Preface

November, 2008 *Anna Schwarz,Christoph Richter and Johannes Janicka*

The reduction of noise emissions is a topic of increasing relevance to the public and the economy. While the research effort has previously concentrated on aerodynamic noise formation by airplanes and other vehicles, the research Initiative "Combustion Noise" promoted the development of methods and design criteria to minimize the noise formation by combustion sources. The research was focused on the generation, propagation and radiation of the combustion noise. With the help of suitable experiments the group developed a better understanding of the underlying processes. Key simulation techniques were the Large Eddy Simulation (LES) and well established industrial application URANS-methods (Unsteady Reynolds Averaged Navier Stokes) to compute the noise sources related to the combustion process. Non-intrusive measurements were performed using laser diagnostics, yielding a better insight into the phenomena and providing data for validation. Direct sources of noise emissions due to the time dependent changes of the heat release and the indirect sources from entropy fluctuations were investigated and included in the modeling process.
The research Initiative "Combustion Noise" was split into 10 sub-projects, each presenting their main results within a separate chapter. Thus, the chapter structure corresponds to the project number given in the following. The organization of the project as distributed research collaboration allowed the contribution of various german experts in combustion as well as in aeroacoustics with experiments, analytical and numerical contributions. Therefore, this book provides a comprehensive collection of works with relation to combustion noise. In the following the involved institutions and their projects will be summarized in short:

1. Institute of Combustion Technology, Stuttgart. (Prof. Dr.-Ing. M. Aigner).
   The first sub-project, "Numerical URANS Simulations of combustion noise", focused on the development of URANS methods. The heat release fluctuations due to the periodical combustion oscillations were described through the various modeling methods. The turbulent broadband was captured through different

modeling approaches. These methods were applied to simulations of indirect entropy noise and direct combustion noise.

2. Institute for Chemical Technology and Engler-Bunte Institute, Division of Combustion Technology, University of Karlsruhe (Prof. Dr.-Ing. H. Bockhorn).
The objective of the second sub-project “Measurements and simulation of noise emitted from swirl-burners with different Burner Exit Geometries” was an experimental identification of sound intensity of turbulent, enclosed and swirled flames, which should provide a basis for physical modeling of quantitative noise formation. The simulations of experimentally investigated configurations with a compressible LES approach were also conducted.
3. Institute for Energy and Powerplant Technology, Technical University of Darmstadt (Prof. Dr.-Ing. J. Janicka)
The third sub-project, ”Modeling of noise sources in combustion processes via Large-Eddy Simulation”, was focused on a further development of the Large Eddy Simulation. The resulting noise sources provide a basis for the noise propagation modeling methods like Linearized Euler-Equations (LEE), Acoustic Perturbation Equations (APE), Acoustical Equivalent Source Methods (ESM) and Boundary Element Methods (BEM). The development of subgrid scale modeling under influence of acoustic perturbation was another aspect of this project.
4. Department of Mathematics, Physics and Chemistry, Technical University of Applied Sciences Berlin (Prof. Dr.-Ing. habil., Dipl.-Math. M. Ochmann) and Institute of Acoustics and Voice Communication, Technical University of Dresden (Prof. Dr.-Ing. habil. P. Költzsch).
The main objective of the fourth sub-project, “Modeling of the sound radiation by means of the equivalent source method”, was an advancement of the simulation of noise formation and radiation due to the acoustic Equivalent Source Methods (ESM) and Boundary Elements Methods (BEM). The aims of these investigations were the coupling between LES-ESM/BEM, the simulation of noise field based on incompressible and compressible LES, the validation of simulation methods of the far fields of flames and the adaption of simulation processes for sound radiation of enclosed flames.
5. Institute of Propulsion Technology, DLR Berlin (Dr.-Ing. I. Röhle).
The “Investigation of the correlation of entropy waves and acoustic emissions in combustion chambers” was the focus of the fifth project. Based on a model combustion chamber with variable length and variable cross section of the combustion chamber outlet nozzle, the contribution of the direct noise and the entropy sound to the total noise in a combustion chamber was investigated. In a model experiment featuring electrical heating to generate non-isentropic perturbations in a spatially varying average flow field a reference test case was set up. Comprehensive experimental data was provided for the validation of numerical methods with respect to entropy noise.
6. Institute of Thermodynamics, Technical University München (Prof. Dr.-Ing. T. Sattelmayer).
The acoustic ambient conditions are very significant for simulations of combustion sources. The sixth sub-project,“Influence of boundary conditions on the

noise emissions of turbulent premixed swirl flames", concentrated on contactless methods for local and high dynamic heat release and velocity measurements. Premixed and diffusion flames were the subject of the study. The focus of the enhanced understanding of combustion induced noise in this work was the formation and development of simpler usable models.

7. Institute of Aerodynamics, RWTH Aachen University (Prof. Dr.-Ing. W. Schröder). The development of noise propagation simulation methods was the aim of the seventh sub-project, "Simulation of combustion noise in the near field of premixed and diffusion flames". The acoustic perturbation equations were developed for the simulation of sound propagation in strong inhomogeneous fields based on the LES of the instantaneous source field.
8. Institute of Fluid Mechanics and Engineering Acoustics, Berlin Institute of Technology (Prof. Dr.-Ing. F. Thiele).
   The technical combustion systems are usually enclosed, so that the interaction of sound, wall and the mean flow are very significant. In the eighth sub-project, "Investigations regarding the simulation of wall noise interaction and noise propagation in swirled combustion chamber flows", a computational aeroacoustics method was applied for the simulation of entropy modes and their sound generation.
9. Institute of Fluid Dynamics and Thermodynamics, Otto-von-Guericke University Magdeburg (Prof. Dr.-Ing. D. Thevenin).
   The ninth sub-project, "Direct numerical simulation of the interaction between flame and acoustic waves", delivered information about the interaction of sound waves and combustion due to the direct numerical simulation of partial adjustment ranges in premixed and diffusion flames. This information was used for detailing the inner structures of flames and for improving and validating the models used in the LES and CAA simulations.
10. Hermann-Föttinger Institute of Fluid Mechanics and Engineering Acoustics, Technical University of Berlin (Prof. Dr.-Ing. C. O. Paschereit) and Institute of Propulsion Technology, DLR Berlin (Dr. rer. nat. L. Enghardt)
   The tenth sub-project, "Acoustical near field holography in combustion chambers", dealt with the indirect determination/identification of sound sources from acoustic pressure measurements. The focus of this work was the reconstruction of sound sources using a Green's function representation of the sound pressure field for the investigated combustion chamber geometries. The method was developed for the combustion chamber from sub-project five and delivered additional validation data for theoretical-numerical sub-projects.

The cooperation of experts in different areas allowed the development of new methods and understandings which gain input from different fields. Besides the contribution of each sub project, this led to an additional impact of the present results. The major advances in describing and understanding combustion noise through the project are summarized as following:

- The understanding of the mechanisms of noise generation was addressed using suitable experiments and simulations in which a wide variety was developed in the current project. Several improvements in combustion noise modeling are presented in chapter 1 for URANS based method as well as in chapter 2 and 3 for LES based methods. A direct numerical simulation was applied in chapter 9. Acoustic propagation and far-field methods for combustion noise are presented in chapter 4, 7 and 8. A large experimental parameter variation for premixed and non-premixed flames is provided in chapter 2, therein LES simulation was applied to identify large scale structures as noise source. Further experiments including advanced instrumentation were provided in chapter 6. Finally, experimental investigations of the indirect entropy noise generation are presented in chapter 5.

- Another topic was the modeling of the reflections from connected duct systems. The numerical simulations in chapter 1 as well as 8 underline the importance of impedance modeling for the simulation of combustion noise. Due to the correct consideration of the reflection from up- and downstream duct sections, the prediction of peak frequencies becomes possible and the swing off was adjusted with the correct impedance applied.
- The contribution of experts from the different fields allowed the development of a variety of hybrid methods for the prediction of the noise propagation and radiation which combine the specific numerical methods. Combustion noise required quite different numerical modeling assumptions for the combustion process and the noise propagation and radiation. The idea to couple two methods which were developed for each of these objectives was obvious. Consequently, there is a large variety of hybrid approaches.
  A hybrid RANS-CAA approach was applied using an extension of the random particle method (RPM) in chapter 1. A boundary element method and an equivalent source method which were both based on the Helmholtz equation were applied in chapter 4 to obtain the far-field characteristics of an open flame based on LES (chapter 3). The extension to a dual reciprocity boundary element method which is capable of handling temperature gradients in the field was discussed in chapter 4. Several parameters influencing the accuracy of the acoustic prediction were also investigated. The acoustic perturbation equations described in chapter 7 were applied using the unsteady sources from LES described in chapter 3 as well as from a direct numerical simulation described in chapter 9. Last but not least the application of a hybrid approach based on URANS-CAA coupling is presented in chapter 8.
- An outstanding result of the project was the development of a theoretical model for the prediction of the sound spectrum. Based on a dimensional analytical consideration a general model for the prediction of the sound power spectrum of a flame was developed in chapter 6. The model parameters were influenced by innovative measurements like simultaneous temporally resolved PIV/LIF measurements. These measurements form a breakthrough in the understanding of flame dynamics and allow the adjustment of the model parameters. The model was shown to be in a good agreement with a wide variety of open and thermal enclosed flames (comp. chapter 6).

- The modeling of indirect combustion noise sources was addressed within the project as a potential noise source in a realistic application of gas turbines and aero-engines. The first experimental evidence of the generation of indirect noise was achieved in the model combustion chamber described in chapter 5. The original model of the combustion chamber was investigated numerically in chapter 3. A more realistic redesign of this combustion chamber was used in chapter 5 in order to provide further evidence of the source mechanism together with comprehensive benchmark data for code validation. However, due to the complexity of the system it was not applicable for a first validation of numerical codes.
  For this reason a simplified experiment was developed which has soon become a reference for code validation with respect to entropy noise. It was described in chapter 5 as well. Based on this simplified experiment with controlled electrical heating a validation of numerical methods regarding the indirect source mechanism was carried out for an URANS-method in chapter 1 and for a CAA-method in chapter 8.
- The interaction between the noise generation and the combustion was investigated numerically as an important source of noise as well as combustion instabilities. The basic source mechanisms for the combustion-acoustic feedback were investigated numerically by a direct numerical simulation in chapter 9 and the contribution of the species to the resulting amplification or damping of sound waves due to the interaction with the flame front was uncovered.
- Finally, for the purpose of modeling and identifying of noise sources, identification techniques were developed in the current project. For identification in a numerical simulation the source terms of different acoustic analogies were applied in chapter 1 as well as chapter 2, whereas the method used in chapter 8 was based on the acoustic intensity and identifies radiating sources. The methods presented in chapter 1 and chapter 8 were feasible to identify the flow in the nozzle of the model experiment and therewith the indirect noise as major source of sound.
  An extended theoretical and numerical analysis of the source terms in reacting flows was provided in chapter 7, in which the source terms were also analyzed in chapter 3. The material derivative of the density was found to be the major source of noise in an incompressible simulation. The analysis is shown in chapter 7. Compared to the numerical simulation with full time resolved field data, the location of the source in experiments is even more challenging. This topic was addressed by a holographic method in chapter 10. It provides a mathematical study of the reproduction of the internal sound field with a minimum number of microphones as they are available for a realistic experimental instrumentation. The fast development of this method is astounding on the background that it joined the project in the last two years.

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