Generation and propagation of sound waves in flow ducts

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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 flows, the acoustic field might interact with the flow field, and its turn couple with the noise generation process.

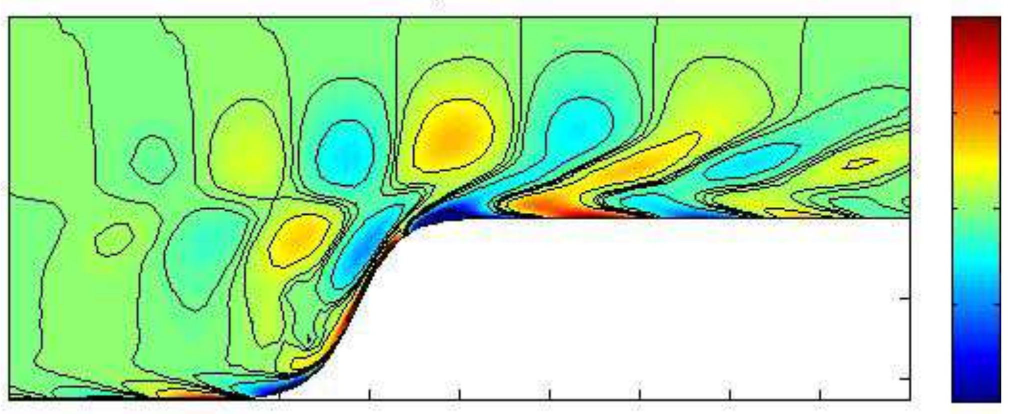
Acoustic Analogy

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 MJ Lighthill in 1952 and in short the basic idea is to recast 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 data of e.g. the pressure and velocity field. However, it can be difficult to clearly isolate and identify the sound generating structures in the solution. Also, performing DNS at realistic Reynolds numbers are computationally expensive.

Together with E Åkervik and D S Henningson at the Mechanics Department we have studied another method to obtain source term 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.



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 source 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 Curle'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.

Sound Generation

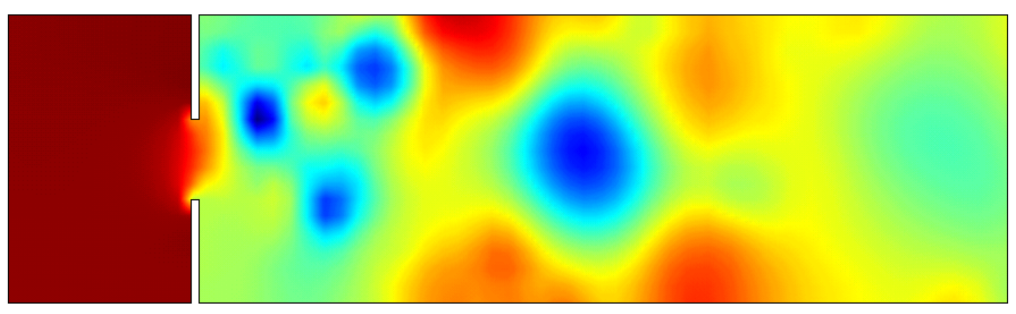
The understanding of sound sources and damping of sound due to non-linear coupling effects is a necessity in order to design sound reduction methods. In order to accurately simulate the generation of sound it is necessary to capture the sound generating structures in the flow. A straight forward, although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

A common geometry suitable as a reference case is the in-duct orifice plate. A time-dependent flow field is obtained from the simulations and the convection of fluctuations in velocity and density, respectively, is analyzed.

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 $Re = 10^4$ 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. Åbom at the MWL.

The code used is a parallel, multi-block high order finite differences 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 corresponds 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 moves 1/M times faster than the vortices.



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.

Acknowledgments

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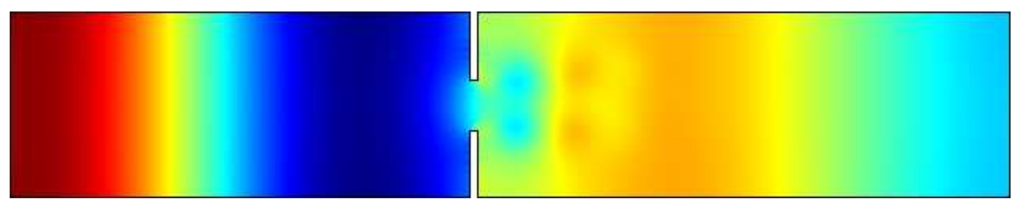
Sound Propagation

In many applications, such as the prediction of acoustic performances of silencers, ventilation systems and intakes/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, reaching 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. The latter is needed when significant coupling between acoustic waves and vorticial motion occurs, such as when sound energy is transformed into vorticity around sharp edges.

In present work the Euler equations are linearized about an arbitrary stationary mean flow, and isentropic conditions are assumed according to general linear acoustics such that the energy equation can be disregarded from the equation system. Also a harmonic time dependence is assumed and the system is solved for a sequence of frequencies instead of in the time domain. This helps to reduce computational time.

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. Åbom at the MWL.



A plane acoustic wave propagates though the duct and generates vorticity shredding at the orifice.

Damping of Acoustical Waves in Ducts

Sound waves propagating in a duct dissipate because of visco-thermal effects at the physical walls. Theoretical models exists that predicts the visco-thermal acoustic plane-wave motion 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 need for higher order accurate solver is crucial especially in areas where fine 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 pressure values at 4 microphone positions which are split into two clusters and separated by a sufficiently long distance to produce a measurable effect of the wave damping. The result is a nonlinear system of equations with 4 equations and 4 unknowns which was solved iteratively using the Gauss-Newton method. In order 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 few points per period/wave length causes increased dissipation. The outcome of the work is an exact knowledge on the resolution in time and space for different orders of accuracy of the numerical solver.