1 Introduction

1.1 The importance of acoustic research

Thomas Hüttl

There are some aspects of acoustics that significantly affect the quality of our daily lives. By speaking, we transfer information and knowledge from one person to another. The sound of rain, of wind or anything else gives us orientation and aids optical perceptions. Music can fascinate us and stimulate our emotions and moods. Pleasant sounds and music positively affect health by their calming character.

The negative side of acoustics is noise. Noise is the most commonly cited form of environmental pollution. Noise is easily detected by the human hearing system. Its effects can be cumulative, and it influences our work environment as well as our leisure. Even the quality of our sleep is reduced if we are exposed to noise. In recent decades, the effects of noise on people have been studied intensively.

1.1.1 Health effects

There is no doubt that noise has an impact on health. Very loud sounds are clearly highly injurious to people as well as animals. Table 1.1 shows sound-pressure levels (dB(A)) for common sounds. At sound-pressure levels of 160–165 dB(20 kHz) flies die when exposed only for a short time. With these exposures levels, human beings become tired, may experience facial pain, and may develop burned skin. When the sound pressure is lowered, reactions to the sound decrease. Long-term exposure to high noise levels of about 90 dB(A) can result in permanent hearing loss. Even for a steady daily noise level of 75 dB(A) for 8 hours per day, there is a risk of permanent hearing damage after 40 years of exposure. Apart from the auditory effects of noise, nonauditory effects on health are well known. Noise can induce a range of physiological response reactions such as increases in blood pressure, heart rate, and breathing, and these reactions are not confined to high noise levels and sudden noise events but are also true for noise levels commonly experienced in noisy environments such as busy streets (Nelson 1987).

Table 1.1. *Sound-pressure levels for common sounds*

(dB(A))	Common sounds
30	whisper
50	rainfall, quiet office, refrigerator
60	dishwasher, normal conversation
70	traffic, vacuum cleaner, restaurant
80	alarm clock, subway, factory noise
90	electric razor, lawnmower, heavy truck or road drill at 7 m
100	garbage truck, chain saw, stereo system set above halfway mark
110	rock concert, power saw
120	jet takeoff, nightclub, thunder
130	jack hammer
140	shotgun, air raid system
180	rocket-launching pad

Exposure to excessive noise during pregnancy may result in high-frequency hearing loss in newborns and may be associated with prematurity and intrauterine growth retardation (American Academy of Pediatrics 1997).

1.1.2 Activity effects

Noise influences human activities such as sleep, communication, and people's general performance. Studies have shown that noise can affect sleep in many ways. Noise may shorten the length of the sleep period and increase the number or frequency of awakenings, and it may affect the duration of the various stages of sleep. Given the importance of sleep for individual health, a perturbation of sleep is usually not tolerated by people.

First- and second-grade school children chronically exposed to aircraft noise have significant deficits in reading as indexed by standardized reading tests administered under quiet conditions. Chronic noise may also lead to deficits in children's speech acquisition (Evans and Maxwell 1997). Other studies show the impact of noise from aircraft, road traffic, and trains on long-term recall and recognition (Hygge 1993; Groll-Knapp and Stidl 1999). Mood and behavioral abnormalities can also be related to noise exposure.

1.1.3 Annoyance

In addition to the direct effects of noise on sleep, communication, and performance there are also indirect consequences of annoyance or disturbance that are related to the way a person feels about noise. Annoyance is a very complex psychological phenomenon, and it is scarcely possible to define or measure it here. For physically loud sounds the perceived annoyance is often equivalent to the perceived loudness. For physically soft sounds (rustling papers at the movies, people talking while watching television), the perceived annoyance deviates greatly from perceived loudness. Thus, for physically soft sounds, more attention is paid to other aspects of the sound than to the loudness-related sound-pressure level (Berglund, Preis, and Rankin 1990). Nevertheless, annoyance effects can also influence mood and behavior and can ultimately cause even severe health problems.

1.1.4 Technical noise sources

Many noise sources are man-made – especially transportation noise from road traffic, aircraft, and trains. Other technical noise sources can also be annoying such as wind turbines or cooling and climate systems. Noise can be produced by several physical interaction mechanisms:

- Solid-body friction noise (e.g., gearbox),
- Solid-body vibration (e.g., unbalanced rotating machines),
- Combustion noise (e.g., piston engines),
- Shocks (e.g., explosions or pneumatic hammer), and
- Aerodynamic noise (e.g., vortex–structure interaction)

In this book we concentrate on aerodynamic, flow-induced noise.

Aerodynamic noise is one of the major contributors to external vehicle noise emission as well as of internal vehicle noise due to the transmission of the externally generated noise through structure and window surfaces into the cabin. Aerodynamic noise becomes dominant at driving speeds exceeding 100 km/h when compared with structure-borne, power train, and tire noise, for which substantial noise reduction has been achieved. The interaction of the flow with the geometrical singularities of the vehicle body produces unsteady turbulent flows – often detached – resulting in an increased aerodynamic noise radiation (Vergne et al. 2002).

Aircraft noise is dominant for residents near airports when planes fly at low altitudes such as during departure and landing. The engines, especially their free-jet flow – but also flaps, wings, airbrakes, landing gear, or openings – contribute significantly to the total sound emission. When an aircraft is flying at cruising altitude, the aerodynamic noise of the aircraft body and propeller, or engine noise, can be annoying for passengers and crew.

For trains, the bow collector and the wheel–rail interaction are dominant noise sources. For high-speed trains, especially unconventional concepts like the magnetic levitation hover train project Transrapid (Figure 1.1), the relevance of aerodynamic noise is increased.

Wind turbines in operation emit aerodynamic noise that can be perceived by humans. With respect to large wind turbines with low rotational speed, the main contribution to aerodynamic noise is the narrow-band noise caused by blade–tower interaction. Smaller, fast-rotating wind turbines, on the other hand, emit broadband noise, which is mostly caused by vortex–blade interaction (Fleig, Iida, and Arakawa 2002).

Cooling and climate systems are designed to regulate temperature and filter out pollution. Their power units often emit tonal noise at constant frequency that is transported through the duct system. Furthermore, tonal noise due to aeroacoustic resonance can

Figure 1.1. Magnetic levitation hover train project Transrapid.

be activated (Hein, Hohage, and Koch 2004). Although the noise level of cooling and climate systems is usually very low, it is annoying and should be considered by the designer.

1.1.5 Political and social reactions to noise

Noise is becoming generally accepted as an environmental and even health hazard to the population. Public reaction to noise problems is causing governments to adopt laws, regulations, and guidelines for the certification of noise-emitting vehicles and machines as well as for temporal or spatial limitations on their use. Aircraft and jet engine manufacturers face increasingly stringent noise requirements for near-airport operations worldwide (Bodony and Lele 2002a). Old-fashioned and noisy aircraft may not be operated from an increasing number of airports or their operators must pay additional fees for noise emission. Some aircraft may not be operated during the night if their noise emission is too high. Airlines have to consider the noise-related airport fees in their operating costs or reduce the noise emissions by adding new or additional noise-reducing devices to their planes and jet engines. A sociocultural aspect of traffic noise is that the prices for houses and apartments are lower if they are close to highways and roads, railways, or flying routes near the airports. Costly noise-reduction measures like fences, walls, and special windows are required to compensate for the increased traffic noise.

Butterworth-Hayes (2004) describes the European Union (EU) plans to overtake the United States as the largest aerospace power in the world by 2020. The 2001 report "European Aeronautics: A Vision for 2020," which was drawn up by a group of "wise men" to advise the European Commission (EC) on the future of the continent's aerospace industry, laid out a series of research objectives that Europe's civil aircraft manufacturers must achieve to ensure dominance of the market. One of the key objectives of "Vision 2020" research is the halving of perceived aircraft noise. This means, in particular, reducing external noise by 4–5 dB and 10 dB per operation in the short and long terms, respectively. For rotorcraft, the objective is to reduce the noise footprint area by 50% and external noise by 6 dB and 10 dB over the short and long terms, respectively.

1.1.6 Reactions of industry

The aircraft industry projects a growth in passenger kilometers of 100% or more in the next 15 years. Satisfying the resulting demand for larger or faster airplanes, or both, requires that new airplanes be designed. The same is true for future high-speed trains, which, in order to be able to compete with air traffic, have to become faster as well. This would boost the emitted noise levels tremendously if these trains were built based on today's technology because the emitted aerodynamic noise increases approximately with the fifth to sixth power of the vehicle speed (Schreiber 1995).

After having achieved significant progress in reducing the level of other primary noise sources such as piston engine noise or road-contact noise, the automotive industry is now contending with the major problem of interior and exterior noise related to aerodynamic effects. Aeroacoustics is becomimg increasingly important in many other fields such as the energy industry or personal computer manufacturing industry.

Sensitivity to noise is increasing all over the world. Therefore, significant noise reduction in new airplanes, trains, and cars is mandatory if this growth in the transportation system is to be accepted by the population and their political representatives. This noise reduction can only be realized if the design process is guided by robust and fast computational aeroacoustic methods. Owing to the lack of commercial software, many companies and research institutes are using their specialized, self-developed, in-house codes for solving engineering problems. Remarkable progress has also been made by designers of commercial codes for aeroacoustic applications, although these codes are currently still under development (Wagner and Hüttl 2002).

1.1.7 Research on acoustics by LES

Aeroacoustics is the scientific discipline between fluid mechanics and classical acoustics. It considers sound generated by aerodynamic forces or motions originating from (turbulent) flows (Ihme and Breuer 2002). Initially, experimental investigations were used to derive some empirical relations for estimating the noise emission of new technical products. However, owing to strongly increased computer performance, the numerical simulation of acoustic fields generated by fluid flow, called computational aeroacoustics (CAA), has become very attractive. At this time no unique solution procedure exists for all acoustic problems. Instead, various strategies have been developed, each with individual advantages and disadvantages (Ihme and Breuer 2002).

For applications with complex, inhomogeneous flows and flow-induced noise radiation, the most promising and commonly used numerical technique is to adopt a hybrid approach.* In such an approach, the sound-generation and sound-propagation processes are considered separately. A nonlinear aerodynamic near field in which the aerodynamic perturbations are generating the sound is matched to a linear acoustic far field in which no flow or homogeneous flow exists and the sound waves are only propagating. The underlying assumption is that there is no feedback of the acoustic waves on the flow.

Coupled or hybrid approaches are currently being created by several research groups and code developers. Such efforts have also been the focus of two recently finished European research projects: Application of Large-Eddy Simulation to the Solution of Industrial Problems (ALESSIA) and TurboNoiseCFD.† The primary aim of the EU ALESSIA project‡ has been to develop software tools for the simulation of fluctuating flows by large-eddy simulation (LES), with a particular focus on flow-induced acoustics (Montavon 2002). Commercial computational fluid dynamics (CFD) and CAA codes have been interfaced within ALESSIA.

The aim of the TurboNoiseCFD project was to contribute to the objective of a 10-dB reduction in 10 years in aircraft external perceived noise through new design technologies. To achieve this objective, the aircraft engine manufacturing industry significantly enforces to reduce engine noise levels at the source. In response to this challenge, new methods have been created that will aid in the design of low-noise turbomachinery components based on the adaptation of existing CFD software and its integration with propagation and radiation models. Besides other techniques, an LES methodology has been tested for aeroacoustical evaluations of broadband noise (Boudet, Grosjean, and Jacob 2003; Jacob et al. 2005).

After the successful funding of noise reserach programs under the Fifth Research Framework Program (1997–2001), the EC continues to invest money in research projects aimed at reducing the environmental impact of aviation (fuel consumption, noise pollution, and emissions of carbon dioxide (CO_2), nitrous oxides (NO_X), and other chemical pollutants) in its Sixth Research Framework Program (2002–2006).

* Other coupling methods are also called hybrid methods such as the coupling of the Reynolds-averaged Navier–Stokes (RANS) approach and large-eddy simulation (LES) for detached-eddy simulation (DES); see Chapter 4.

† Turbomachinery noise-source CFD models for low-noise aircraft designs. This project was funded by the EC within the GROWTH Fifth Framework Program 1998–2002.

‡ ALESSIA is an ESPRIT Project funded at 50% by the EC.

1.2 Introduction to computational aeroacoustics

Manuel Keßler

Computational fluid dynamics (CFD) has reached a level of maturity that permits many industrially relevant problems to be solved routinely using commercially available tools, although some difficult problems are still out of reach. Consequently, the research interest in the fluid mechanics community has shifted slightly, and there is now a large and still growing group of experts engaged in the field of acoustics. For a long time their work was mostly based on analytical and experimental studies, but the astonishing advances in computer technology have made a numerical approach feasible. That approach is called computational aeroacoustics (CAA).

1.2.1 Definition

Numerous definitions exist for CAA reflecting the many people who have been attached to this subject. We understand CAA here in the broadest possible sense – that is, as a process using some kind of numerical computation to produce acoustical information for aerodynamic phenomena. That obviously includes all flavors of acoustical transport techniques (Lighthill's acoustic analogy, the Kirchhoff method, the Ffowcs Williams–Hawkings equation), linearized Euler approaches, combined procedures with CFD, semiempirical treatments like stochastic noise generation (SNGR), and even compressible direct numerical simulation (DNS) – admittedly very rarely used for acoustic analysis these days.

Experimentors evidently use numerical computations for data processing and evaluation as well. However, although experimental studies are of substantial significance in the efforts to find appropriate models, tune constants, and validate computations, they do not constitute CAA.

1.2.2 History

Even though sufficient computing power has become available only recently, CAA has quite a long tradition in the fluid mechanics community. Among the earliest efforts was the paper by Gutin (1948) published first in Russia in 1936. However, modern CAA rests mostly on the shoulders of Sir James Lighthill (1952, 1954), who published what are certainly the most influential and therefore the most cited papers in aeroacoustics. He introduced the idea of representing sound as the difference between the actual flow and a reference flow – usually a quiescent medium at rest. Because sound pressure and velocities are in general small perturbations around a background flow, approximations are possible to simplify the problem. In the late 1960s, his *acoustic analogy* approach was extended by Ffowcs Williams and Hawkings (1969) to the case of moving surfaces immersed in the flow (and acoustic) field, which is second in citations only to the work of Lighthill. Another classic of its time was Goldstein's (1976) book.

Nevertheless, owing to the highly abstract and mathematical presentation of the subject and the lack of appropriate aerodynamic simulation data, progress was slow during the next two decades. Only sound emitted from jets received considerable interest in the early days of CAA – mostly for their simple geometry (because there are no solid walls) as well as the importance of this sound source for the noise levels of aircraft developed at that time. Many discoveries of basic sound-generation mechanisms and scaling laws date from this time.

Computers have only recently become powerful enough to tackle other, more difficult aeroacoustical problems one way or another with sufficient accuracy to provide results valuable for industry in the design process. Associated with increasing societal interest in noise reduction, another golden age in aeroacoustics dawned in the late 1980s and early 1990s. CAA gained momentum since then, and there is still no slowdown in sight.

1.2.3 Aeroacoustics

Aerodynamic noise occurs because of two basically different phenomena. The first one is *impulsive* noise, which is a result of moving surfaces or surfaces in nonuniform flow conditions. The displacement effect of an immersed body in motion and the nonstationary aerodynamic loads on the body surface generate pressure fluctuations that are radiated as sound. This kind of noise is deterministic and relatively easy to extract from aerodynamic simulations because the required resolution in space and time to predict the acoustics is similar to the demands from the aerodynamic computation. Aerodynamic noise arises primarily from rotating systems (e.g., helicopter rotors, wind turbines, turbine engine fans, and ventilators). If the surfaces move at speeds comparable to the speed of sound or there is an interaction between a rotor and a stator wake, these tonal noise components can be dominant.

The other noise mechanism is the result of *turbulence* and therefore arises in nearly every engineering application. Turbulence is by its very nature stochastic and therefore has a broad frequency spectrum. Interestingly enough, turbulent energy is converted into acoustic energy most efficiently in the vicinity of sharp edges (e.g., at the trailing edge of an aircraft wing). In this case the uncorrelated turbulent eddies flowing over the upper and lower sides of the edge have to relax with each other, generating locally very strong equalizing flows that result in highly nonstationary pressure spikes. Another major source of turbulence sound is jet flows, in which the shear layer in the mixing zone again radiates into the far field.

A third – but here neglected – phenomenon is the case of combustion noise, which is a result of the chemical reactions and the subsequent introduction of energy into the flow.

As previously stated, turbulence noise almost always exists, and as a consequence aerodynamic noise is usually a broadband noise sometimes augmented by narrow-band tonal components coming from impulsive noise sources. Impulsive noise can usually be derived from nonstationary aerodynamic calculations. Like CFD, turbulence noise is much more difficult to simulate because the turbulence has to be either simulated fully, as in DNS, or modeled as in the Reynolds-averaged Navier–Stokes (RANS) approach, or something in between, as in large-eddy simulation (LES) or hybrid computations.

1.2.4 Conceptual approaches

In the CFD area, several tools have been developed to a very high level of maturity that makes them not only useful as a scientific research instrument but also as an industrial design tool. Some of these tools have reached sufficient reliability to make them helpful for users not considered experts in their field. However, pushing tools to their limits can lead to disaster – and often to nonobvious paths.

Because CAA is a more recent domain of activity, the situation is much less favorable. There is not yet a clear path to follow for reliable acoustical information for each and every application, which may consist of such different things as a cooling fan for a personal computer or a supersonic jet driving an airplane. Consequently, many different techniques exist nowadays, each working well in one area and failing totally in another. We try to classify a few of them in the following paragraphs.

Direct methods can be considered the most exact technology for CAA and are comparable to the DNS in the CFD field. The complete, fully coupled compressible Euler or Navier–Stokes equations are solved in the domain of interest for the unsteady combined flow and acoustic field from the aerodynamic effective area down to the far-field observer. They do not include any modeling of the sound (besides, possibly, a turbulence model) and thus do not suffer from modeling or approximation errors. Of course, they require tremendous computational resources because – especially in the case of small-Mach-number flows – flow and acoustics represent a multiscale problem with its inherent difficulties. The difficulty here is that the small acoustic perturbations are not drowned out by numerical errors of the much larger aerodynamic forces. Space and time resolution requirements for the aerodynamic data combined with the large distances up to an observer in the far field give rise to ridiculously high numbers of cells and time steps. Even if the necessary computer power were available, the discretization schemes well known from CFD do not work very well in CAA applications because they have dispersion and diffusion errors that are much too high. A plane wave is usually severely distorted and dampened after being transported for just a few wavelengths, which is clearly too short for the common case of an observer in the far field.

Direct methods are deceptively attractive because well-known and well-understood CFD packages promise to provide aerodynamic and aeroacoustic data at the same time. Sometimes they do work surprisingly well – mostly in those cases in which the differences between aerodynamics and aeroacoustics are negligible – as in transonic problems. However, for many or most other problems they do not because the basic requirements of CFD and CAA are just too different. Several CFD schemes are tuned specifically to suppress spurious acoustic waves, which of course is a bad idea when one is interested in the acoustic properties of a problem at hand. CFD usually is designed to solve a near-field problem because the perturbations from the mean flow vanish quickly. Furthermore, the flow in this region is usually highly nonlinear but basically stationary, or at least changing only slowly (aside from turbulent motions). Acoustics, on the other hand, is clearly a far-field problem in which sound is generated locally in the aerodynamic active area and passively radiated outside to an observer with a smaller exponent of decrease. Outside the aerodynamic active area where the sound is generated the perturbations are small, and a linear description is usually sufficient. However, noise is inherently unsteady with time scales quite comparable to turbulent eddies even if the spatial wavelengths are large compared with aerodynamic ones by an order of the reciprocal of the Mach number.

These different properties (linear versus nonlinear, far-field versus near-field, time-dependent versus (quasi) stationary, large versus small spatial scale) obviously necessitate different tradeoffs regarding computational schemes. No currently known schemes score best on all possible requirements of CFD and CAA; therefore, methods especially adapted for the specific demands of an application will always be superior to more general ones that necessarily have to balance all their characteristics carefully.

Most of the computational aeroacoustic tools in successful use nowadays are therefore of the *hybrid* type in which sound generation due to aerodynamics is more or less decoupled from the acoustic transport process to the far field, making it possible for tailored algorithms to be used for both tasks. This decoupling leads straightforwardly to an arbitrary combination of a sound *generation* method with another sound *transport* method.

CFD Sources: On the sound-generation side some kind of CFD tool is primarily in place. If a direct coupling mechanism to the transport method is used it has to provide sound data in the coupling region (surface or volume). In this case aeroacoustic applicability is very important; that is, dispersion and diffusion errors must be at the lowest possible levels. However, the demands are not as high as for direct methods because an undistorted transport has to be sustained only up to the coupling regions, which are seldom farther away than a few wavelengths. A small error in phase and amplitude is therefore acceptable.

Semiempirical Sources: Alternatively, the sound sources can be reconstructed semiempirically from CFD data derived mostly from turbulence quantities. A straightforward, steady RANS computation provides information about turbulent length and time scales that translate by empirical relations into sound-source spectra. These spectra are then radiated by one of the transport methods described in the next paragraph. Of course, this process depends heavily on the soundness of the empirics and the validation data used to calibrate them. However, the methods can be very fast and reliable for obtaining a judgment between two close configurations (e.g., in the acoustic optimization of an airfoil shape). In such situations, with a small and well-defined application domain close to the calibration data, they are fairly useful.