Thermo-Fluid Dynamics

Modelling and high fidelity simulation of thermo-acoustic instabilities

■ *In 2019 we have made significant progress in analysis, modelling and simulation of thermoacoustic combustion instabilities. Developments include the use of machine learning techniques for the training of surrogate models with applications to uncertainty quantification, and the analysis of the physical nature of thermoacoustic eigenmodes.*

Highlights

Alp Albayrak received the Rudolf Schmidt-Burkhardt Gedächtnispreis for his dissertation ‘Time Scales of Equivalence Ratio and Inertial Waves in Unsteady Combustion Dynamics’. The prize is awarded annually by TUM’s Faculty of Mechanical Engineering for the best dissertation.

Shuai Guo received the Young Engineer Award of the American Society of Mechanical Engineers to present his results on Gaussian process models at the Turbo Expo Conference.

With funding from DFG/ANR, the project SelfiXs will explore the application of modern ideas from non-hermitian physics to self-excited instabilities in aero- and thermoacoustics. Project partner is Prof. Guillaume Penelet and colleagues from the Laboratoire d’Acoustique de l’Université du Maine, France.

Combustion of hydrogen from renewable sources is an emerging technology that can replace fossil fuels and so provide carbon-neutral energy. In 2019 the EC/H2020 Marie Curie Initial Training Network POLKA – ‘Pollution Know-how and Abatement’ has started. Four doctoral researchers of the TFD group will address technical challenges associated with thermoacoustic instabilities and flashback in hydrogen combustion.

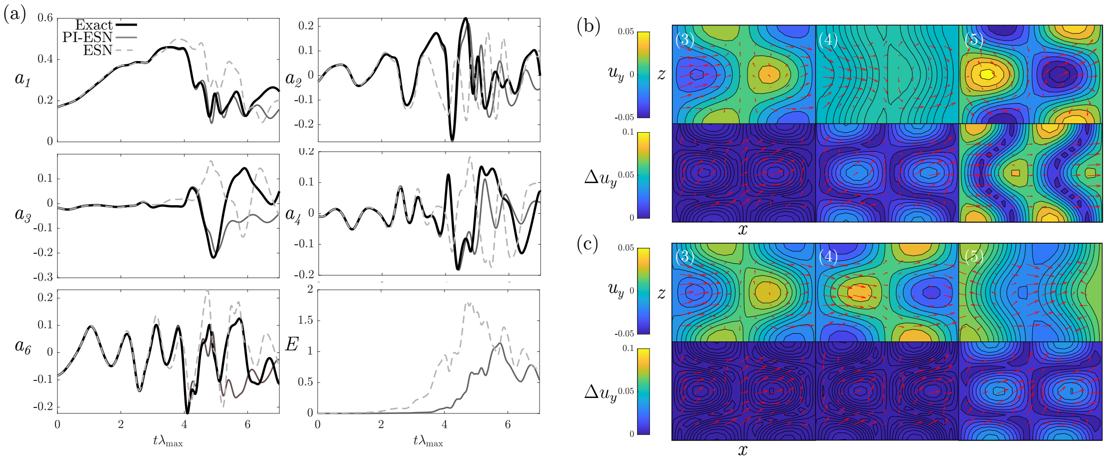
Research Focus

In the past year, the research efforts of the TFD group have concentrated on thermoacoustic combustion instabilities. This type of self-excited instability results from a feedback between fluctuations of heat release rate and acoustic perturbations of velocity and pressure, and may occur in combustion applications as diverse as domestic heaters, gas turbines for power generation and propulsion, or rocket engines. Possible consequences are increased emissions of noise and pollutants, limited range of operability, even severe mechanical damage to a combustor. Thermoacoustic instabilities continue to hamper the development of low-emission, reliable and flexible combustion technology. Due to their multi-scale and multi-physics nature, the prediction and control of such instabilities is a challenging problem with a wide variety of exciting research challenges.

Data-Based/Physics-Informed Surrogate Models

Thermoacoustics instabilities are not only highly undesirable, but also highly unpredictable because of their extreme sensitivities to any change in operating or boundary conditions. Indeed, they exhibit features of chaotic systems that render them extremely difficult to model. To tackle this challenge, several data-driven and deep learning-based strategies have been developed in the TFD group.

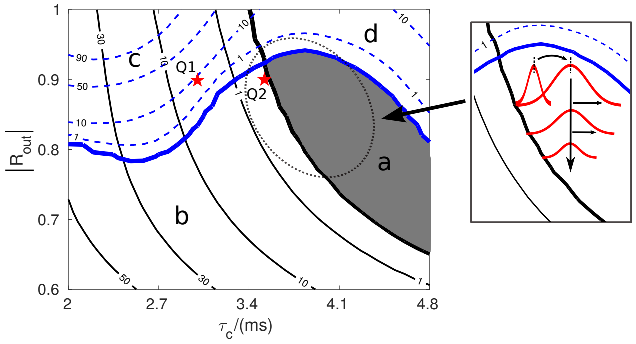
A hybrid, physics-informed/data-driven method has been developed for time-accurate prediction of chaotic systems. This framework combines physical knowledge of the sys-



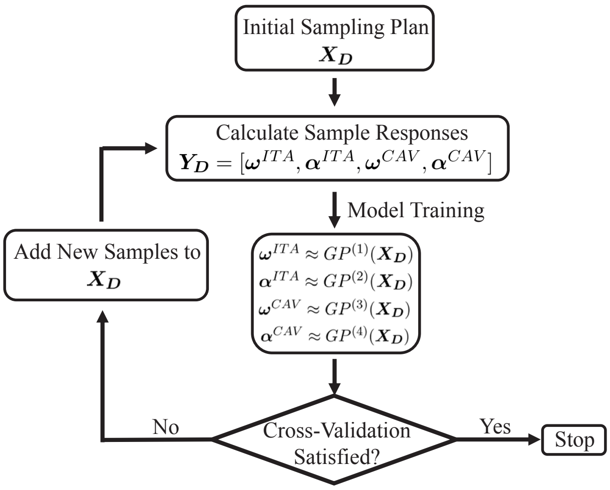
(a) Evolution of the principal modes of a turbulent shear flow. ESN: data-only; PI-ESN: hybrid physics/data approach. Predicted flow patterns at various instants in time for (b) hybrid PI-ESN and (c) the data-only ESN.

tem with an Echo State Network (ESN), a machine learning approach that is based on reservoir computing. Compared to machine learning approaches trained only on data, this hybrid PI-ESN approach was found to time-accurately predict the evolution of a prototypical chaotic system and the occurrence of extreme events in turbulent shear flows. These successes pave the way for a time-accurate prediction and control of combustion instabilities. Additionally, a framework has been developed to automate the identification of low-order model parameters from sparse pressure measurements of complex thermoacoustics systems. This will support the rapid estimation of stability maps, or the development of countermeasures.

To quantify the uncertainty of model predictions, surrogate modeling techniques have been developed to facilitate fast uncertainty quantification and risk analysis. A machine learning method based on Gaussian Processes has been employed to approximate high-fidelity, computationally expensive acoustic solvers and integrate the results into a global optimization routine to explore various aspects of robust thermoacoustic design. Applications range from fundamental risk analysis, or ideal/realistic control design to tolerance design. The demonstrated adaptability and efficiency make this surrogate modeling approach very appealing for industrial practices.



Risk contours of thermoacoustic modes computed with Gaussian Process models allows visualization of the thermoacoustic instability risk over the entire parameter space (from Guo et al, J. Eng. GTP, 2019)



Flowchart of Gaussian Process model training (from Guo et al, J. Eng. GTP, 2019)

In addition, extensions of the fundamental Gaussian Process methodology have also been investigated. To name a few, an active learning approach is adopted to further improve the surrogate model training efficiency; a Gaussian Process-based framework is proposed to efficiently perform high-dimensional thermoacoustic uncertainty quantification analysis; a multi-fidelity version of Gaussian Process is constructed to achieve accurate and robust identification of flame frequency response.

Projects

- EC/H2020 Marie Curie Initial Training Network MAGISTER – ‘Machine Learning to predict and understand thermoacoustics in aircraft engine combustors’
- Hans Fischer Junior Fellowship for Dr. Luca Magri (U. Cambridge) of the Inst. of Advanced Studies @ TUM
- CSC Scholarship for Shuai Guo

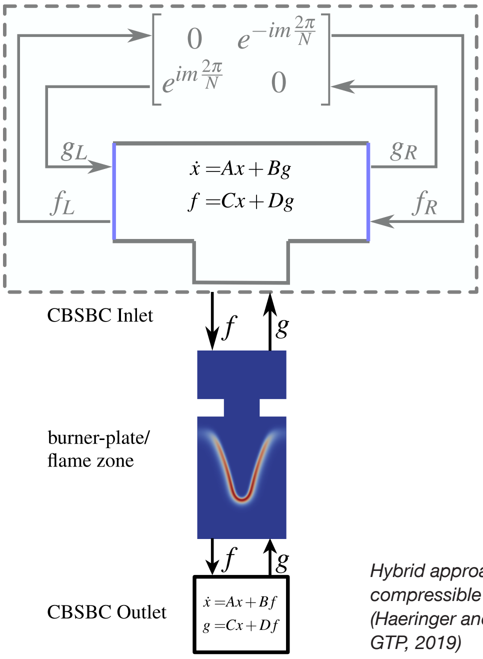
taX – a Thermoacoustic Modelling Toolbox

taX is an open-source Matlab package developed by the TFD group to build and solve low-order thermo-acoustic network models with a state-space approach. It enables the user to compute mode shapes and the stability of eigenmodes for models of arbitrary topology. Unlike most other codes, taX solves a generalized linear eigenvalue problem, which facilitates the use of direct solvers to compute the complete spectrum of eigenvalues and eigenmodes. This key feature proved to be crucial for the recent successes of the TFD group in identifying and investigating so-called ITA modes, which are governed by the intrinsic thermoacoustic feedback loop and have a small basin of attraction.

Recent efforts have concentrated on three main aspects: code development and validation, interconnection with other softwares, and user support improvement. Regarding the first work package, taX is now able to handle not only acoustic waves but also entropy waves. The unsteady combustion generates acoustic waves, called direct noise, as well as disturbances convected with the flow such as entropic inhomogeneities. By themselves, these disturbances are quiescent, but generate indirect noise when accelerated, and thereby contribute to the overall noise or trigger an instability.

Another significant achievement was the development of a new network element that represents the propagation of

acoustic waves in a duct with a non-uniform cross-sectional area and a varying mean temperature in the presence of mean flow. The formulation is based on the quasi one-dimensional form of the linearized Euler equations. Furthermore, software quality assurance has been improved. After significant developments, several test cases are run for regression testing to prevent bugs and to ensure that previously developed and tested code still performs.
taX also proves to be easy to connect with other software, especially in the context of hybrid methods that aim to reduce computational costs. A fully compressible OpenFOAM CFD simulation of the burner-flame region serves as an accurate flame model that accounts for nonlinear dynamics. The latter was coupled to a taX low-order state-space model of the plenum acoustics via the CBSBC method. This hybrid approach successfully predicted limit-cycle oscillations of a can-annular combustor
Finally, taX is user-oriented. Models are built with Simulink, which provides a clear and simple graphical interface, making the overall experience user-friendly. Latest developments are pushed to the taX GitLab repository, so all users can benefit from the latest improvements. A complete documentation helps the user to understand the code architecture, the underlying physics of every elements in the library, how to use the software, etc. The open-source format also allows every user to develop their own new elements.

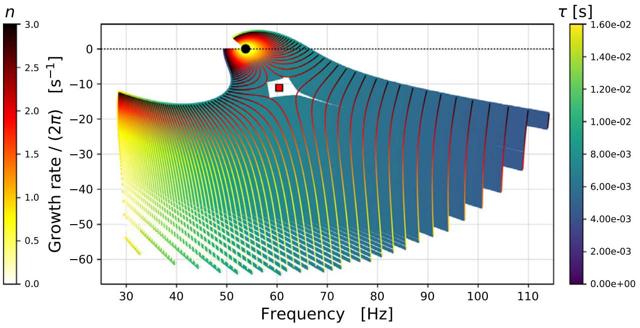


Hybrid approach of coupling compressible CFD to taX (Haeringer and Polifke, J. Eng. GTP, 2019)

Projects

- EC / H2020 Marie Curie Initial Training Network ANNULIGHT – ‘Instabilities, Ignition and Blow-Off in Annular Gas Turbine Combustors’
- FVV project ROLEX ‘Hybrid Reduced Order/LES Models of Self-eXcited Combustion Instabilities in Multi-Burner Systems’

Exceptional Points



Eigenvalue trajectories under variation of parameters n, τ of the flame model. The trajectories with constant n and constant τ are highlighted with different colormaps. An EP (red square) is located in a region that is avoided by the eigenvalue trajectories (from Orchini et al, CNF, 2020)

The concept of exceptional points (EP) accounts for a number of fascinating phenomena in quantum mechanics, optics and acoustics. In thermoacoustics, exceptional points can be found for specific values of parameters that describe the flame dynamics or the system acoustics, where two eigenvalues and their associated eigenfunctions coalesce.

At an EP, the sensitivity to changes in parameters becomes infinitely large, giving rise to strong veering of adjacent eigenvalue trajectories. Parametric changes may at first stabilize, but ultimately destabilize eigenvalues in the vicinity of an EP, thus a profound impact on thermoacoustic stability analysis must be expected.
In a recent publication, Silva and co-workers identified EPs in axial as well as annular combustors. The approach relied on infinite sensitivity and was limited to a simplistic flame model. Ongoing work at the TFD group expands these studies to more realistic models of flame dynamics and identified unstable EPs with a positive growth rate for the first time. Further effects of EP on the uncertainty of thermoacoustic stability analysis are investigated in the context of Gaussian Process surrogate models mentioned above.

Projects

- EC/H2020 Marie Curie Initial Training Network ANNULIGHT – ‘Instabilities, Ignition and Blow-Off in Annular Gas Turbine Combustors’
- DFG/ANR project SelfiXs

Thermo-Fluid Dynamics

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Research Focus
- Thermo- and aeroacoustics
- Turbulent reacting flow
- Heat and mass transfer

Research Competence
- Modelling and simulation
- Stability analysis
- Machine learning
- Model reduction
- Uncertainty quantification
- AVBP, OpenFOAM, Matlab
- taX

Courses
- Engineering Thermodynamics (MSE)
- Wärmetransportphänomene
- Grundlagen der Mehrphasenströmung
- Introduction to Nonlinear Dynamics and Chaos
- Grundlagen der numerischen TFD
- Computational Thermo-Fluid Dynamics
- Simulation of Thermofluids with OpenSource Tools

Selected Publications 2019
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Google Scholar ID VWuhsecAAAAJ

- Albayrak, A., Juniper, M. P. and Polifke, W. Propagation Speed of Inertial Waves in Cylindrical Swirling Flows. J. Fluid Mech., Vol. 879, 2019, pp. 85–120. doi:10.1017/jfm.2019.641.
- Ghani, A., Steinbacher, T., Albayrak, A. and Polifke, W. Intrinsic Thermoacoustic Feedback Loop in Turbulent Spray Flames. Comb. and Flame, Vol. 205, No. 7, 2019, pp. 22–32. doi:10.1016/j.combustflame.2019.03.039.
- Guo, S., Silva, C. F. and Polifke, W. Efficient Robust Design For Thermoacoustic Instability Analysis: A Gaussian Process Approach. J. Eng. Gas Turbines and Power, 2019. doi:10.1115/1.4044197.
- Haeringer, M. and Polifke, W. Time Domain Bloch Boundary Conditions for Efficient Simulation of Thermoacoustic Limit-Cycles in (Can-)Annular Combustors. J. Eng. Gas Turbines Power, Vol. 141, No. 12, 2019, p. 121005. doi:10.1115/1.4044869.
- Orchini, A., Silva, C. F., Mensah, G. A. and Moeck, J. P. Thermoacoustic Modes of Intrinsic and Acoustic Origin and Their Interplay with Exceptional Points. Comb. and Flame, Vol. 211, 2020, pp. 83–95.