Investigations of the Sound Generation in a Slat Cove of a High-Lift Wing Configuration: Simulation and Experiment

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Summary

Numerical and experimental investigations on the generation of sound in the slat cove of a high-lift airfoil at 13 degree angle of attack are presented. Two model configurations with different chord lengths are considered. Numerical simulations of the fluid flow are performed in two and three space dimensions using different turbulence models including time-dependent DES, SAS, and LES. The computation of sound generation and propagation is based on Lighthill’s analogy and the surface integral method of Ffowcs-Williams and Hawkings, respectively. For comparison purposes, one model configuration with a chord length of 0.1 m is investigated experimentally in an aeroacoustic wind tunnel. Numerical and experimental results concerning the flow field and the generated sound are discussed.

1 Introduction

Noise reduction is a topic of major interest in the aviation industry. One important step in reducing aircraft noise was done by developing high-bypass jet engines. As a consequence, the focus has shifted to airframe related sound sources such as the landing gear and high-lift devices. Measurements pointed out that the slat cove contributes significantly to the overall noise level (slat noise). Therefore, a better understanding of the mechanisms leading to slat noise is important for further reduction of aircraft noise. A number of investigations were done in order to find robust methods to predict aeroacoustic effects during the design process and to find countermeasures for the slat noise problem in particular. Various numerical methods were presented e.g. in [1] and [2], experimental results have been contributed by [3].

In the present work, the generation of sound in a slat cove of a high-lift airfoil was investigated both numerically and experimentally. Two model configurations have been considered: one was the same benchmark profile as used in [3] (see Figure 1), the other, on which the major part of the work was focused, was a smaller version of the benchmark profile scaled by a factor of 1/4. The emphasis of our work is on the numerical evaluation of different turbulence models such as the Shear-Stress Transport Model (SST), Detached-Eddy Simulation (DES), Scale-Adaptive Simulation (SAS), and Large-Eddy Simulation (LES). For a direct comparison to the own experimental results, the investigations concentrate on the smaller model configuration with a Reynolds number of about $Re = 2 \times 10^5$, for which the experimental study was carried out. The smaller model was designed based on the spatial limitation of the aeroacoustic wind tunnel of the University of Erlangen. An important advantage of the smaller model is that it offers the potential to compare between two- and three-dimensional flow simulations because of the lower Reynolds number.

The numerical prediction of the flow induced noise is based on a hybrid computation scheme. For the simulation of the flow field, a finite volume code is employed. The acoustic sources and the sound propagation to the far field are computed by solving a weak formulation of Lighthill’s analogy by means of the finite element
Table 1: Parameters of the investigated configurations (see Figure 2)

<table>
<thead>
<tr>
<th>Model</th>
<th>A</th>
<th>B</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>chord length $c$</td>
<td>100</td>
<td>400</td>
<td>[mm]</td>
</tr>
<tr>
<td>velocity $U_1$</td>
<td>30</td>
<td>56</td>
<td>[m/s]</td>
</tr>
<tr>
<td>Reynolds number $Re$</td>
<td>$2 \times 10^5$</td>
<td>$1.4 \times 10^6$</td>
<td>-</td>
</tr>
<tr>
<td>angle of attack</td>
<td>13</td>
<td>13</td>
<td>[degree]</td>
</tr>
<tr>
<td>gap width RSP</td>
<td>0.0207</td>
<td>0.0207</td>
<td>as to $c = 1.0$ m</td>
</tr>
<tr>
<td>overlap XRXD</td>
<td>-0.0175</td>
<td>-0.0175</td>
<td>as to $c = 1.0$ m</td>
</tr>
</tbody>
</table>

method. The coupled regions have different discretisations on both sides of the computation. Interpolation of data is performed in the time domain using an in-house coupling code. As an alternative to Lighthill’s analogy, the surface integral method of Ffowcs-Williams and Hawking is applied. The experimental investigations of the flow and acoustic field were done in a low-noise wind tunnel by using different measurement techniques. Therefore, we have a very extensive experimental data basis for the comparison of numerical results concerning the flow and the radiated sound field. Finally, the advantages and disadvantages of the investigated turbulence models are discussed.

2 Numerical Method

Numerical investigations have been performed for two different model configurations shown in table 1. Model (A) and (B) have been simulated in two space dimensions using a finite-volume solver for compressible flows (ANSYS-CFX). Both time-independent and time-dependent calculations using an implicit time discretisation scheme have been performed. Turbulence was modeled by employing the SST and the DES model, respectively. Mesh studies have been carried out to ensure that the solution is independent of the mesh characteristics. A mesh with 220,000 and 390,000 cells was used for the low and the high Reynolds number case, respectively.

In order to investigate the influence of the three-dimensionality of the flow, full 3D-simulations of model (A) based on the SAS model have been done. For this purpose, the mesh was extruded to a width of $W = 0.03$ m (corresponding to about 1/3 of the chord length $c$) by using 32 cells in the spanwise direction and a total number of 3.4 million control volumes.

Additional investigations based on LES using the Smagorinsky model have been performed for model (A) in both two and three space dimensions with complete resolution of the boundary layer. The incompressible flow simulations were done with the in-house code FASTEST-3D. The underlying numerical scheme is based on a procedure described in [4], employing a fully conservative second-order finite volume space discretisation with collocated arrangement of variables on block-structured, boundary-fitted grids. For the time discretisation an implicit second-order scheme is employed with a time step of $\Delta t = 10^{-6}$ s. For the 2D test case, the number of control volumes was 797,000 with one cell in spanwise direction. In the three-dimensional case, the grid was extended in spanwise direction to 32 cells, yielding a total of about 25.5 million control volumes. In accordance with the SAS case, the spanwise length of the domain was $W = 0.03$ m.

The wave propagation for the flow induced noise problem is solved following a hybrid approach. The computational domain for the acoustic field is splitted into two subdomains, the source and the propagation domain. Within the source domain, which corresponds to the CFD domain, a finite-element (FE) discretisation of Lighthill’s inhomogeneous wave equation is used [5]. A crucial point is the transformation of the acoustic sources from the computed flow data to the acoustic grid. In order to preserve the acoustic energy, we perform an integration over the source volume within the FE formulation and project the results to the nodes of the flow grid, which are then conservatively interpolated to the coarser acoustic grid. By this procedure, the interpolation preserves the overall sum of the total acoustic sources. Within the propagation subdomain, we assume no acoustic sources and solve for the standard homogeneous wave equation. To guarantee free field radiation at the outer boundaries of the computational domain, the propagation subdomain is enclosed by a Perfectly Matched Layer (PML) [5]. The overall computational domain for model (A) (see table 1) has a geometric...
dimension of 1 m and is discretised using 1.8 million finite elements. Therewith, a resolution of the computed acoustic field up to 20 kHz is guaranteed.

As an alternative to the Lighthill approach, the surface integral method of Ffowcs-Williams and Hawkings (FW-H) was applied. The key feature of this method is that the computational effort is independent of the observer point distance. Therefore, it is well suited especially for the calculation of the far-field sound. In the applied computational scheme, the FW-H integral is evaluated at each time step. Interpolation and differentiation in time are carried out by using second-order Lagrangian polynomials. For the surface integral, a second-order scheme is employed. The order was chosen to match the order of the applied CFD code, which is also of second order in space. The integration surface is constructed by generating an isosurface representation of the surface based on the CFD grid. Using this approach, it is implicitly guaranteed that the resolution of the integration surface is according to the resolution of the CFD grid and no additional grid generation has to be done.

3 Experimental Setup

The acoustic measurements are carried out in an aeroacoustic wind tunnel which is integrated into an anechoic chamber with dimensions $9 \times 6 \times 3.6$ m. The chamber has a lower cut-off frequency of 300 Hz. The anechoic environment allows for the measurement of the directional pattern of the respective sound sources. The closed-return wind tunnel has an open test section with a nominal cross section of $200 \times 260$ mm and yields a maximum exit velocity of 50 m/sec.

Wind tunnel measurements were performed on an aluminum model of configuration (A) to give an experimental validation of the numerical results for the low Reynolds number case. In order to ensure a flow field comparable to the simulations, the angle of attack was adjusted to match pressure values on the wing surface. For this purpose, steady pressure sensors were integrated into the wing and slat surfaces at selected positions. Figure 3 shows a photograph of the wing model in the test section. The angle of attack of the wing configuration can be varied in the range from 10 to 25 degree. This yields a maximum blockage ratio $b$ in the test section of about 9%, which defines the ratio between the frontal area of an obstacle and the jet cross-section. Typical values are in the range $b = 1\%$ to $b = 10\%$. To clarify the influence of $b$, additional measurements were carried out in a large aerodynamic wind tunnel with $b < 1\%$. Measurements were performed with and without side walls applied to the model, the latter in order to avoid reflections contaminating the sound distribution.

4 Results

Based on the investigation in [3], an angle of attack of 13 degree was used in the simulation. A comparison of the nondimensional pressure coefficient $c_p$ is shown in Figures 4 and 5 for both models (A) and (B). At the lower side of the wing, the agreement between simulation and experiment in Figure 4 is quite good. However, there are differences at the upper surface meaning that the flow through the gap between the main wing and the slat is less accelerated in the measurements depending on $b$. Furthermore, there is a distinct effect of the side walls. The results show that the experiments were very sensitive to the blockage ratio. Only for $b < 1\%$ a good overall agreement with the numerical predictions was obtained at the same angle of attack.

Both the two-dimensional SST and DES simulations show a physically reasonable flow field. Figure 6 documents the pressure distribution in the cove for the DES simulation. In the transient SAS simulation we obtain vortical structures developing in the shear layer between the main flow and the cove. Moreover, a pressure wave was observed radiating from the gap whenever eddies were leaving the cove area through the gap. This effect is a major characteristic of the pressure far-field. The distribution of the sound sources according to the Lighthill method is shown in Figure 7. In the radiated acoustic far-field (see Figure 8), the sound coming from the slat region dominates the sound generated at the trailing edge.

The results of the 2D LES computation are qualitatively similar to the DES case. However, differences were obtained for the 3D-LES. Figures 9 and 10 show a comparison of the simulated instationary pressure signal at a monitor point in the gap between the slat and the main wing for the 2D and the 3D case. Owing to vortices being flushed through the gap between the slat and main wing, a low frequency pressure fluctuation
with high amplitude is observed in the 2D simulation. In contrast to this, in the 3D LES results a mainly high frequency pressure fluctuation with a much smaller amplitude is found. This behaviour is attributed to the three-dimensional vortex structure of the separated flow in the slat cove.

Based on these results, the Figures 11 and 12 depict the sound pressure spectra at three different distances from the wing configuration for both simulation cases. The sound propagation to the far field was computed using the FW-H method. For the 2D simulation, two peaks around 1 600 and 1 800 Hz are found. In the higher frequency range, the SPL values decrease significantly. In the 3D simulation, maximum amplitudes are located at about 2 500 and 3 400 Hz. These values are in good agreement with the data from the experiments shown in Figure 15. Besides a broadband noise contribution, the measured sound spectra exhibit discrete frequency peaks in the range from 1 000 to 10 000 Hz. These tonal components correspond well to calculated Rossiter modes. The relation between the tonal components and Rossiter modes for slat noise problems was suggested by Kolb et al. [3].

The difference between the 2D and 3D simulation results is also found in the predicted sound directivity pattern (see Figures 13 and 14). Based on the 2D LES, the resulting directivity pattern shows a dipole characteristics for different frequencies. In the 3D simulation, the classical dipole is disturbed because of the strong three-dimensional flow structure in the slat cove. Thus, the CAA results strongly depend on the resolution of the three-dimensional vortex structure in the separated flow region below the cove. This leads to the conclusion that is important to cover the whole three-dimensional flow structure in the CFD simulation.

Figure 16 shows some modifications of the wing design which can reduce the level of sound radiation. In this respect, three modifications were successful. In two of them, the boundary layer at the lower edge of the slat was controlled with an additional tripping wire and a pronged shape of the edge, respectively. The aim was to disturb a 2D separation vortex line at the trailing edge. Another method was to fill the slat cove to a degree of about 30%. With these modifications, a reduction up to 20 dB in the level of the tonal frequency peaks was achieved.

5 Conclusion

Numerical and experimental investigations of the sound generation in the slat cove of a high-lift airfoil were carried out. Different turbulence models were employed for the numerical prediction of the flow field, including time-dependent DES, SAS, and LES. The sound propagation to the far field was computed using Lighthill’s analogy and the surface integral method of FW-H, respectively. The resulting experimental and the numerical data were discussed. The studies show that unsteady turbulence models and three-dimensional simulations are essential for the decent prediction of the sound characteristics of highly turbulent flows.

References


Figure 1: Benchmark configuration used for the investigations

Figure 2: Definition of the position of the slat

Figure 3: Experimental setup

Figure 4: Simulated $c_p$-distribution for model (A) ($c = 0.1$ m) compared to experiments

Figure 5: Simulated $c_p$-distribution for model (B) ($c = 0.4$ m) in comparison to data of EADS [3]

Figure 6: Instantaneous pressure distribution in the slat cove (DES model)
Figure 7: Instantaneous sound sources in the slat cove (DES model)

Figure 8: Instantaneous sound field

Figure 9: Pressure at a monitor point between slat and main wing (2D LES)

Figure 10: Pressure at a monitor point between slat and main wing (3D LES)
Figure 11: Spectra of the simulated sound pressure level (FW-H method, 2D LES)

Figure 12: Spectra of the simulated sound pressure level (FW-H method, 3D LES)

Figure 13: Directivity pattern of the computed sound pressure level (FW-H method, 2D LES)

Figure 14: Directivity pattern of the computed sound pressure level (FW-H method, 3D LES)
Figure 15: Measured frequency spectra of the radiated sound

Figure 16: Frequency spectra of the measured sound with slat modifications