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A Study of Incompressible Flow Fields for Computational Aero Acoustics

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Abstract

This thesis focuses mainly on sound generation and propagation evaluated from incompressible flow fields. A temporal form of the acoustic analogy pioneered by Curle is used for this purpose. Sound generation is evaluated from the dipole terms in the acoustic analogy and the radiated sound is evaluated by the surface integral of the same terms by a forward time projection.

Two fundamentally different cases have been investigated, first, the laminar flow past an open two-dimensional cavity and secondly turbulent flow past a generic side mirror.

The findings in the open cavity case showed good agreement with respect to sound generation for all cases conducted. The sound signature results were also promising when integrating over the cavity walls and the inlet wall located upstream and gave almost identical sound directivity with an offset of typically 1 dB. When the downstream wall was included in the surface integral, the differences in results increased. The use of a damping zone over the outlet improved the emitted sound levels to a maximum discrepancy of 3 dB. The resulting discrepancy was most probably caused by still existing resolution issues over the last wall.

A first attempt was also made to evaluate sound radiation and propagation past a generic side mirror. The flow state over the mirror was identified from measurements to be sub-critical with an upstream laminar separation. The DES model combined with a "trip-less" approach still showed too high a production of turbulent viscosity preventing separation to occur. However, the results were promising in terms of both sound generation and propagation for several locations up to 200 Hz.

Keywords: CAA, aero acoustics, Curle, low Mach number, cavity, side mirror, CFD, DES, incompressible flow, sound generation, sound propagation

List of Papers

This thesis is based on two papers and one research report:

1. Ask, J., Davidson, L., An acoustic analogy applied to the laminar upstream flow over an open cavity, In press, C.R. Mecanique, (2005)
2. Ask, J., Davidson, L., An investigation of outlet boundary conditions for incompressible near field acoustics, AIAA-2005-2992, (2005)
3. Ask, J., Davidson, L., The Near Field Acoustics of a Generic Side Mirror based on an Incompressible Approach, Research Report 2005:5

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Contents

Chapter 1

Motivation

The only legal restriction on sound emissions for car manufacturers in Sweden concerns "by-pass" noise at 50 km/h measured 7.5 meters from the center plane of the car. At this distance and speed, the flow induced noise is negligible as compared to noise caused by the engine and the road-tire noise. The only motivation for reducing flow induced noise in future cars thus concerns the driver's and the passenger's subjective experience.

Flow induced noise can however be the overall dominant component in the car compartment at lower speeds. This is typically the case in the presence of open windows or sunroofs and this noise is often referred to in the literature as *buffeting*, *booming* or *wind-throb* noise. This is a resonance phenomenon that is purely compressible in its nature and occurs typically in the range between 40 and 90 km/h and can generate as much as 120 dB inside the compartment.

Another contributing noise source more prominent at lower speeds is the Heating, Ventilation and Air Conditioning (HVAC) system. The cause and effect in noise levels when increasing the mass flow over the vents is however more accepted by the driver and is more or less present in all kinds of cars. A remark here is that the driver of a more "silent" vehicle will experience a higher relative change when the HVAC system is actived which can generate more customer complaints than a more "noisy" vehicle. This makes noise reduction a delicate task when isolated systems or components are analyzed.

Concerning noise generated by external flows, this is commonly expected to be the dominant source at speeds above $100 - 140$ km/h if leakages over door, windows, sunroof and similar structures are prevented. The noise in this case enters the cabin through structural excitation of the external flow. This is typically the case in flow separated regions such as behind side mirrors, A-posts, rails and roof racks. This phenomenon is more hydrodynamic than acoustic or in other words more incompressible than compressible in its nature.

Solutions to flow induced noise issues in the car industry have traditionally been prevented by empirical relations or engineering "know-how" in the early phases of the car projects. The outcome is typically followed up by measurements of mules, prototypes or of production vehicles. These physical models are produced comparably late in the car project as compared to the release of virtual geometry, which often means that problems detected at this stage must be solved in an adhoc manner and sometimes with expensive solutions as a consequence.

Computational capacity on the other hand has gone through a tremendous evolution during the past decade, and flow simulations that were beyond imagination only a few years ago are now regularly used in car projects to evaluate thermodynamic and aerodynamic properties. Even though flow simulations require a great deal of the user to be accurate, they still serve as powerful engineering tools in the early phases of a car project to explain the effect of different design proposals and build a fundamental understanding of widely different flow states. The focus of this thesis is therefore a rapidly growing branch of Computational Fluid Dynamics (CFD) called Computational Aero Acoustics (CAA) that studies predictions of both noise generation and propagation.

The purpose of this thesis is to investigate issues related to hydrodynamic dominated flows. An incompressible approach is proposed for these kinds of flows which will reduce the computational effort substantially for low Mach number flows. Several researchers have used this assumption to compute sound radiation at low Mach numbers, but to the author's knowledge none have made quantified investigations of what the assumption imposes on the acoustic analogies combined with reduced surface integrations. Some authors have suggested the use of the assumption of incompressibility because of the simpler boundary conditions, i.e. there is no need for treatment of sound wave reflections, which is true. On the other hand the pressure field in an incompressible approach is highly coupled to the flow characteristics, and small distortions in the pressure fields will have an instantaneous effect over the whole domain. This is cumbersome since the dominating sources needed to compute the radiated sound includes the fluctuating surface pressure and its temporal derivative.

1.1 Objectives

The research hypotheses for the present work are as follows:

1. Is the assumption of incompressibility justified for low Mach number, wall bounded flows where the hydrodynamics is the dominating cause of the noise generation?
2. Are the near and far field wall fluctuating pressure terms sufficient to evaluate the radiated sound?

Chapter 2

Future Work

Even though major improvements in the results from the open cavity have been made in the first two papers there still exist some issues that should be investigated further.

- Mesh dependency is still not fully investigated over the outlet wall. This most probably causes the differences in the levels of the wall sources and might have a major impact on the sound directivity.
- The inlet zone shows deviations from the compressible study and is probably the reason for the 1 dB offset in sound levels.

So far a first attempt has been made to solve the flow field over the generic mirror that has raised several questions that should be investigated further.

- The fundamental frequency and statistics of the mirror are not fully representable due to too short a simulation time. Further studies should include at least twice as long simulation times.
- The upstream laminar separation is not captured. Forcing the turbulent viscosity to a sufficiently low value over the suction side should therefore allow quantification of eventual differences in flow state due to the laminar separation.
- Radiated sound is poorly predicted for some observers in the present simulation, possibly owing to the neglected volume sources and the

unresolved plate boundary layer. Further studies should primarily focus on alternative methods to include the volume sources.

- Three-dimensional wall resolved turbulent flows are extremely costly to simulate and at present are not well suited for the short turn-around times in car projects. In the author's experience, time-dependent simulations are best suited for capturing the lowest frequencies and could be combined with more adhoc techniques for sound radiation to estimate higher frequencies. This has not been investigated in the present work but should be investigated in future work.

Chapter 3

Summary of Papers

Paper 1: Ask, J., Davidson, L. *An acoustic analogy applied to the laminar upstream flow over an open 2D cavity*, In press, C.R. Mecanique, 2005

The sound generation and propagation based on an incompressible approach was proposed for the laminar upstream flow past an open two-dimensional cavity at the corresponding Mach number of 0.15 previously investigated by Larsson et al. [1, 2]. With the incompressible approach significantly larger time steps can be taken compared to explicit compressible codes. The sound radiation was calculated from the modified Lighthill-Curle analogy [1,3] and the sound generation was evaluated from the two dominating dipole sources in the analogy and compared to the same terms obtained from a compressible code. Parameter studies of spatial resolution as well as temporal resolution were investigated. The findings showed a perfect match, both in the sound generation as well as the sound signature above the cavity when the dipole terms were integrated over the cavity walls. However, when integrating the dipole terms over the wall extending from the cavity trailing edge to the outlet, a significant deviation in the sound signature was found. These discrepancies were proposed to be caused either by the outlet boundary condition or by resolution issues over the wall or a combination of the two.

Paper 2: Ask, J., Davidson, L. *An investigation of outlet boundary conditions for incompressible near field acoustics*, AIAA-2005-2992, 11th AIAA/CEAS Aeroacoustics Conference, 23-25 May, 2005

The assumption of incompressibility for the open two-dimensional cavity was further investigated by studying different outlet boundary conditions. The findings indicated that the outlet boundary could not alone handle the vortex flow present in the open cavity case, causing strong pressure oscillations in the whole domain. A buffer or damping zone was thus proposed over the outlet by adding source terms to the governing equations. The present technique is similar to buffer zones used for compressible simulations but aims at damping the vorticity to obtain a steady state target field over the outlet. The use of this technique gave almost identical results compared to no buffer zone for the surface source levels but major improvements in the radiated sound. The resulting discrepancy in results was then argued to be caused by resolution issues that should be investigated in further studies.

Paper 3: Ask, J. *The Near Field Acoustics of a Generic Side Mirror based on an Incompressible Approach*, Research Report 2005:5, Department of Applied Mechanics, Chalmers University of Technology, 2005

A first simulation was made to predict sound generation and propagation for the flow past the generic side mirror mounted on a flat plate [4–8]. Indications from previous investigations showed the presence of an upstream laminar separation, and the aim of the simulation was to evaluate its effect on both sound generation and propagation. To capture this flow state, the trip-less approach by Shur et al. [9] was chosen, combined with the DES modeling technique pioneered by Spalart et al. [10]. Although a zero level of turbulent viscosity was found near the stagnation region of the mirror a rapid increase in turbulent viscosity prevented separation from occuring. The findings from this first attempt however showed good predictions in pressure levels in the near wake and up to 200 Hz.

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