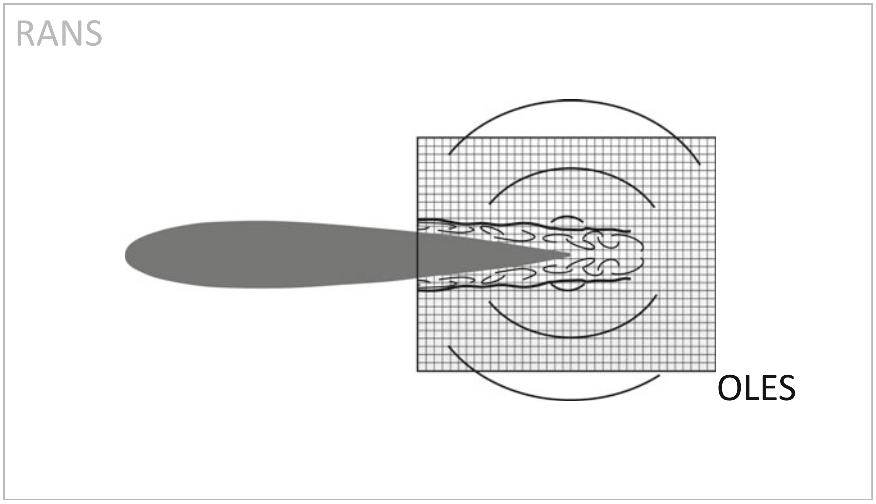

Fig. 2 Schematic showing a 2D slice of RANS and Overset-LES (OLES) domain for trailing-edge noise computation

The here presented 3D Overset-LES simulation is processed as illustrated in Fig. 2. The less time consuming RANS simulation is performed for the complete airfoil, while the more demanding scale-resolving perturbation analysis is carried out in a restricted domain around the trailing edge. From Fig. 2 it becomes clear that with such a setup the incoming boundary layer is intersected. To expedite the generation of realistic turbulence, inflow turbulence is generated by the Fast Random Particle-Mesh method [9]. Fluctuating velocities are generated on the basis of the turbulence information of the underlying RANS.

In a second step, this synthetic turbulence is injected with the aid of the so-called eddy-relaxation source term [11]. This source terms for the momentum equations, read

$$-\nabla \times \left[\sigma \left(\boldsymbol{\Omega}' - \boldsymbol{\Omega}^{\mathrm{ref}}\right)\right], \tag{4}$$

where the actual vorticity is denoted by $\boldsymbol{\Omega}'$ and the target vorticity by $\boldsymbol{\Omega}^{\mathrm{ref}}$ (the latter is prescribed by FRPM). Note that this eddy-relaxation term is somewhat similar to the one proposed by Freund [12]. Preliminary studies of a flat-blade boundary layer revealed that the stochastically generated turbulence match the kinetic energy and turbulence length-scale very well.

4 Results

Firstly, the seeding of inflow turbulence upstream from the airfoil trailing edge is discussed. Thereafter, the application of Overset-LES to the NACA0012 trailing edge is presented in Sect. 4.2 by means of principal results from a 3D simulation focused around the trailing edge itself (as illustrated in Fig. 2). These results are complemented in Sect. 4.3 by a 2D directivity analysis of a completely enclosed NACA0012 in similar flow conditions as the 3D simulations.

4.1 Stochastic Forcing with FRPM

The injection of proper inflow turbulence is a non-trivial issue. By means of slat-noise computations, Dierke [7] showed that the interplay of FRPM and the CAA-tool PIANO (using the Linearised Euler Equations), is successful and provides for accurate sound source information that can be further propagated. Instead of the Linearised Euler Equations we force the full Navier-Stokes equations, by also using FRPM in combination with the eddy-relaxation source term. Figure 3 displays that the vorticity target obtained from the FRPM tool (left) is properly injected into the computational domain (right). The data is evaluated from a 3D NACA0012 computation (for details see Sect. 4.2) and the vorticity is obtained from the fluctuating viscous PIANO velocities $\boldsymbol{v}'$. A visual comparison reveals that the vortical structures are accurately reproduced and are of identical size and magnitude.

The coupling parameter σ that was introduced in Eq. (4) reappears as a blending factor for a smooth initiation of the source term. As indicated in Fig. 3 (right), σ varies from 0 at the patch boarder smoothly to its maximum value (order of 10^{-4}) between the two dashed lines. The patch dimension measures approximately 5δ in width and 2δ in height, based on the local boundary layer thickness δ.

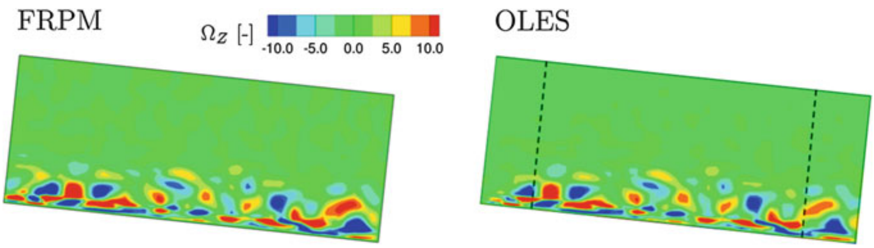

Fig. 3 Instantaneous vorticity distribution (Ω_Z) in the FRPM patch (*left*) and in the Overset-LES (*right*). The vorticity is obtained from the fluctuating viscous PIANO velocities $\boldsymbol{v}'$

4.2 *Overset-LES of a NACA0012 Trailing Edge*

Figure 2 is not only exemplary for the general application of such Overset perturbation analysis, but also describes the computational setup for the here presented NACA0012 trailing-edge computations at zero angle-of-attack. The moderate Reynolds number based on the chord length c is chosen to be $\mathrm{Re}_c = 2.0 \times 10^5$, whereas the Mach number was set to $\mathrm{Ma} = 0.15$. For the underlying steady RANS a Reynolds stress model like the JHh-v2 [5] is favourable, as it provides the individual entries of the stress tensor τ'_{ij} (turbulent contributions from base flow). Note that a quantitative comparison with [14] is not possible due to the here used reduced Reynolds number.

The Overset-LES grid is a structured grid with $400 \times 200 \times 35$ points in streamwise-, normal-, and spanwise-direction (i.e., x, y, and z direction, respectively). The physical extent in spanwise direction measures 10% of the chord length. With a non-dimensional $\Delta y^+ < 1$ the boundary layer (measures around 15 mm at the trailing edge) is well resolved. On the airfoil surface a no-slip boundary condition is considered, whereas the outer domain boundaries are taken to be a radiation condition that allows acoustic waves to leave the domain without reflections. The rear part of the domain, downstream from the trailing edge, is dominated by strong hydrodynamic fluctuations inside the wake. To avoid their interaction with the far-field boundary condition (radiation) a sponge layer is furthermore added to damp such hydrodynamic fluctuations. Turbulence reconstruction and injection is facilitated as described in the previous section. As soon as the first vortices reach the trailing edge, acoustic waves are promptly generated. These sound sources can in a subsequent step be propagated into the far field by using PIANO in its CAA modus as depicted in the middle and upper level of Fig. 1. An average velocity distribution from a vertical line at $x/c = 1.0038$ shows a fully developed turbulent profile (see Fig. 4). Due to the wake influence from the blunt trailing edge the velocity does not reduce to $u = 0$ at $y = 0$.

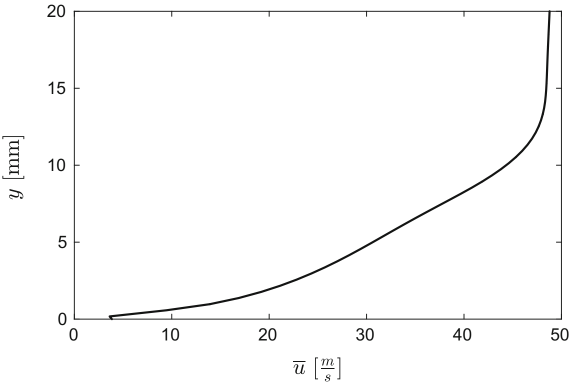

Fig. 4 Turbulent velocity profile at the trailing edge extracted from a vertical line at $x/c = 1.0038$

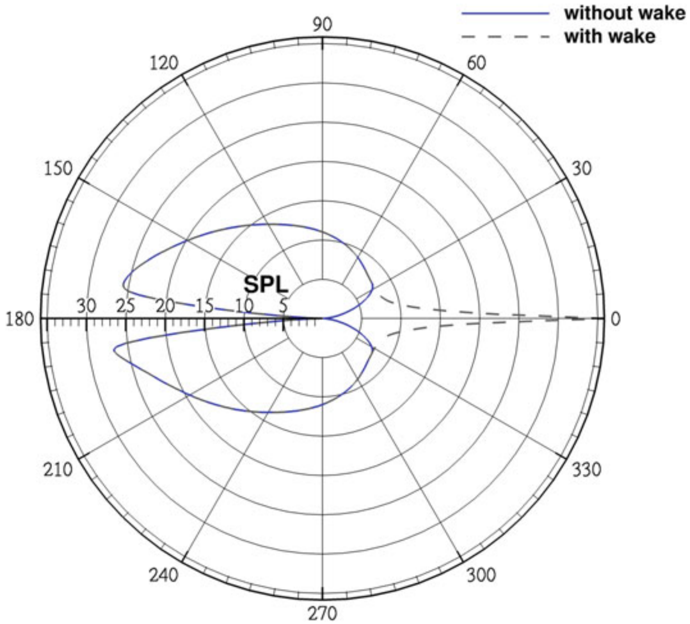

Fig. 5 Directivity plot of sound pressure level (SPL) from a 2D simulation of a completely enclosed NACA0012 profile

4.3 2D Aeroacoustic Evaluation of NACA0012

From a secondary, less demanding 2D simulation of a NACA0012 profile which is completely enclosed, a directivity analysis was carried out at similar flow conditions as above (see Sect. 4.2). This 2D domain could be significantly enlarged as compared to the previous computations, i.e., the domain measures 2.5 times the chord length in streamwise and around 2.2 times the chord length normal to it.

Figure 5 displays the directivity plot of Sound Pressure Levels (SPL), obtained from a circular arrangement of virtual microphones around the profile (centred around the trailing edge with a radius of 1.1 times chord length). Downstream, the microphones intersect the turbulent wake of the airfoil and thus experience high SPLs due to the strong hydrodynamic pressure fluctuations (cf., dashed line in Fig. 5 with solid line where in the latter case the wake was explicitly excluded from the data). A dipolar-like radiation characteristic with strongly upstream directivity is observed. This results from near-field effects as the microphone array is placed rather close to the airfoil. Another useful outcome of this 2D simulation is that the upstream travelling acoustic waves remain unaltered when passing the forcing region (as is expected for the eddy-relaxation term for the LEEs [10]), however, here confirmed for the eddy relaxation term in combination with Overset-LES.

5 Conclusions

In this contribution, a Overset-LES method suitable for trailing-edge noise investigations was presented. As opposed to the commonly known embedded approach, the Overset approach performs a perturbation analysis on top of a background flow. Since the governing equations represent the full Navier-Stokes equations it is a CFD tool (denoted as viscous PIANO).

The application of Overset-LES for sound source prediction is illustrated with trailing-edge noise of a NACA0012 airfoil at zero-angle-of attack. Most hybrid RANS/LES face the problem of providing proper inflow turbulence. FRPM proved to be a suitable tool, as it reconstructs isotropic turbulent velocity fluctuations that match the underlying background flow statistics. Further results from a separate 2D NACA0012 simulation revealed the expected dipole emission characteristic as well as the absence of interactions of acoustic waves with the forcing region. The presented results are obtained from low moderate Reynolds number computations and therefore, are difficult to compare with other results (neither with numerical or experimental). The presented results are promising and deserve further investigation at higher Reynolds number, that can be directly compared with corresponding references (such as [14]).

Acknowledgements This work was partly funded by the Collaborative Research Centre SFB880 "Fundamentals of High Lift for Future Civil Aircraft". Computational resources were provided by the North-German Supercomputing Alliance HLRN.

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