Introduction

In recent years, numerical solutions of aero-acoustic problems have received increased attention. Both generation and propagation of sound in internal and external flows are of interest for e.g. the aeronautic industry and manufacturers of cars and trucks.

The noise can be thought of as generated in an isolated part of the flow, considered as the sound source. Thereafter the noise is radiated into the far field. However, in the near field or in other parts of the domain with complicated flow, the acoustic field might interact with the flow field, and its turn couple with the noise generation process.

Acoustic Analogy

A common method to study the generation of sound by air flows is to use a so-called acoustic analogy. This methodology was first pioneered by M. Lightfoot in 1932 and in short the basic idea is to revert the Navier-Stokes equations into an inhomogeneous wave equation with all terms not included in the wave equation acting as sources of sound. An integral is then evaluated over the region with the sound sources to obtain the sound that is radiated to the far field, i.e. far away from the source region.

To obtain the radiated sound, the time-dependent flow in the source region needs to be known. For generic model problems this can be given by analytic functions. For more complex flows however, time-dependent solutions of e.g. the non-linear Euler or Navier-Stokes equations need to be obtained numerically.

In a Direct Numerical Simulation (DNS), the non-linear Navier-Stokes equations are solved numerically, yielding time-dependent solutions of e.g. the pressure and velocity field. However, it can be difficult to locally isolate and identify the sound generating structures in the solution. Also, performing DNS at realistic Reynolds numbers are computationally expensive.

Together with E. Alvebro and D. S. Henningsen at the Mechanics Department we have studied another method to obtain source data to the acoustic analogy. The essence is the use of so-called global modes to obtain a reduced model of the dynamics of the system. The global modes were in this case first developed to study flow control and stability, but are here used to study sound generation.

Sound Generation

The understanding of sound sources and damping of sound due to non-linear coupling effects is a necessity in order to design sound reduction methods. In order to accurately simulate the generation of sound it is necessary to capture the sound generating structures in the flow. A straightforward, although computationally demanding, way to capture the coupling of the flow field and the acoustic field, is to numerically solve the non-linear Navier-Stokes equations. When the generating mechanism is located within a region of turbulent flow on a stationary object, the so-called Numerical Schlieren Methods (NSM) or Large Eddy Simulations (LES) have in general to be performed.

A common geometry suitable as a reference case is the in-duct. This setup was applied to the case of an in-duct orifice plate. A plane-parallel duct is often modelled as a tube of infinite length. The flow field was calculated by numerically solving the compressible Navier-Stokes equations by means of a direct numerical simulation. The Reynolds number was set to \( Re = 10^6 \) and is based on the duct height. The peak Mach number is \( M = 0.1 \). No turbulence model was used. The simulated results were compared to experimental data from S. Allam and M. Åkervik at the Mechanics Laboratory.

A parallel, multi-block high order finite-difference method based on Summation-By-Parts (SBP) operators and penalty techniques for imposing the boundary conditions.

The code is proven linearly stable and no technique that cannot be proven stable in a linear sense exist in the code. Along with the periodic vortex structures, corresponding density perturbation are generated. Two main mechanisms govern the pressure fluctuations. The first is the fluctuations that correspond to the convecting vortices. They convect slowly, and give rise to slow velocity fluctuations. The other mechanism is the actual sound waves propagating downstream. These are more difficult to isolate, but take the shape of smaller peaks that move 1/3 times faster than the vortices.

Sound Propagation

In many applications, such as the prediction of acoustic performance of vehicles, ventilation systems and intake/ exhaust systems of vehicles, knowledge is needed of the propagation properties of sound waves through these geometries. This is often referred to as the characterization of the acoustical system and is often performed assuming linear conditions, such as a frequency domain approach can be taken.

Several approaches can be taken to this task, ranging from the simplest Helmholtz equation when no mean flow is present, up to the Euler or Navier-Stokes equations linearized about an arbitrary mean flow.

This setup was applied to the case of an in-duct orifice plate with an area contraction ratio of 0.277 where the mean flow was calculated by averaging the time steps of the DNS as described under the headline Generation above. The simulated results were compared to experimental data from S. Allam and M. Åkervik at the Mechanics Laboratory.

Instantaneous pressure field generated at the orifice.

A main challenge when simulating generation of sound is to separate the actual sound from the fluctuations associated with vorticity. In low Mach number flows the particle velocity and pressure of the sound waves can be several orders of magnitude smaller than that of the hydrodynamic flow quantities, which pose high requirements on the accuracy of the simulation results.

Instantaneous vorticity in the cavity.

Since each global mode represent one separate source mechanism, the study of individual modes gives a much clearer picture of the sound generation processes than the study of sound data obtained by the N-S equations, where all mechanisms are present at once and are difficult to isolate.

The method is evaluated and applied to a flow case in the form of a low Mach number flow over an open cavity. The reduced model is incorporated into Cale’s equation (a version of the acoustic analogy which accounts for effects from solid boundaries), and an equation for the sound generation is derived. In addition to the advantage of a clearer view of the source mechanism, this methodology also turned out to be very fast and efficient.

Damping of Acoustical Waves in Ducts

Sound waves propagating in a duct dissipate because of viscous thermal effects at the physical walls. Theoretical models exist that predicts the viscous-thermal acoustic plane wave attenuation in pipes with mean flow. To accurately simulate the damping of acoustical plane waves in a duct a higher order multi-block parallel Navier-Stokes solver has been used. The novel for higher order accurate solver is crucial especially in areas where linear structures are of interest such as aeroacoustics and turbulent flows. Several simulations were performed to compare the damping of plane waves in a straight 2D duct to a theoretical model. Acoustical waves were introduced at the left and right boundaries and the solution was computed up to the time when a steady state solution was reached. The frequency was chosen to ensure plane wave propagation and avoid excitations of higher modes. The Reynolds number was 10000. To evaluate the damping of acoustic waves the theory of full wave decomposition method was applied to the simulated results. As a result, complex wave amplitudes and wavenumbers could be determined by using the source values at 4 microphones positions which are split into two clusters and separated by a sufficiently large distance to produce a measurable effect of the wave damping. The result is a non-linear system of equations with 4 equations and 4 unknowns which was solved iteratively using Newton’s method to accurately predict the damping in simulations the numerical dissipation needs to be under control. To what extent the amplitude is damped by numerical dissipation depends on the resolution of the wave in time and space. Having four points per period/wave length causes increased dissipation. The outcome of this work is an exact knowledge on the resonance time and space for different orders of accuracy of the numerical solver.

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Generation and propagation of sound waves in flow ducts

Axel Kierkegaard
Mac Panahbeyagh

axelk@kth.se macp@kth.se

Linnæus Flow Centre
KTH The Marcus Wallenberg Laboratory

A plane-parallel wave propagates through the duct and generates vorticity shedding at the orifice.