Abstract

High-lift devices in an aircraft are important sound generators. These devices should be studied in order to further reduce overall aircraft noise. The high-lift devices operating at a high angle of attack promote the formation of large wakes. Owing to the generation of lift these wakes are asymmetric. A model has been proposed to investigate the sound generation and the vorticity dynamics in a two-dimensional asymmetric wake profile under spatial development. A DNS code was developed for this purpose and the investigation was based on direct numerical simulations of a two-dimensional compressible flow. The results indicated a significant increase in sound level due to vortex pairing which occurs after a substantial vortex deformation.

Keywords: Aeroacoustics; Asymmetric wake; Vortex pairing; DNS

1. Introduction

Wakes are recognized as potential sources of airframe noise and have been investigated. Recently, the legislation of aircraft noise is increasingly demanding and currently the noise from the airframe during landing has become an important issue. Aircrafts exhibit several lifting surfaces, such as wings and high-lift devices. These lifting surfaces operating at high angle of attack promote the formation of relatively large wakes and the two dimensional wake of such surfaces is asymmetric. Moreover, because of the increasing environmental requirements and the reduction of noise from engines, those devices should be studied in order to further reduce the overall aircraft noise.

The sound generated by such asymmetric wakes has not been investigated and may exhibit different characteristics. Two-dimensional symmetric wakes display a very stable vortex pattern, the von Karman vortex street. For an asymmetric wake, this stable pattern is prevented and severe vortex deformation can take place. This deformation is known to be potentially an important sound source. In addition, for a large degree of asymmetry the wake will resemble a mixing layer, and may exhibit vortex pairing, which can be an even more important sound source.

In this context, we were motivated to investigate the sound generation in an asymmetric wake. A computational code was specifically developed for this purpose and the investigation was based on direct numerical simulations of a...
two-dimensional compressible Navier-Stokes equations. It was found that a dramatic increase in sound was found in asymmetry levels above 20%.

2. Methodology

Two-dimensional numerical simulations of asymmetric wakes, subject to a small disturbance, was performed for a parallel base flow produced by a combination of a Gaussian and a hyperbolic tangent mixing layer curve,

\[ U(y) = (1 - e^{-y^2}) + C \tanh(y) \]  

where the asymmetry level of the wake is controlled by parameter \( C \).

The asymmetry was measured as the absolute value of the difference between the free flow velocity on either side of the wake and the mean velocity, relative to the mean velocity. The length scale adopted was the averaged wake width from both sides.

The study was carried out by solving the compressible two-dimensional Navier-Stokes equations in conservative form. A fourth-order finite difference scheme for the spatial derivatives and a 4th order Runge-Kutta scheme for the time integration were employed to solve these equations.

An eighth order implicit filtering scheme was also employed to keep the numerical simulation without aliasing problems. The filter consists in solving a tridiagonal linear system where coefficients were chosen so that the filter acts only at high frequencies.

Dirichlet boundary conditions were used at the inflow for the velocity components and temperature, while the pressure was extrapolated from the interior domain. Non-reflexive conditions were used in the outer flow boundary and a relaxation condition for pressure was applied. The non-reflexive condition was assisted by a buffer zone provided essentially by grid stretching in the normal direction (upper and bottom boundaries) and up-wind differentiation. The inflow condition was a given wake profile and either a periodic or a white noise disturbance.

Tests were performed to ensure that the vertical computational domain was sufficiently large that the results became independent on the domain size. Tests based on linear stability theory were performed and a comparison with the theoretical results was good.

The code was developed in Matlab platform and achieved a good performance. For instance, the CPU time per point per time step was around 1\( \mu \)s, in a personal computer.

3. Results

The two-dimensional direct numerical simulations were carried out for Reynolds number \( Re = 1000 \), Mach number \( Ma = 0.4 \), Prandtl number \( Pr = 0.8 \) and \( C \) (the asymmetry parameter) ranging from 0 to 0.3.

Fig. 1 shows the vorticity field at different levels of asymmetry: symmetrical case, 10% and 30% levels of the asymmetry. The vorticity field was obtained by direct numerical simulations and it is seen that for higher levels of asymmetry the flow dynamics is more complex, and may include vortex pairing. Note the form, the position as well as the magnitude of the vortices being modified by the asymmetry proving changes in vortex dynamic of the wake with possible implications on the generation of noise.

Acoustic pressure fluctuations were recorded along horizontal lines close to the upper and lower boundaries of the domain, just before the buffer zone. The RMS of the acoustic pressure for different positions along the lines are shown in Fig. 2, while their spectra are shown in Fig. 3. The numerical simulations were carried out for resolutions up to 2000 \( \times \) 500 points per spatial direction (horizontal and vertical, respectively) where the convergence of the physical results was achieved. For the symmetric case, the sound emission is essentially symmetric and relatively small. Up to 10% of asymmetry, the sound emission remained small roughly constant, however, an increase of about 5 dB at 20% and 12 dB at 30% was observed. In all asymmetric wakes, the sound emission remained relatively symmetric, with a difference no more than 3dB between the measurements performed at the upper and lower sides.

The position of the highest sound measured moves downstream with increasing asymmetry. At the point where maximum sound pressure was recorded for each asymmetry level, the spectra were obtained, 3. For symmetric and 10% asymmetry cases, there are two clear peaks at frequencies 0.61 and 1.22. Those peaks are still present in the 20%
asymmetry case, at a somewhat similar magnitude. The spectral content outside the peak is what is much increased at 20\% asymmetry and appears to account for the increase in the overall noise.

The vorticity and acoustic pressure (in dB) fields are illustrated in Fig. 4 at a non-dimensional time $t = 500$, in the case of 20\% asymmetry. For these fields we note the complexity of the sound generation. Results were similar to a larger computational domain.

The sound is generated at the vortex generation point, throughout the vortex deformation region and, in particular, via vortex pairing at later stages.

It was also found that the dominant sound generation mechanism varies with the level of asymmetry and hence, the position of the strongest sound level measured. For reference, the position where the strongest sound level was measured for different levels of asymmetry are shown in Fig. 3. Points 1, 2 and 3 correspond to symmetric, 10\% and 20\% asymmetry levels. As the asymmetry increases, the position of strongest sound level measured moves substantially downstream.
Fig. 3. Spectra at the sound pressure level peak at different asymmetry levels, at positions of maximum recorded sound.

Fig. 4. 20% asymmetry case, vorticity field (middle) and acoustic pressure field (top and bottom)

Overall the results are interesting and point to some important effects of the wake asymmetry on sound emission which relate to the instability of the flow.
4. Final remarks

In the present paper, results of numerical studies are described which were performed for an asymmetric wake profile.

It was found that above 20% of asymmetry, there was a significant increase in sound level due to vortex pairing which occur after a substantial vortex deformation.

It was shown that flows in asymmetric wakes share characteristics from both symmetric wakes and pure shear flows, with their intensity depending on the asymmetry level.

As a side result, it was found that, using certain programming techniques, Matlab can be used to create CFD codes with both good runtime and precision, although it is still unknown how this performance would scale to larger, tri-dimensional problems.

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References