Thermo-Fluid Dynamics

Modelling and high fidelity simulation of thermo-acoustic instabilities

■ *In 2018 we made considerable progress in the development of modelling concepts and simulation software for combustion dynamics and combustion noise. Particular emphasis was put on model order reduction and uncertainty quantification.*

Dr. Luca Magri, Lecturer at Cambridge University, was awarded a Hans Fischer Junior Fellowship by the TUM Institute of Advanced Studies. He will collaborate with us during the next three years on the prediction and control of extreme events in turbulent reacting flows, employing artificial intelligence and adjoint methods. Dr. Anh Khoa Doan, who recently completed his doctorate at Cambridge University, will support these efforts as post-doctoral research associate in the TFD group.

In highly competitive selection processes we successfully secured funding for a total of six doctoral researchers from the European Commission's Marie Sklodowska Curie Actions and from ANR/DFG. During the next three years, these funds will support research activities on reduced order modelling and machine learning for thermoacoustic instabilities in (annular) aero-engine combustors, with emphasis on liquid and alternative fuels. Localized unstable eigenmodes in such configurations will be scrutinized by applying recent developments in the physics of non-Hermitian systems. The projects will be carried out in collaboration with research groups in Cambridge, Eindhoven, Genua, Le Mans, Keele, Paris, Trondheim and others.

Research Focus

In 2018, the research efforts of the TFD group have focused almost exclusively 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 or rocket engines. Possible consequences are increased emissions of noise or pollutants, limited range of operability or severe mechanical damage to a combustor. Thermoacoustic instabilities have hindered the development of low-emission, reliable and flexible combustion systems for power generation and propulsion. 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.

Analytical Models of Flame Dynamics

Analytical models for the response of a premixed flame to acoustic perturbations often rely on a convective velocity model, where a perturbation that propagates with a velocity of the order of the mean flow speed, generates local perturbations of flame shape and surface. In a recent paper (Steinbacher et al, 2018) we have scrutinized the origin and nature of such convective perturbations in flow-flame-acoustic interactions. The velocity field induced by an acoustic perturbation was decomposed into irrotational-potential and vortical parts, which are both computed using a 'classical' analytical method, i.e. Schwarz-Christoffel mapping. The respective effect of each contribution to the flame response was evaluated. In contradiction to the widely accepted premise that vorticity shed at the point of flame anchoring accounts for the convective nature of flow perturbations, it was found that the potential velocity field dominates the flame response, while vortex shedding has only a negligible impact. Based on the observation that the potential part displaces predominantly the flame base, a novel flame-base-displacement model was proposed, which compares well with high-fidelity CFD data at early times, i.e. right after an acoustic perturbation is imposed. However, growth of advected flame front perturbations leads to increasing discrepancies for later times, presumably due to exothermic effects generating vorticity via the Darrieus-Landau mechanism. The important conclusion developed from this study is that in order to properly represent the causality of flow-flame interactions, exothermic effects must be taken into account.

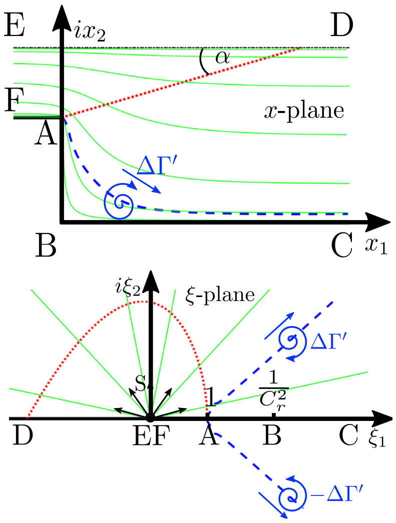

Fig. 1 Illustration of Schwarz-Christoffel mapping: Mean flame position (···), shear layer (- - -) and straight lines from the origin of the image domain (—); each in the physical (top) and the image domain (bottom). A point vortex at the shear layer, as well as its mirror vortex, are represented by spirals.

Follow-up work by the same authors investigated the consequences of flame geometry for the linear response of laminar premixed flames to acoustic perturbations. Building on our seminal works on the impulse response of premix flames, corresponding analytical models were derived for slit, Bunsen and wedge type flames; their respective characteristics were analyzed and validated against high fidelity numerical simulation. Motivated by the poor agreement between numerical and analytical flame response predictions, particularly for slit flames, an extension to the incompressible-convective velocity model was proposed, which employs a Gaussian kernel function. Such a kernel disperses the flame response in time and leads to very good agreement with simulation as well as experimental data. Detailed analysis of the temporal development of flame shape and surface allowed development of explanations for characteristic features of transfer functions of various flame types. A paper will appear in Combustion and Flame in early 2019.

An analytical model for the response of technically premixed flames to equivalence ratio perturbations was developed and validated by Albayrak et al. (2018). The flame impulse response to a local, impulsive, infinitesimal perturbation that is transported by convection from the flame base towards the flame surface is computed with an extended flame surface tracking model based on the so-called G-equation. It was found that the contributions of laminar flame speed and heat of reaction to the impulse response exhibit a local behavior, i.e. the flame responds at the moment when and at the location where the equivalence ratio perturbation reaches the flame. The time scale of this process is related to the convective transport of fuel from the base of the flame to the flame surface. On the contrary, the flame surface area contribution exhibits non-local behavior: albeit fluctuations of the flame shape are generated locally due to a distortion of the kinematic balance between flame speed and the flow velocity, the resulting wrinkles in flame shape are transported by convection towards the flame tip with a restorative time scale. The impact of radial non-uniformity in equivalence ratio perturbations on the flame impulse response was also demonstrated.

The analytical models of flame dynamics developed in the above mentioned studies will guide and facilitate the development of reduced order models of acoustic-flow-flame interactions.

Project

- FVV ‘Vorhersage von Flammentransferfunktionen’

Model Order Reduction

The TFD group pioneered the utilization of system identification (SI) in order to estimate low-order models of flame dynamics from high-fidelity simulation data. Most recently, Merk et al. (2018) employed advanced SI techniques in order to estimate concurrently impulse and frequency responses as well as combustion noise source terms of a turbulent, premix swirl flame. In a joint project with Ecole Centrale Paris it was confirmed that quantitative agreement with experiment is exceptionally good. Furthermore, advanced SI techniques allow the uncertainty of results to be quantified (see below).

Impulse or frequency responses suffice to fully characterize flame dynamics at low perturbation amplitudes, i.e. in the linear limit. At higher amplitudes, nonlinear effects become important, use of flame describing functions is pervasive in this regime. However, this approach is only weakly nonlinear in the sense that it completely ignores the effects of higher harmonics. Häringer et al. (2018) have formulated an extended flame describing function (xFDF), which takes into account higher harmonics in both input and output. Fortunately, the generation of this type of nonlinear reduced order model does not require more time series data than the generation of a standard describing function. It was shown in the case of a strong instability of a laminar flame that the xFDF brings significant improvement in prediciton of limit cycle frequencies and amplitudes.

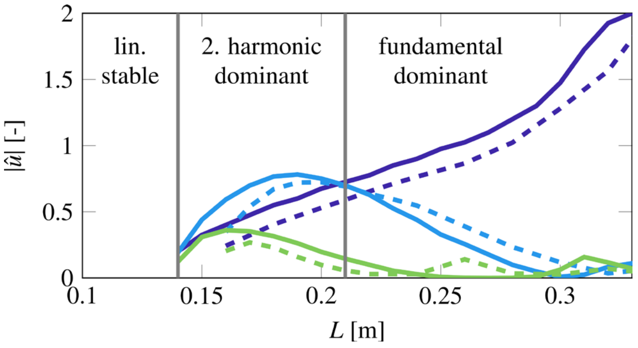

Fig. 2 Variation of limit cycle velocity amplitudes of fundamental (violet), second (blue) and third harmonic (green) with plenum length. Hi-fidelity CFD data (dashed lines) vs. results of xFDF (from Häringer et al., 2018).

The studies by Merk et al. and Häringer et al. concentrated on model order reduction (MOR) for the flame dynamics. Beyond that, MOR of a complete model for

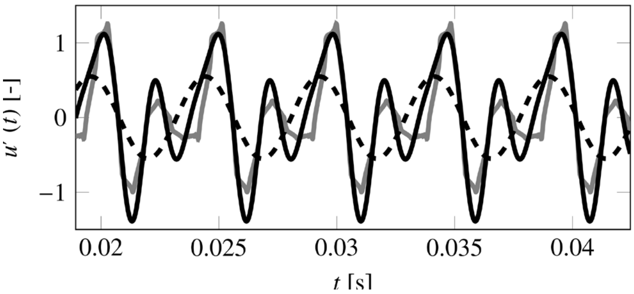

Fig. 3 Limit cycle velocity time series for plenum length L = 0.18. CFD results (grey) compared to prediction by xFDF with three harmonics (black line) vs. standard FDF (black dashed line) (from Häringer et al., 2018).

thermoacoustic stability analysis is important to reduce computational requirements, and facilitate uncertainty quantification or robust design in thermoacoustics (see below). In 2018 we have seen significant progress in this regard; In collaboration with the Inst. for Automatic Control (Prof. Boris Lohmann) the suitability of three established MOR algorithms for thermoacoustic stability analysis was scrutinized. Interestingly, it was found that acoustic modes are not always an optimal choice for modal MOR.

For systems that are influenced by several parameters and system variables, dimensional analysis based on Buckingham's π-theorem allows the minimum number of non-dimensional groups that govern the problem at hand to be identified. Surprisingly, this classical approach has not seen much application in thermoacoustic stability analysis. Silva et al. (2018) deduced a set of non-dimensional π-groups from a modal expansion of the quasi-1D Helmholtz equation with a time-lagged heat source. It was found that the non-dimensional frequencies and growth rates of the fundamental thermoacoustic mode is dominated by only two π-groups. Physical interpretations of these two π-groups were developed, and it was shown that stability maps of three distinct thermoacoustic configurations can be represented consistently in terms of the two π-groups.

A novel analytical approach for dimensionality reduction in thermoacoustic stability analysis was developed by Guo et al. (2018). This approach determines by projection the relationship between variations of flame impulse response coefficients and variations of modal growth rates, effectively reducting the dimensionality of the problem to one. When applied to a problem of forward uncertainty quantification, this allowed a reduction of computational cost by more than three orders of magnitude compared to Monte Carlo simulation.

Projects

- FVV ROLEX project 'Hybrid Reduced Order/LES Models of Self-eXcited Combustion Instabilities in Multi-Burner Systems'
- ANR/DFG NoiseDyn project 'Identifikation des Verbrennungslärms und der Dynamik eingeschlossener turbulenter Flammen'

Uncertainty Quantification

Thermoacoustic instabilities are highly unpredictable, because they respond in a very sensitive manner to slight changes in operating or boundary conditions. Consequently, instabilities are detected often only in full combustor tests during the late stages of development, resulting in significant overruns of development cost or time. It is essential to deploy robust and reliable simulation methodologies that include strategies to quantify the uncertainty of model predictions and their sensitivity to parameter changes.
The TFD group has developed and applied successfully a variety of strategies for uncertainty quantification in thermoacoustics. Residual and covariance analysis as part of advanced system identification (Merk et al., 2018) in combination with non-intrusive polynomial chaos expansion (Avdonin et al., Comb. & Flame, 2018; J. Eng. GTP, 2018), or

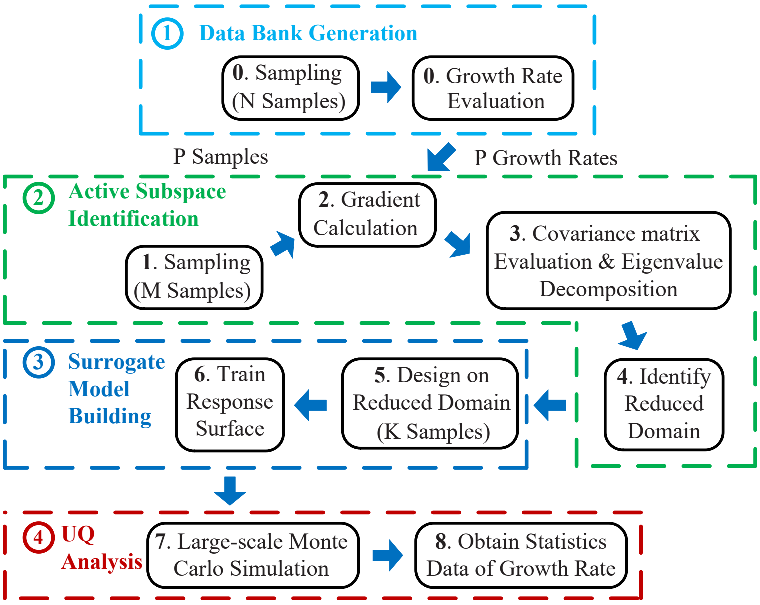

Fig. 4 Workflow for uncertainty quantification with active subspace approach (from Guo et al., JEGTP 141 (2), 2018).

active subspace allow, e.g. to estimate the length of time series required to reduce the uncertainties of combustion modelling and system identification to a desired level (Guo et al., J. Eng. GTP, 2018). The development of low-dimensional surrogate models by exploiting adjoint numerical solutions, by analytical means (Guo et al, 2018), or most recently with Gaussian process models, has played an increasingly important role in these efforts.

Project

- CSC Scholarship, AG Turbo COOREFLEX

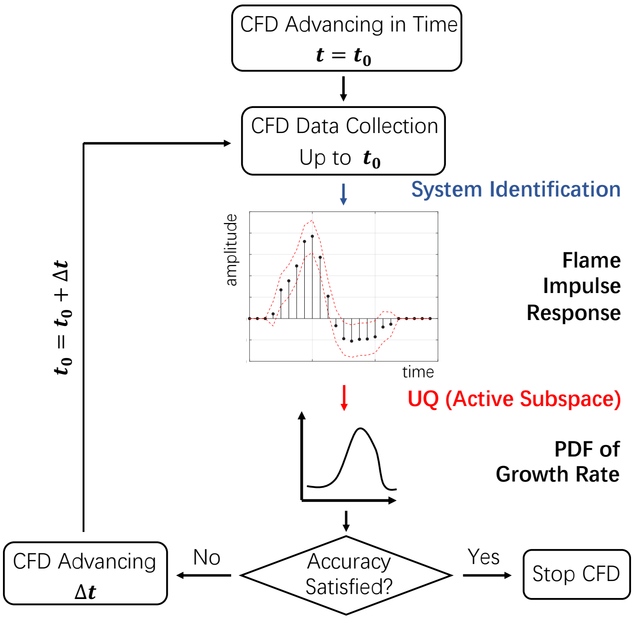

Fig. 5 Workflow for estimating CFD time series length required to achieve desired confidence in system identification (see Guo et al., JEGTP 141 (2), 2018).

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

Research Competence
- Modelling and simulation
- Stability analysis
- System identification
- 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 2018
- Albayrak, A., Polifke, W., 2018. An analytical model based on the G-equation for the response of technically premixed flames to perturbations of equivalence ratio. Int. J. Spray Comb. Dynamics 10, 103-110. https://doi.org/10.1177/1756827717740776
- Guo, S., Silva, C.F., Bauerheim, M., Ghani, A., Polifke, W., 2018. Evaluating the impact of uncertainty in flame impulse response model on thermoacoustic instability prediction: A dimensionality reduction approach. Proceedings of the Combustion Institute 37. https://doi.org/10.1016/j.proci.2018.07.020
- Merk, M., Gaudron, R., Silva, C., Gatti, M., Mirat, C., Schuller, T., Polifke, W., 2018. Prediction of Combustion Noise of an Enclosed Flame by Simultaneous Identification of Noise Source and Flame Dynamics. Proceedings of the Combustion Institute 37. https://doi.org/10.1016/j.proci.2018.05.124
- Häringer, M., Merk, M., Polifke, W., 2018. Inclusion of higher Harmonics in the Flame Describing Function for Predicting Limit Cycles of self-excited Combustion Instabilitites. Proceedings of the Combustion Institute 37. https://doi.org/10.1016/j.proci.2018.06.150
- Steinbacher, T., Albayrak, A., Ghani, A., Polifke, Wolfgang, 2018. Response of Premixed Flames to Irrotational and Vortical Velocity Fields Generated by Acoustic Perturbations. Proceedings of the Combustion Institute 37. https://doi.org/10.1016/j.proci.2018.07.041