Research strategy for
Low-Mach number aeroacoustics

Introduction

Until today, most aeroacoustic research has focused on aeronautical applications where high-frequency sound is the dominating issue. For low-Mach number aeroacoustics, the focus is naturally on lower frequencies, for which the coupling between the acoustic source and the surrounding geometry is stronger compared to the high frequency case. This implies that more details of the geometry need to be included and that phenomena such as whistling are more frequent.

In the low frequency regime the effect of fluid-structure interaction is also more prominent. Here, sound generated by vibrating structures or the influence of a vibrating structure on the scattering of waves are studied. Both experimental and numerical studies are essential to gain insight. An example of fluid-structure interaction is the human speech apparatus.

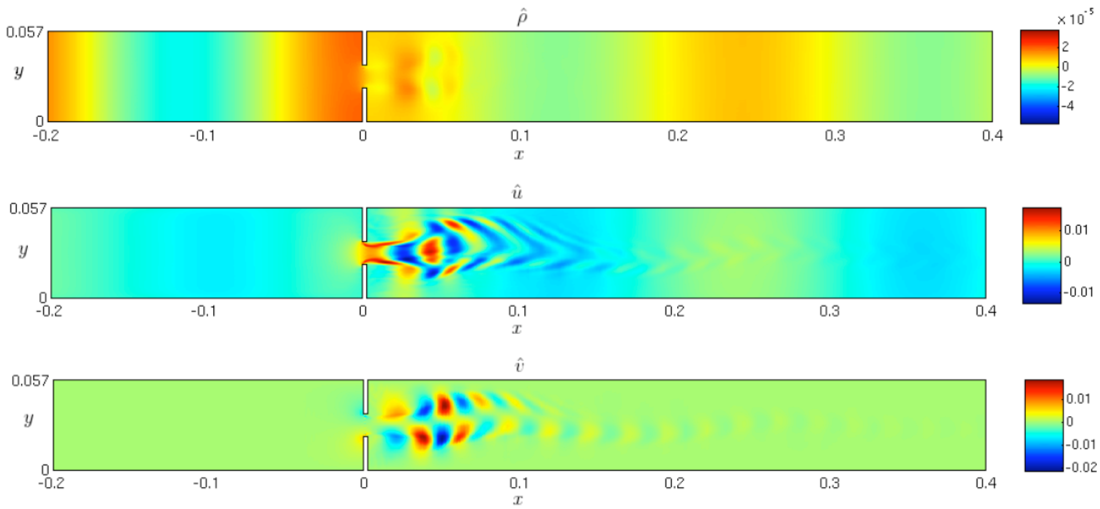

Figure 1. Simulation of the propagation of plane waves in a duct with an orifice.

In present aero-acoustic research, an important trend is to couple aero-acoustics with numerical solutions of the non-linear Navier-Stokes equations. Important problems where the use of large scale computations can enable new insights are problems involving complex turbulent flows and flows where sound and flow interact. Other research trends involve the development of improved and accurate experimental techniques to characterize sound generation and propagation.

We have over the years developed system identification techniques to extract linear acoustic source data from experimental tests. For in-duct sources so called multi-port models, dependent on the geometrical configuration and frequency content of the source, are used. A multi-port model contains an active part, i.e., source strength, and a passive part, i.e., the scattering properties. The passive part is important for describing the interaction and matching between the source and the surrounding system. Typical application areas are sound generation from IC-engines, ducted fans and flow constrictions in ducts. Recently, we have developed a non-linear one-port model applicable for weakly non-linear sources. Another area of activity is the development of models for predicting sound generation from first principles. Based on these models, simulation codes for prediction of sound generation from a ducted rotor and from a piston-constriction system have been developed.

An activity has been initialized that studies the generation of sound in separated regions of internal flow via large scale computing. Within the research area we investigate sound generation by looking at the full compressible Navier-Stokes equations. Here, higher order accurate codes are used in order to solve these demanding problems in an efficient manner. Also, studies on sound generated by fluid-structure interaction have been initiated, including both experimental and numerical investigations on a mixer plate in a pipe. The simulations are performed with a duality based adaptive FEM solver.

The coupling between sound and flow at a boundary often allows for the existence of unstable modes. Such growing modes can dissipate, generate or amplify sound and can also affect the mean flow. Here there are interesting connections between acoustic control and flow control. One important application of this type of research is liners, i.e. the perforated wall elements used to attenuate sound in for instance aero-engines. Of interest is also the related flow – acoustic interaction at sharp edges or other points of flow separation.

Recent investigations are related to sound propagation in ducts at low Mach-numbers. For example, flow-acoustic interactions that can occur in regions with flow separation are studied. For flows at a sudden area variation in ducts we have shown that for low Helmholtz numbers, the flow effects on the acoustic scattering can be described via the use of the Kutta condition, by only modelling the region in the vicinity of the sharp edge where the flow separates. Within the research area, the experimental techniques to determine transmission and reflection properties, the passive part, of complex acoustic systems have been developed. These techniques have been applied to investigate the scattering of sound at, e.g., open pipe terminations and in-duct orifice plate constrictions. To continue this work a new test rig is planned, which also will allow more detailed flow mapping (PIV) in co-operation with the fluid mechanics group. The experimental works have recently been complemented by numerical simulations of the linearized Navier-Stokes equations, where the output data is post-processed with the same methodology as the experimental data.

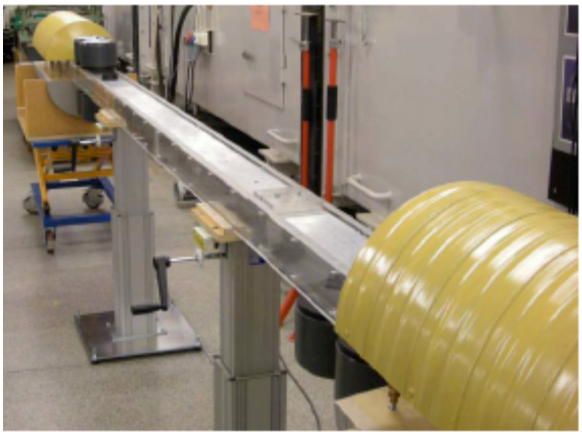

Figure 2. Experimental methods for flow duct acoustics. The new 3-port aero-acoustic test rig for detailed investigation of sound and flow interaction in a region with flow separation.

Research environment

The research within aeroacoustics at the Marcus Wallenberg Laboratory KTH (MWL) has concentrated on low Mach number internal flows, such as flows in ducts and pipes. In particular the work has focused on the development of linear aeroacoustic models and experimental techniques. For the future research development of the experimental techniques, combining fluid mechanics and acoustics, as well as increased activities in large scale computations are two key factors. In particular, the areas of flow-acoustic and fluid-structure interaction are important research areas. The projects associated with FLOW are listed in the table.

Areas/ Projects	**PhD stud. Postdocs**	**Senior researchers**	**Proj. Start**	**Sponsor**
Sound generation				
CFD modelling of sound in flow ducts	Axel Kierkegaard	Efraimsson, Åbom	2009	VR/Linné, FFI
Advanced Aero-Acoustics Investigations of Flow Duct Singularities		Allam, Efraimsson, Åbom	2009	VR
Numerical simulation of generation of sound in separated internal flows	Ciarán O´Reilly, *Postdoc*	Efraimsson, Åbom, Henningson	2009	
Sound propagation				
Long range sound propagation		Bolin, Karasalo	2010	EU/FORMAS/Vindforsk
Flow acoustic interaction				
Scattering of sound at duct discontinuities		Boij		VR
Experimental characterization of aero-acoustic sources	Andreas Holmberg	Bodén, Boij, Åbom	2008	VR/Linné, FFI
Numerical methods for fluid-structure interaction aero-acoustics	Rodrigo Vilela De Abreu	Hoffman, Åbom	2008	European Research Council

Table 1 Ongoing research activities within FLOW

Areas/ Projects	**PhD stud. Postdocs**	**Senior researchers**	**Proj. end**	**Sponsor**
Sound generation				
Modelling of ambient and masking of windturbine noise	Bolin	Åbom, Khan	2009	Vindforsk
Cooling fan noise	Jiang	Åbom, Bodén	2008	EU SILENCE
Sound propagation				
Low frequency noise control for exhaust systems	Karlsson	Glav, Åbom	2009	Scania/EMFO
Flow acoustic interaction				
Propagation of sound waves in aeroengine intakes		Efraimsson, Nordström	2009	EU NACRE

Table 2 Finished projects within FLOW

Seniors working within the research area
Mats Åbom (theoretical and experimental methods)
Hans Bodén (signal analysis, theoretical and experimental methods)
Susann Boij (theoretical and experimental)
Johan Hoffman (numerical simulations)
Gunilla Efraimsson (numerical simulations)

Overall Research Goals

The overall research goals within the low-Mach number aeroacoustics area are

- to obtain detailed understanding of the generation and scattering of sound in internal flows for efficient acoustic characterization of in-duct low-Mach number flows.
- to combine advanced numerical, theoretical and experimental work.
- to combine acoustic and flow control in internal flows with application to adaptive liners and new concepts for noise control.

The short-term goals are

- to develop in-duct experimental methods correlating in-duct acoustic parameters in the radiated field with flow data in the source region of the acoustic source, for complex flows.
- to extract acoustic multi-port descriptions of duct elements from DNS/LES simulation of complex flows using advanced signal processing and system identification methods. This includes performing the underlying DNS/LES simulations.
- to investigate the possibility to predict sound that is generated and scattered by fluid-structure interaction via experiments and advanced FEM simulations, using so called unified continuum description for robust fluid-structure coupling and adaptive mesh refinement with error control.
- via theoretical and numerical work study the influence of parameters such as boundary layer thickness on the stability of modes between flow and incoming plane and non-plane waves, respectively at sharp edges.
- to use and evaluate the latest findings on flow control in aero-acoustic simulations, e.g. global modes and adjoint equations.
- to tighten the two-way link between the development of reduced analytical models and advanced numerical simulations or experiments.

The researchers within the area have a strong international network in particular in Europe with links and co-operation with leading centers for acoustic research and computational methods. The most important contacts are:

Prof. Jeremy Astley, ISVR - The Rolls Royce UTC in Gas Turbine Noise
Prof. Yves Aurégan, LAUM, Univ. Le Mans, France
Prof. Timothy Barth, Nasa Ames, USA
Prof. Daniel Bodony, University of Illinois at Urbana-Champaign, USA
Prof. Jean-Luc Guermond, Texas A&M University, USA
Prof. Avraham Hirschberg, TU-Eindhoven, The Netherlands