Hybrid Overset-LES Simulations of Noise Reduction Concepts of Loaded Airfoils

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Abstract. The noise reduction potential of a loaded airfoil is investigated by means of a novel Overset-LES simulation method. This aerodynamic noise prediction tool solves the compressible Navier-Stokes equations, supplemented with a sub-filter-stress model, in perturbation form over a background flow. The such obtained noise sources are subsequently propagated with wave propagation equations to the far-field (e.g., with the Acoustic Perturbation Equations). This hybrid prediction method is applied to a noise reduction investigation of a loaded airfoil. For this purpose, two geometries are considered, i.e., a reference geometry and a modified geometry with a long-chord slat. The effect of the long-chord slat on the turbulent sound sources is investigated by mainly considering turbulence statistics in the slat cove and shear-layer reattachment location. Moreover, the acoustic far-field propagation revealed the influence of a long-chord slat on the directivity. The slat noise reduction primarily results from the combined effect of the less intense shear-layer instabilities and the larger distance between reattachment location and upper trailing-edge, rather than a shielding effect by the long-chord slat. The predicted noise reduction matches well with values reported in literature.

1. Introduction
The aircraft industry is met with increasing restrictions regarding emissions, whether it be related to NO\textsubscript{X} from aero-engines or acoustic emissions from aircraft. Due to the steadily growing demand for air transportation, significant improvements have been made to reduce the noise resulting from engines and airframe. This has led to the situation that airframe noise is similarly important as engine noise during the landing phase. Typical airframe noise examples (e.g., landing gear and high-lift devices such as slat and flap) are shown in figure 1. Such aeroacoustic

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{figure1.png}
\caption{Typical contributors to airframe noise during the landing phase.}
\end{figure}
source investigations on first principle basis require the use of scale-resolving simulations.

Direct Numerical Simulation (DNS) is for many applications impractical due to the high computational demand. Therefore, several methods exist that alleviate this demand by modelling, instead of resolving, certain physical phenomenon. One of such methods is based on the Reynolds Averaged Navier-Stokes (RANS) equations, where a steady simulation is performed and all influence of the unsteady (turbulent) flow is modelled. One could also split the problem in large and small length-scales where the latter ones are modelled. This leads to the Large-Eddy Simulation (LES) approach with a possible reduction in computational cost as compared to DNS. Lastly, it is possible to combine the RANS and LES approaches such that only LES is applied to regions with unsteady flow whereas the remaining part is covered with RANS, leading to the so-called hybrid RANS-LES approach. Note that the above named approaches are by far not a complete description of available methods. For an overview, the reader is referred to Refs. [1] for DNS/LES and [2] for hybrid RANS-LES methods.

It should be mentioned that “hybrid” is used in a different way in the Computational AeroAcoustics (CAA) community than in the CFD community. In CFD (e.g., in hybrid RANS-LES) it refers to a combination of RANS and LES in a single computation through a suitable choice of the modelling terms. As opposed to this, in CAA it refers to the situation that the sound generation (usually obtained by CFD) and sound propagation (CAA) are computed separately. Unless stated otherwise, in this manuscript the definition of hybrid is used in the CFD sense.

In this manuscript, a hybrid Zonal LES tool is presented and applied for the computation of sound sources on a loaded airfoil. Such a loaded airfoil can be considered as a generic case for a stator stage. The hybrid approach is based on the CAA-code PIANO [3], which solves equations for acoustic propagation such as Linearized Euler Equations (LEE), Acoustic Perturbation Equations (APE) [4], or non-linear Euler Equations in perturbation form [5]. After extending the Non-Linear Perturbation Equations with fluctuating viscous terms, one obtains the compressible Navier-Stokes equations in perturbation form, i.e., a DNS capability. The such obtained code is denoted as “Overset-LES” to emphasize the compressible Navier-Stokes equations as governing equations are used (i.e., it can be used as a CFD-tool as opposed to PIANO in its traditional usage as a CAA-tool).

The loaded airfoil that will be considered is the LEISA2 geometry [6], which is a 3-element airfoil and has been used extensively for benchmarking [7]. In the schematic presented in figure 2 (left), the qualitative flow features in the slat region are described [8, 9]. A shear layer develops from the lower trailing-edge of the slat (the slat cusp), and impinges on the upper part of the slat. This impingement leads to a fluctuating load and produces sound. One part of the shear

![Figure 2](image-url). (left) Schematic of the flow field in the slat gap (after [8, 9]). (right) Comparison of the reference (LEISA2) and the modified (Very Long Chord Slat, VLCS) geometries.
layer forms a large vortex in the slat cove, while the other part accelerates and convects to the upper slat trailing-edge. The large scale vortex in the slat cove moves slowly and is known to contribute to the low-frequency part of the spectrum [10].

Moreover, slat noise reduction is investigated by considering a modified geometry. For this modified geometry, the Very Long Chord Slat (VLCS) is used [6], which is again based on the LEISA2 geometry. In comparison to the LEISA2, the VLCS geometry has a longer slat chord and an overlap with the main wing element, as depicted in figure 2 (right). In this way, the long chord slat could reduce velocities near the slat’s trailing edge and provide enhanced shielding. Note that there are several “versions” of the VLCS geometry: the “original” one, one with the slat cusp chopped off (vertically), and one with a splitter plate attached to the chopped cusp. In the current study, the chopped slat cusp version of the VLCS is considered and will be simply referred to as VLCS in the remainder.

This paper is organized as follows. In Section 2 the computational approach is presented, covering the governing equations as well as the far-field propagation method. Hereafter, in Section 3 the computational set-up is given covering the baseline and modified geometry. The results are then described in Section 4. Finally, in Section 5 the main conclusions are summarized.

2. Computational Approach

In this section the computational approach is concisely presented, starting with the governing equations and hereafter, the far-field propagation. The interested reader is referred to Ewert et al. [11] and Akkermans et al. [12] for a more detailed discussion regarding the governing equations.

2.1. Governing Equations

The derivation of the compressible Navier-Stokes equations in perturbation form is rather straightforward and is here concisely presented. A decomposition of the variables is performed into a background part (denoted by superscript “0”) and a disturbance part (primed variables), and this decomposition is hereafter substituted in the equations. Terms only containing background contributions are grouped on the right-hand-side and can be replaced by using the fact that a compressible RANS background flow is used. The mass equation then becomes

$$\frac{\partial \rho'}{\partial t} + \frac{\partial}{\partial x_i} (\rho' v_i + \rho_0' v_i) = - \left[ \frac{\partial \rho_0}{\partial t} + \frac{\partial \rho_0' v_i}{\partial x_i} \right] = 0,$$

where the right-hand-side terms vanish due to the compressible RANS equation. In a similar way, one can easily find for the momentum and energy equations the following expressions

$$\frac{\partial v'_i}{\partial t} + v_j \frac{\partial v'_i}{\partial x_j} + \frac{\partial v_0'}{\partial x_j} + \frac{\rho'}{\rho} \frac{\partial v'_i}{\partial x_j} - \frac{1}{\rho} \frac{\partial (\tau_{ij})_{turb}}{\partial x_j} = - \left[ \frac{\partial \tau_{ij}}{\partial x_j} \right]_{turb},$$

$$\frac{\partial p'}{\partial t} + \frac{\partial}{\partial x_i} (p' v_i + p_0' v_i) - (\gamma - 1) \left[ \sigma_{ij} \frac{\partial v_i}{\partial x_j} + \sigma_{ij}^0 \frac{\partial v'_i}{\partial x_j} - \frac{\partial q'}{\partial x_i} \right] = (\gamma - 1) \left[ (\tau_{ij})_{turb} \frac{\partial v_0}{\partial x_j} - \frac{\partial (q'_{ij})_{turb}}{\partial x_i} \right].$$
method similar to the one of Terracol [13], albeit formulated for the non-conservative variables. In previous work, a simple but sufficient subgrid-scale model was implemented, i.e., a classical Smagorinsky model with wall-damping (see, e.g., [14, 15]).

It is worth noting that the method fundamentally differs from the embedded hybrid approach (see, e.g., [2]) in the sense that a perturbation simulation is performed on top of a background flow. The here used method is denoted by “Overset” as there exists a region in the domain where the RANS and LES overlap (as opposed to the embedded approach).

2.2. Acoustic Far-Field Propagation

For the far-field propagation a hybrid CAA approach is used, i.e., the sources which have been obtained by a separated CFD simulation (Overset-LES) are now propagated to the far-field with the APE equations. The 3D sound source information from the region of interest is sampled from the Overset-LES simulation and from this the perturbed Lamb vector \( q = -(\omega \times v)' \) is computed. Interpolation errors that might result from differences in the used CFD and CAA meshes are avoided by using identical meshes in the source region.

Subsequently, a 2D CAA is performed which uses the APE [4] for far-field noise propagation of the sound sources. Therefore, the perturbed Lamb vector \( q \) is spatially averaged in the span-wise direction to obtain a 2D variable that can directly be used in the 2D CAA computation with PIANO as the CAA tool. Span-wise averaging of the 3D Lamb vector has the advantage that, besides the reduced data handling, maintains the influence of the span-wise varying coherence length. To account for differences between 2D and 3D propagation and differences between the considered span-wise extent of the simulations and experiments, the corrections by Oberai [16] and Kato [17] are applied, respectively. The above described far-field propagation approach has been applied with success for several different configurations (see, e.g., [12, 18, 19, 20, 21]).

3. Computational Setup

The reference geometry is the LEISA2 which consists of a 3-element high-lift airfoil. See figure 2 (right) for a zoom view of the geometry around the slat area. The used flow parameters, presented in table 1, have been chosen to match the LEISA2 experimental data [7]. The chord length \( c \) equals 0.3 m (referring to the clean wing configuration with both slat and flap retracted). Based on these flow parameters, the Reynolds number \( Re_c \) and Mach number \( M_\infty \) equal to \( 1.23 \times 10^6 \) and 0.18, respectively. In figure 3 (left) the Mach number distribution is shown for the slat region, obtained from a (steady) RANS. This RANS simulation of the LEISA2 geometry was provided by Marc Terracol (ONERA), where the Spalart-Allmaras one-equation model was used. The mean flow topology of this RANS clearly indicates a large vortex in the slat cove, as well as shear layer which impinges on the slat cove’s upper part. The corresponding surface pressure distribution (not shown) agrees well with the measurements obtained from the F2 wind tunnel [23]. This RANS is used as the background flow for the Overset-LES simulation, i.e., for the variables with superscript “0” in Eqs. (1)-(3).

In figure 3 (right) the Overset-LES computational domain of the slat region is depicted. It consists of 1,100 blocks, each with less than 50,000 points. Fine resolution has been taken near

| Parameter | Value |
|-----------|-------|
| \( c \) [m] | 0.3   |
| \( \alpha \) [°] | 6.15  |
| \( u_\infty \) [m/s] | 61.5  |
| \( T_\infty \) [K] | 289.46 |
| \( \rho_\infty \) [kg/m³] | 1.2053 |
walls and at the approximate location of the free shear layer. The first grid point is located at an $y^+$ between 2.7 (at the slat cusp) and 4.5 (at the slat's upper trailing-edge), the corresponding physical time step equals $2.3 \times 10^{-8}$ s. The signal lengths of the LEISA2 and VLCS simulations are 0.0240 s and 0.047 s, respectively, yielding a lowest frequency of at least 42 Hz. Note that the “coarse” near-wall resolution (i.e., $y^+ > 1$) is motivated by the implicit wall-modelling in the Overset-LES through the RANS background flow which already contains the mean-flow gradients at the wall (in the underlying RANS the near-wall region is well resolved with $y^+ < 1$). For a similar hybrid-zonal approach, Labourasse and Sagaut [22] showed that a near-wall resolution of $y^+ \approx 5$ gives results of the same quality as a wall-resolved LES. The span-wise extent measures 5% of the chord and it is discretized with 190 points. All in all, this amounts to a total of $45 \times 10^6$ mesh-points. At the wall a no-slip boundary condition is applied and in the span-wise direction periodic boundary conditions. As can be seen in figure 3 (right), a sponge region is appended at the outflow boundary to remove strong vorticity in the wake and thereby prevent the generation of spurious noise at this boundary. The 5% span-wise extent is rather small in combination with a periodic boundary condition. However, comparison of the shear layer turbulence statistics at several different positions with LDV experiments (see [23]) revealed a good agreement and suggests that the flow is marginally but sufficiently decorrelated in the span-wise direction. For the VLCS case, the same mesh topology and resolution is used, resulting in approximately $50 \times 10^6$ grid points. More details can be found in Ref. [23].

4. Results

Results are presented here of the Overset-LES approach applied for a slat noise reduction study, by comparison of the LEISA2 reference in section 4.1 with the modified geometry in section 4.2.

4.1. Reference Case: LEISA2

The instantaneous turbulent flow field around the slat is presented in the numerical Schlieren image in figure 4 (left). The numerical Schlieren is here defined in the following way $|\nabla \rho| = \sqrt{(\partial \rho/\partial x)^2 + (\partial \rho/\partial y)^2 + (\partial \rho/\partial z)^2}$. Fine structures in the shear layer develop into larger ones with increasing development length. At impingement, one part of this shear layer flows in the slat cove forming the large recirculation flow in the slat cove and is subsequently fed back into the shear layer at the slat cusp. Furthermore, some artefacts in the numerically obtained Schlieren
Figure 4. (left) Numerical Schlieren of a vertical slice obtained with Overset-LES and (right) fluctuating wall-pressure spectrum $G_{pp}$ at the reattachment location, showing Overset-LES (red) and forced-eddy simulation (blue). The latter was provided by D. Heitmann (DLR).

image can be seen due to spatial differentiation near block boundaries. Note that due to the restriction of the computational domain to the slat cove flow, acoustic waves are not clearly visible in the Schlieren image.

The position where the shear-layer reattaches is of interest as the impinging vortices exert an unsteady force on the cove surface which results in low-frequency noise [24]. For this reason, the surface pressure spectrum $G_{pp}$ is evaluated at this impingement location (located 3.2%c before the trailing edge) and is presented in figure 4 (right). In blue color the same is shown but then obtained with a forced-eddy simulation provided by D. Heitmann (DLR). A very good resemblance is seen between the two simulations illustrating the proper determination of the sound sources with the Overset-LES simulation.

The obtained sound sources are sampled with the approach described in section 2.2 and propagated to the far-field. The sound sources (i.e., Lamb vector) in the entire cove, including the upper and lower trailing-edge of the slat, are sampled. The far-field results will be presented together with the modified VLCS geometry in the next subsection.

4.2. Noise Reduction of Modified Geometry

In this subsection a direct comparison is made between the VLCS and LEISA2 geometry. For this comparison to be meaningful, it is done at the same lift condition as for the above discussed LEISA2 geometry. All the flow parameters remain unaltered for the modified case, except the angle of attack which was slightly increased from $\alpha = 6.15$ to $6.5^\circ$. In a similar way as before, the numerical Schlieren image in figure 5 (left) reveals similar flow features as for the LEISA2 case. However, the shear-layer development is longer, i.e., this longer shear layer is less strongly curved. This in turn leads to a more skewed appearance of the gap vortex. The reduction in flow velocity at the upper trailing-edge reported in Refs. [6, 25] could not be confirmed. This is most likely related to the chopped slat cusp.

The spectra of wall-pressure fluctuations at the slat’s trailing edge in figure 5 (right) shows an almost constant noise reduction over the complete frequency range. This hints at similar spectral characteristics of the shear-layers, however, its intensity level is significantly lower for the VLCS case. Comparison of the Schlieren images of the LEISA2 and VLCS cases reveals that the impingement of the shear-layer is less “perpendicular” than the LEISA2 geometry. This is an additional effect. A comparison of the surface spectra $G_{pp}$ at the reattachment location of the shear layer (not shown) revealed similar results as presented above for the trailing-edge position. Note that the LEISA2 spectrum is noisier than the VLCS one due to the shorter signal length.
Figure 5. (left) Numerical Schlieren of a vertical slice from the VLCS case and (right) fluctuating wall-pressure spectrum $G_{pp}$ at the trailing-edge location.

As described in subsection 2.2, the sound sources are sampled for the two cases (LEISA2 and VLCS) and subsequently propagated to the far-field with the aid of a 2D CAA simulation. The far-field noise is recorded with a circular microphone array, which is centered around the slat with 1 m radius). Figure 6 displays this directivity for both cases. In the background an instantaneous $p'$ is depicted of the VLCS case, clearly showing the dipolar-like sound radiation from the VLCS. This dipolar directivity is also seen for both cases in figure 6, where a noise reduction between 2 to 5 dB can be observed for the VLCS as compared to the reference, except for radiation angles between 210 and 240 deg. This suggests that shielding plays a minor role in the observed noise reduction. The noise reduction matches well with that reported in Ref. [25].

5. Conclusions
In this manuscript, the application of a hybrid zonal method called Overset-LES for a slat noise reduction study was presented. The method is based on the compressible Navier-Stokes
equations in perturbation form. From such an Overset-LES the sound sources are obtained and these are subsequently propagated into the far-field via the acoustics perturbation equations. Application to a reference (LEISA2) geometry and a modified one (Very Long Chord Slat, VLCS) allowed a noise reduction investigation. To make a comparison useful, they are compared for the same lift coefficient (accomplished by a slightly changed angles of attack).

Comparison of the two cases revealed qualitatively the same noise sources. For the VLCS case, a less curved shear-layer was seen exhibiting less instabilities as compared to the reference case. Surface pressure spectra at the trailing-edge location confirmed this. Based on the OASPL directivity comparison, a noise reduction between 2 to 5 dB was observed for almost all radiation angles. The obtained noise reduction matches well with that reported in literature. The noise reduction for the VLCS case results from the combined effect of the less intense shear-layer instabilities and the larger distance between reattachment location and upper trailing edge. For the here considered conditions, shielding effects from the longer slat chord are of minor importance for the observed noise reduction.

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