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HF Combustion Stability - Research Activities in Germany

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ABSTRACT:
High Frequency (HF) combustion instabilities are a major topic in rocket engine combustion chamber design. Due to the relevance of this topic, research in high frequency instabilities is an integral element in the German aerospace research activities and these are embedded in a European network. The publication gives an overview of the main contributors to research activities in Germany, as well as on the main topics of research.

1. INTRODUCTION

The Ariane program stands for Europe's successful, independent access to space and is also the name for the launcher. The present version of the launcher is Ariane 5 (Figure 1) with a successor, namely Ariane 6, currently in development. The partnering nations contribute to the program and acquire certain work packages for the launcher. In this context, Germany focuses on the upper stage technology and on liquid rocket propulsion. As a consequence of the latter, the rocket thrust chambers are manufactured by Airbus DS in Ottobrunn, near Munich in southern Germany. The Vulcain Engine is an example that is equipped with a thrust chamber from Ottobrunn (Figure 2)

Figure 1. Sketches of different versions of the Ariane 5 Launcher (source: ESA)

One of the most challenging topics of such combustion chambers is High Frequency (HF) combustion instabilities. Apart from other negative effects, HF instabilities can cause increased heat transfer to the combustion chamber walls and therefore can lead to structural failure [1].
The American F1 rocket engine is one of the most famous examples of engines suffering from HF issues during the development phase [2]. In spite of the long history in worldwide HF research, the problem remains challenging and is not yet fully solved. It is, however, known that HF instability is driven by different factors such as propellant combinations. The combination hydrogen-oxygen (H2-O2), for example, for example is relatively uncritical, whereas storable propellants, such as MMH-NTO are much more critical ([3]).
Methane, for example, is a propellant combination which has moved into focus in different countries recently.

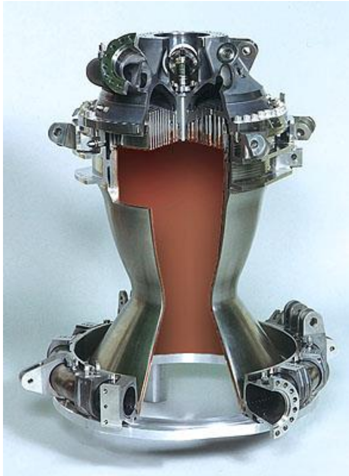

Figure 2. Vulcain engine thrust chamber produced by Airbus DS (copyright: space-propulsion.com)

2. SET UP OF RESEARCH LANDSCAPE

2.1. Airbus DS

Airbus DS' Ottobrunn facility origins from Bölkow Entwicklungen and its heritage in Rocket propulsion dates back to the 1960s. Developments include the staged combustion P111 engine demonstrator, the HM-7 and Vinci thrust chambers, the Aestus Engine and the thrust chambers of the Vulcain family. The present portfolio consists both of H2-O2 thrust chambers and MMH-NTO engines. In terms of HF this constitutes an important difference as the propellant combination MMH-NTO is known to be more sensitive to HF, whereas H2-O2 is relatively uncritical.

Airbus DS supplies all liquid propellant main thrust chambers for the Ariane 5. Reliability is a key selling point for the Ariane 5. Consequently, Airbus puts considerable effort into the development of tools to ensure reliable and efficient products.

2.2. DLR

The Deutsches Zentrum für Luft- und Raumfahrt (DLR) is Germany´s national research center for aeronautics and space. DLR operates large-scale research facilities for DLR's own projects and as a service provider for its clients and partners. Test and research facilities for liquid rocket propulsion are housed at the DLR Institute of Space Propulsion in Lampoldshausen, founded in 1959.

Research expertise at the institute is reflected in its investigations of technical combustion processes with high energy density and high combustion quality and mastery of the associated experimental procedures. These activities are performed in the framework of a series of formal multi-national projects with partners from research organizations and industry.

The Department of Rocket Propulsion investigates the basic physical understanding of all processes in cryogenic high pressure combustion chambers. This specifically covers the analysis of reactive turbulent flows at subcritical and supercritical pressures, heat transfer management in rocket combustors, life prediction of structures under high thermal loads, combustion stability, nozzle flows and ignition transients. In addition, the work aims to develop and apply new technologies to increase the performance of rocket engines, for example by testing advanced propellant injection concepts and nozzle designs, laser ignition technology, nozzle side load reduction strategies, and new materials and manufacturing processes. For these investigations dedicated test benches and research combustors have been designed enabling tests at representative conditions with tailored measurement approaches.

2.3. Lehrstuhl für Thermodynamik, TUM

Basic research as well as the development and improvement of stability assessment tools play an important role during the design process of new rocket engines. In order to support these tasks in industry, the Lehrstuhl für Thermodynamik of the Technische Universität München has established a research group focusing on combustion instabilities in rocket engines. For the research activities and tool development, the Lehrstuhl uses its extensive knowledge gained during years of research in the field of combustion instabilities in gas turbines.

The great advantage in academia compared to the industrial environment is that new aspects of thermoacoustics can be investigated without being limited to rocket engine development time lines. The goal is nevertheless to implement stability assessment tools which are applicable to industrial time scales. To meet this requirement, projects are conducted in cooperation with Airbus DS to benefit from the industrial experience.

The focus of the research at the Lehrstuhl is manifold. For the development of reliable and efficient stability assessment tools, isolated effects involved into the complex thermoacoustic feedback loop are considered and appropriate models are derived. For the investigation of the different aspects, experimental procedures as well as numerical simulations are employed. The task is hence not only to understand the physical processes but also the implementation of meaningful measurement techniques and diagnostics as well as of adequate simulation methods. Experimental and simulation results are finally used for mutual validation.

3. INDUSTRIAL ACTIVITIES

The primary driver for Airbus DS' activities is the criticality of HF with respect to its prediction. Airbus, like any other producer of thrust chambers, is interested in designing stable combustion chambers right away. However, globally seen, neither academic, nor industrial activities have demonstrated a comprehensive predictive capability for HF instabilities. This capability, however, is desired due to the high cost of HF instability occurrences: The problem of HF usually arises at a certain point of maturity in the test phase. As a consequence, the hardware usually needs to be redesigned. Since full predictive capabilities are not present, often, several iterations are necessary until a fully satisfying solution is found. This is a costly process, especially in the later stages of a project.

In the case of anomalies in test series, the capability to react on such events is crucial.

From its history, Airbus DS has a large database of tests using different hardware, propellants and injection technologies. This database is continuously expanded by full scale and pre-development tests. These data support the understanding of the underlying phenomena and can serve as basis for validation purposes.

Research activities aim at a better understanding of the underlying mechanisms of combustion instability. This understanding is important to develop the engineering capabilities towards predictive analyses. Furthermore, such understanding can help to transfer the existing design parameters to new designs or new propellants combinations. Methane - Oxygen, for example, has recently moved into the focus of European space activities and the European heritage on this propellant combination is limited.

For traditional propellant combinations, like H2-O2, kerosene or hypergolic propellants, there are several guidelines for the design of rocket engines also with respect to HF in order to minimize the risk. Apart from other factors, these guidelines involve the estimation of the frequencies both of the combustion chamber and injection system.

These analyses are well known and have been conducted for years. The combustion chamber usually is approximated as cylindrical volume and analytical solutions are used. Injection systems are characterized by 1D acoustic models and can be described in a fairly straightforward mannar.

Approaches like this, however, are still quite limited in their fidelity. The flame source term, for example, is reduced to an n-tau term [4].

In order to improve the situation, Airbus and TUM have established the Piano-Sat Code which is the result of a joint development in the frame of a DLR project. Apart from a significantly improved acoustic model and acoustic solver, the flame dynamics are an integral part of the approach pursued with Piano Sat. The approach is a hybrid, "divide et impera" method which separately characterizes the flame dynamics in an unsteady CFD simulation and uses the result to describe an energy source in the acoustic solver. The flame calculations are made using a single flame in boundary conditions representative of a large injection system. Compared to a full calculation, this reduces the numerical effort significantly. Furthermore, it permits a clean, nearly laboratory like set-up for the flame. This facilitates the extraction of the source model and contributes to understanding of the underlying processes. This single flame simulation method is described in more detail in Section 5.

4. INSTITUTIONAL ACITIVITIES

The Department of Rocket Propulsion at the DLR Institute of Space Propulsion has a research group dedicated to combustion dynamics, which addresses fundamental aspects of combustion instabilities. Leveraging the test facilities and experimental expertise housed in DLR Lampoldshausen, the group has concentrated on experimental investigation of thermoacoustic phenomena in liquid propellant rocket engines. To date, three hot-fire test setups have been operated; the Common Research Combustor, Combustor H, and Combustor D. These setups allow thermoacoustic phenomena to be studied under hot-fire conditions on various scales, from laboratory conditions to scales representative of upper stage engines, both with artificial acoustic forcing and self-sustained oscillations.

4.1. Common Research Combustor

The Common Research Combustor (CRC) was an experiment dedicated to studying flame-acoustic interaction operated for many years by the DLR research department at the laboratory scale M3.3 test bench. While no longer in operation, the CRC produced important results and provided the group with invaluable experience in acoustic measurements under hot-fire conditions and visualising high frequency combustion dynamics.

The CRC was a product of the REST initiative [5], and multiple instances with differing configurations were operated in parallel in both France and Germany. The CRC at DLR was configured to study the behaviour of cryogenic spray flames under a forced acoustic environment, by means of optical diagnostics. The combustion chamber dimensions were such that a single, radially injected spray flame could be submitted to acoustic perturbation from a first tangential (1T) mode with frequencies close to those found in real upper-stage engines (Figure 3). Siren modulation of exhaust nozzle flow was used to excite acoustic resonance, and the position of the modulated nozzle could be changed to position the flame in an acoustic pressure antinode or a transverse velocity antinode. The shear coaxial injector on the side wall was operated with either liquid oxygen (LOx) and hydrogen (H_2) or LOx and methane (CH_4).

Signals from multiple dynamic pressure sensors distributed around the circumference of the combustion chamber were used to reconstruct the instantaneous pressure field distribution throughout the chamber volume. With the help of numerical model analysis, distortion of the mode distribution due to coupling with nozzle volumes and siren forcing could be explained [6]. Additional cold gas measurements in the CRC to address this aspect of acoustic characterisation served as a modelling test case for the REST community. Damping properties of coupled resonator volumes could also be addressed with this test case.

Without acoustic forcing, the 1T mode can rotate due to the near-perfect cylindrical chamber volume. An algorithm was developed to reconstruct the mode distribution from the superposition of two counter-rotating tangential modes with time varying relative amplitude [7]. The reconstruction revealed the fascinating temporal evolution of the 1T mode excited naturally by a spray flame. The mode displays changeable character, transitioning from a rotating to a standing wave, and then back to rotating with opposite direction of rotation. Statistical analysis of the occurrence of the standing wave revealed preferred angular orientation of the 1T nodal line. Knowledge of mode orientation is important for understanding the coupling of acoustics with combustion and for effective design of damping measures.

Quartz windows permit optical access to the combustion chamber of the CRC. High-speed shadowgraph imaging was used to visualise the dense LOx jet and its atomisation behaviour. Filtered hydroxyl radical (OH*) emission imaging was used to visualise combustion. Pressure response factors for LOx/H_2 and LOx/CH_4 flames were calculated using the reconstructed acoustic field and the simultaneous high-speed combustion imaging [6] [8] [9]. To the authors' knowledge, this was the first attempt to capture the distributed response of a rocket flame to acoustics. Temporally resolved flame response distributions remain an essential yet elusive component of engine stability prediction models. While the CRC results lacked sufficient resolution for use in such models, the ability to obtain such response distributions experimentally was successfully demonstrated.

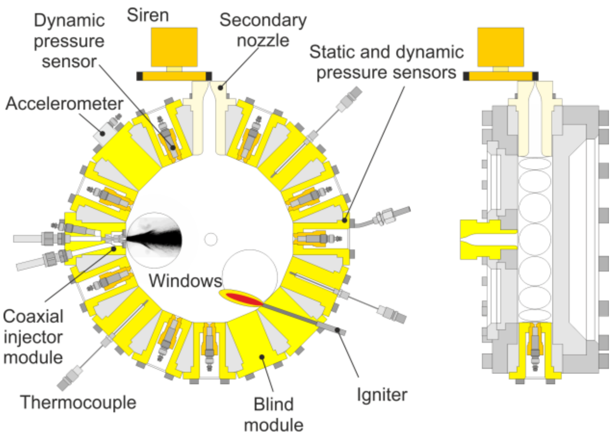

Figure 3. Illustration of the CRC

4.2. Combustor H

The experimental principle of the CRC was extended to more representative conditions with the development of Combustor H (BKH). This combustor was designed to be operated at the more powerful P8 test bench and is specially configured for the visualisation of rocket flame response to forced acoustic perturbations. The goal was to capture flame response phenomena on physical scales and under pressures relevant to real rocket engines, especially pressure levels above the critical pressure of oxygen.

The configuration of BKH, shown conceptually in Figure 4, was inspired by a similar experiment operated by ONERA [10] [11]. BKH has a rectangular cross-section and five shear coaxial injection elements clustered centrally. Operating conditions with LOx/H_2, such as injection temperatures, mass flow rates, and chamber pressure, are targeted to be representative of upper stage cryogenic engines. A siren is incorporated in the upper wall for acoustic forcing. Forcing at the frequency of the first transverse mode of the combustion chamber, around 4200 Hz, subjects the five flames to high amplitude, transverse acoustic velocity perturbations.

Multiple dynamic pressure sensors flush mounted in the chamber walls allow reconstruction of the acoustic field using the same principles as in the CRC. The recorded signals also allowed characterisation of the acoustic response of the combustor to different operating conditions [12]. Methods for measuring acoustic damping under noisy, high-power combution conditions were developed, and quantitative values were offered to the community [13] [14].

Optical access windows allow the flame response to acoustics to be observed in the near-injection region using simultaneous shadowgraph and flame emission imaging. Shadowgraph imaging has revealed significant response of the LOx core to transverse instability. The intact core shortens in length due to accelerated breakup and mixing driven by the transverse acoustic gas oscillations. As acoustic amplitude is increased, a change in the dominant breakup behaviour of the LOx core can be observed, and continuously decreasing intact core length was measured [15] [16].

Simultaneous OH* imaging shows corresponding change in the extent, emission intensity, and dynamics of the flame [17] [18]. This significant change in LOx core and flame character undoubtedly influences the heat release distribution and thereby its coupling with the acoustic field. Such details should be accounted for in system stability models, and the BKH experiment provides a database for validating such models.

The BKH experiment is also being modelled using the DLR TAU code flow solver. The goal of these modelling efforts is to investigate flame-acoustic interaction with higher fidelity and complete access to all locations within the flame. Steady-state flow field results have been coupled with an acoustic solver to improve the accuracy of modal frequency and distribution results. Unsteady RANS simulations are also conducted to reproduce the temporal response of the flame to transverse acoustic excitation. Results to date have demonstrated the ability to capture major aspects of the LOx jet response observed with shadowgraph imaging in BKH [19] [20]. These aspects of the experiment were also opened to the REST community to serve as a modelling workshop test case.

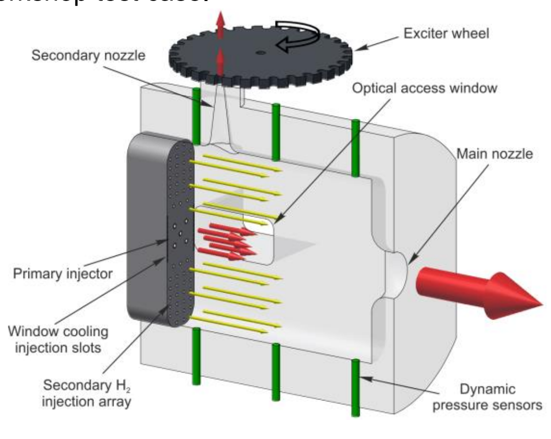

Figure 4. Conceptual illustration of BKH

4.3. Combustor D

The research Combustor D (BKD) is a multi-purpose, sub-scale rocket combustor operated with LOx/H_2 at the P8 test facility. With a conventional configuration, multiple injectors, and high operating power, it operates at conditions close to those of operational upper-stage engines. For certain operating conditions it exhibits spontaneous high frequency combustion instability acoustic resonance, and is a valuable test bed to investigate thermoacoustic phenomena under highly representative conditions.

As shown in Figure 5, BKD has a cylindrical combustion chamber with 80-mm diameter and 42 shear coaxial injection elements. It is operated with LOx/H_2 at chamber pressures up to 80 bar with a total flow rate of up to 6.7 kg/s and thermal power of approximately 80 MW. For certain operating conditions, the 1T mode amplitude grows to sustained amplitudes greater than 20% of the mean chamber pressure (peak to peak). The prediction of which operating conditions are stable and unstable was the goal of a test case for a REST modelling workshop.

For the measurement of chamber acoustics and flame dynamic response, a special measurement ring is installed between the injector head and the cylindrical segment. The ring, depicted in Figure 6, is equipped with multiple, flush mounted dynamic pressure sensors, thermocouples, and fibre-optical probes. The optical probes were specially developed by the DLR group to withstand the harsh conditions in real rocket engines, and have provided unique data from the naturally unstable flames in BKD.

The acoustic reconstruction routine developed for the CRC was successfully applied to the cylindrical configuration of BKD. The field reconstruction again revealed an active 1T mode as dominant in the instability, with dynamic and changeable rotational character. With increasing instability amplitude the mode tended towards a standing wave with a statistically preferred orientation. This indicates some asymmetry in the combustor system which defines an orientation for which energy transfer to the 1T mode is most efficient [21] [22] [23]. The as yet unidentified source of this preferred orientation may be key to understanding which design measures can influence the stability behaviour of full scale LPREs.

Optical probes in the measurement ring were connected to photomultiplier detectors to measure high frequency fluctuations of the flame radiation intensity in order to study the reaction of the combustion process to acoustic pressure oscillations. The fluctuations of emission intensity show dominant frequencies corresponding to LOx post acoustic resonance frequencies, independent of chamber acoustics. Instability of the 1T mode occurs when one of the LOx post resonance frequencies coincides with the chamber 1T frequency [24]. This mechanism is not in line with the historically purported response of LOx posts to chamber acoustics found in literature. Thus, optical access has proved to be indispensable in understanding the mechanism of instability dominant in BKD.

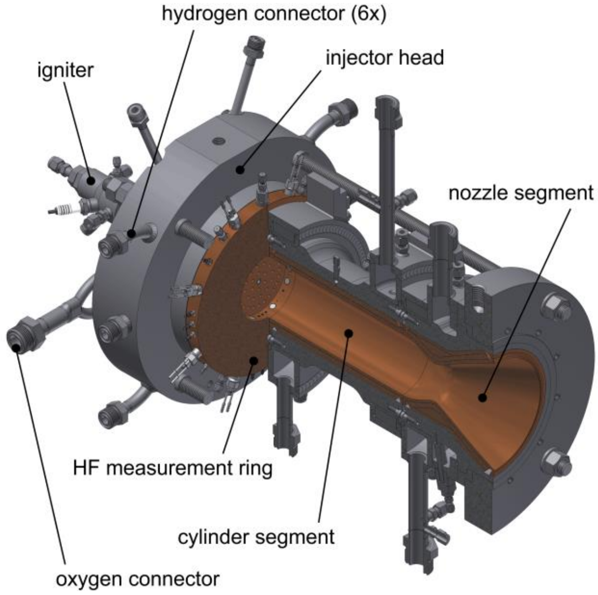

Figure 5. Illustration of BKD

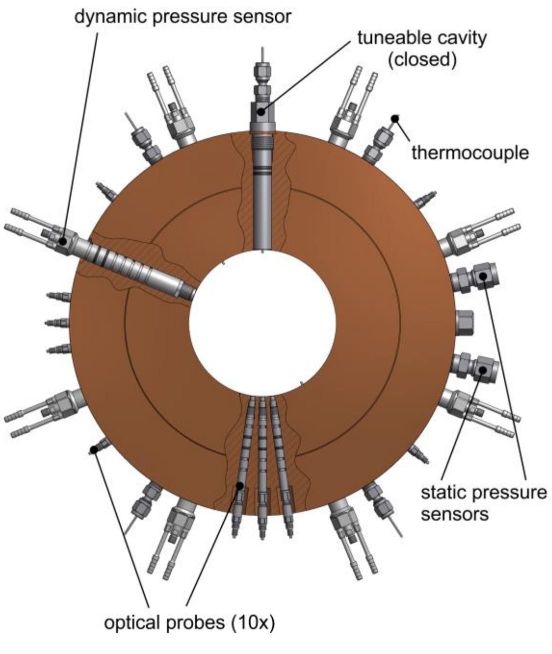

Figure 6. Measurement ring in BKD

5. LEHRSTUHL FÜR THERMODYNAMIK, TUM

As explained before, a multifaceted approach is employed to investigate combustion instabilities and develop efficient assessment tools at the Lehrstuhl für Thermodynamic at TUM. In order to investigate the coupling mechanisms between combustion and acoustics as well as to derive flame transfer functions (FTF) for later usage in hybrid approaches, a single flame excitation methodology has been developed. Using a radial compactness assumption a single flame configuration is subjected to purely varying pressure and only insignificant fluctuating velocity contributions by considering a flame located in the pressure antinode. The excitation is realized through source and sink terms at the boundary of the virtual single flame domain. In turn, the response of combustion to velocity fluctuations is studied for a single flame configuration located in the velocity anti-node. Due to the absence of relevant pressure fluctuations the effects of displacement are investigated. The single flame excitation methodology has been used to analyze the flame dynamics for subcritical combustion in [25] [26] and for supercritical combustion in [27] showing reasonable results and indications of relevant coupling mechanisms.

For the validation of the simulated FTF, experimental data is required. For this purpose, the Lehrstuhl für Thermodynamik explores the possibilities of using flame radiation data. In particular, it is investigated whether OH* radiation can be used as a marker of the fluctuating heat release rate for the non-premixed flames in rocket engines [28]. These investigations are performed on the basis of laminar counter-flow diffusion flames under high pressure conditions. Figure 8 shows a schematic sketch of the experimental high pressure burner. The transfer to turbulent combustion in the chamber is realized with the flamelet combustion modeling approach. However, not only the applicability of OH* radiation but also the properties of the so-called Blue Radiation are analyzed [29]. Results show that the Blue Radiation provides modeling advantages due to negligible self-absorption.

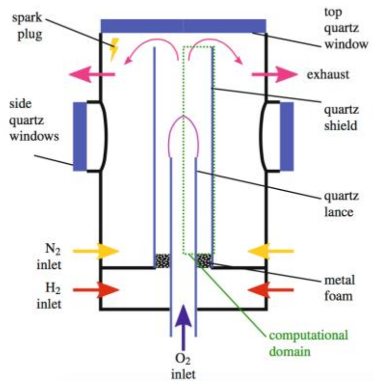

Figure 7: Schematic drawing of the experimental high-pressure burner [28].

For the generation of validation data in order to test the acoustic simulation tools, experimental procedures under non-reactive conditions are performed. The non-reactive test configuration is shown in Figure 8. To deepen knowledge about quarter-wave absorbers to damp transverse modes, a cold-flow setup with air at ambient conditions is used at the Lehrstuhl für Thermodynamik with representative inlet and outlet conditions. Using dynamic pressure measurement data, frequency response plots show the occurrence of additional modes for all cavity lengths considered *[30].*

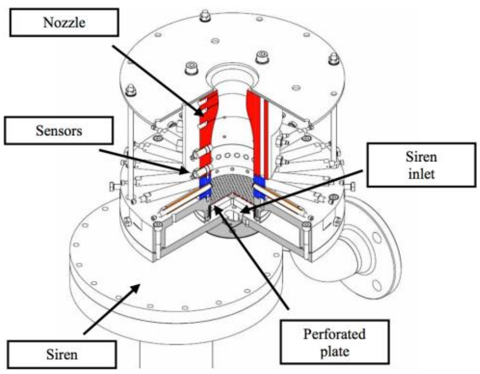

Figure 8: Non-reactive test configuration

The 1T peak decomposes into the 1T- and 1T+ peaks, confirming the observations made during former investigations by other groups [31]. The change of mode frequencies is interpreted as mistuning of the chamber acoustics.

The same test rig is used to determine the damping contributions from the nozzle. It could be shown that the nozzle acts as a strong damping device for longitudinal modes and the first transverse mode, in turn, is damped significantly less [32]. In consequence, unstable rocket engine configurations are usually subjected to higher-order mode amplitudes.

It is unlikely that stability of rocket engine configurations is based on the weak nozzle damping capabilities for higher-order modes exclusively. Additional damping mechanisms can be found in the region of injection. Here, stratified flow conditions interact with transverse acoustic mode fluctuations. At TUM-TD different investigations are conducted to analyze the relevance of stratified flow conditions in terms of damping. For a perforated plate configuration and a Mach number of 0.4 in the holes, strong damping rates are found for the first transverse mode. This configuration served as a test case for a REST Modelling Workshop [33], where the damping properties of perforated plate geometries were systematically investigated for longitudinal waves showing high losses of acoustic mode energy for a Mach number as low as 0.2. It is suggested that the damping stems from the transformation of acoustic wave energy into acoustic vorticity mode fluctuations, which are, in consequence, convectively transported out of the system.

The Lehrstuhl für Thermodynamik works on more efficient acoustic simulations tools. Recently, it was shown that frequency space transformed linearized Euler equations are very suitable for the prediction of acoustic propagation with low amplitudes in the rocket thrust system [34] [35] [36]. Currently, the frequency space LEE are subjected to further intense validation. For validation purposes, the DLR's BKD test combustor is used. Furthermore, the possibilities to describe the acoustic propagation at higher amplitude is revealed. Non-linearity is gradually incorporated in terms of flame dynamics, acoustic propagation and further non-linear models of dome coupling and absorber devices. Finally the relevance of each non-linear component is evaluated on the basis of experimental data recorded in high pressure limit cycle conditions.

6. PROGRAMMATIC STRUCTURE

Ongoing HF research requires dedicated research funding. Funding programs in the field generate progress and provide a mechanism for monitoring activities. The most important research programs are briefly described below.

6.1. Piano-Sat

The Piano-Sat program constituted an important basis for development of sophisticated tools for the simulation of HF combustion stability. The Program was conducted in a partnership between TU München and Airbus DS funded by DLR under reference 50RL1040.

Over the course of 3 years, a method and a tool was developed which simulates combustion instability processes. Two Ph.D. students worked in close cooperation with Airbus DS at TUM and successfully developed the Tool Piano-Sat. The tool uses a method that separates the characterization of the flame dynamics from the acoustic calculation. Similar approaches are known from the Gas-Turbine industry, and according to common practice, the characterization of the flame is named Flame Transfer Function (FTF).
The tool represents a state of the art approach that was successfully developed in close partnership between industry and academia.

6.2. Tares

Tares is a DLR co-funded research program with a duration of 4 years. It is the successor of the Tekan (Technologie für kryogene Antriebe – Technology for cryogenic propulsion) and Telan (Technologie für Lagerfähige Antriebe – technology for storable propulsion) programs in a series of DLR projects. It constitutes the framework for a multitude of rocket propulsion related topics, for example combustion modelling and turbupump technology, and combustion stability. The Tares budget constitutes the basic funding that permits the tracking of international activities in combustion stability research. In the frame of this project, several low order tools for basic applications have been developed. Presently, Tares grants the funding for exchange platforms like Propulsion 2020 and REST.

6.3. Propulsion 2020

Propulsion 2020 is an exchange platform between DLR and industry. It has been established in 2012 to permit an uncomplicated exchange of research results and data in a national context. This holds true especially for DLR funded, national technology development programs. The set-up eases the discussion on sensitive and nationally funded topics and significantly improves the collaboration of DLR and Airbus DS. Regular meetings are held and permit quick discussion on recent results. Propulsion 2020 does not provide funding but a formal framework for exchange and discussion in a protected environment

6.4. SFB

The Special Research fund Sonderforschungsbereich (SFB) trans-regional topic 40 (TRR40) is administered by the Deusche Forschungsgemeinschaft (DFG) and encompasses a variety of institutions. It aim is to develop the technological basics for the design of thermally and mechanically highly stressed components. There are different groups of sub-projects focusing on topics such as structural cooling, combustion chamber, nozzle, and thrust chamber. Within the combustion chamber group, there is a dedicated topic on combustion stability. Two sub-projects from TUM and DLR address system stability modelling and experimental stability characterization, respectively. Furthermore, acoustic absorbers and their thermal balance is addressed in a sub-project which is part of the structural cooling group [37].

6.5. REST

REST is a Franco-German Network that was founded in 2000 to foster international exchange and to coordinate activities in HF research. It includes most major players in this field in France and Germany, such as Airbus DS, Safran, DLR, CNES, and many research institutions [38].
Regular scientific workshops are held in rotating order. In these workshops, current research results and relevant achievements and data are communicated and shared.
Every 2-3 years modeling workshops are organized. In the modeling workshops dedicated test cases are defined from experiments operated by REST members and occasionally invited international guests [39] [40]. The members and associated institutions are invited to treat these cases in order to demonstrate progress in modelling and permit benchmarking.
The cases to date have included purely acoustic cases where the participants can show their ability to handle complex, turbulent and high Mach number acoustics. Other test cases involve the calculation of acoustically forced flames and also naturally oscillating combustors.

6.6. Overview

The following graphic (Figure 9) visualizes the interconnection of the different research partners in Germany in a simplified way.

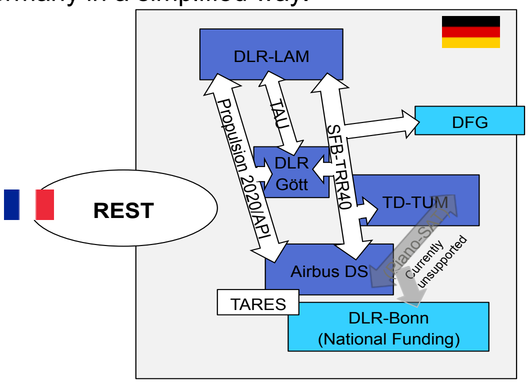

Figure 9. Simplified research Network in Germany

7. TOOLS

7.1. Low Order Tools

Low order tools represent the classical approaches with their roots dating to the 1960s. They mostly rely on basic Bessel function solutions for a cylindrical domain (Figure 10). The combustion influence is characterized using the classical n-tau model by Crocco [4]. This is a straightforward implementation due to implementation in the time domain for the tools. Basic results include eigenfrequencies, eigenmodes and sensitivity to the combustion process.

The modeling, although based on the Bessel-functions, spans from pure, ideal cylinders to combustion chamber contours with mean flow and approaches that permit the estimation of absorber effectiveness.

The most basic model is based on Sirignano's approach in NASA SP194 [1]. Using Bell-Zinn's method for the calculation of nozzle admittances [41], the NASA method can be run with a realistic nozzle model. Furthermore, the Bell-Zinn algorithm has been extended and now can be used to calculate combustion chamber eigenfrequencies [42]. Using a face plate admittance model including Crocco's n-tau model [4], the stability of a system with concentrated combustion can be examined.

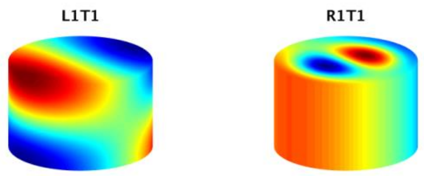

Figure 10. Analytical Solution for different eigenmodes of a cylinder

When absorbers are used (Figure 11), the very simple models become inaccurate because the absorber modifies the internal acoustic field of the combustion chamber. For this case, Mitchell [43] has developed an approach which again uses the basic cylinder functions. However, in this case, they are used as basic functions to construct the solution. In combination with a n-tau model, quick stability examinations and trends can be calculated.

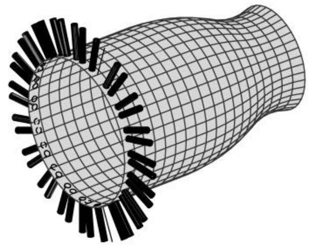

Figure 11. Sketch of a combustion chamber with acoustic absorbers

7.2. Hybrid Tools

Hybrid methods separate the coupled system into sub-problems which are individually easier to handle. In the present context a hybrid tool has been developed in the frame of the aforementioned Piano-Sat Project [44]. The main idea is to separate the calculation of the flame dynamics from the acoustic calculation.

The flame dynamics are calculated using CFD and a single flame in representative boundary conditions. This saves computational power because the entire engine can have several hundreds of injection elements. Therefore, a full CFD would be computationally extremely expensive.

The characterization of the flame is done by using a transient CFD simulation of the single flame. In the simulation, the flame is exposed to pressure fluctuations and heat release response is recorded. By relating the two, a FTF can be established that replaces and represents the flame later in the acoustic calculations.

For the acoustic calculations, two different approaches have evolved. At Airbus a time domain solver based on Piano is used. This solver, Piano-SAT, permits complex 3-D geometries as well and admittance boundary conditions [45]. Furthermore, it can handle high Mach numbers. The FTF is included via a filter source term. The calculation is then excited using a single pulse and the oscillations are recorded over time. Post processing methods like FFT or DMD are used to identify eigenmodes and growth rates.

The Lehrstuhl für Thermodynamik also develops an alternative approach to the time domain description. Frequency space transformed linearized Euler equations provide shorter turnaround times of the simulations and filter representations of the FTF are not required ([34]).

7.3. CFD approaches

At DLR, the ability to study thermoacoustic phenomena in rocket engines with CFD based approaches is being developed. Researchers at the DLR Institute of Aerodynamics and Flow Technology are extending the DLR TAU code flow solver for rocket propulsion applications.

The DLR TAU code is a three-dimensional, finite volume, Navier-Stokes flow solver based on hybrid structured / unstructured grids. The TAU code is validated for and applied to a wide range of flow conditions covering subsonic to hypersonic and high-enthalpy flows as well as combustion problems. Its extensions for reacting flow and combustion applications include models to perform chemical and thermal equilibrium and non-equilibrium computations for multi-species flows with detailed reaction mechanisms. These extensions include models for the chemical source term (based on the law of mass actin), the interaction of turbulence and chemistry (assumed-PDF), for multi-species diffusion, and for real-gas equations of state [46].

The researchers in the Combustion Dynamics group at Lampoldshausen are modelling the BKH experiment as a test case for TAU. By simulating the BKH configuration and comparing with experimental results, the ability of the model to capture high amplitude acoustics and rocket flame response phenomena is being examined. A validated model could in future be used to predict the stability of real engine configurations.

8. SUMMARY

The research activities for HF combustion stability in Germany are mainly carried out by DLR, TUM and Airbus DS. The limited amount of participants permits an efficient and coordinated usage of the available funding and workforce. On the other hand, the research activities are limited to a small number of approaches and relevant topics.

A portfolio of different tools and data has been built by the participants. The focus is on industrial applicability and relevance.

In the future, the national arrangement is expected to change somewhat due to the formation of the Airbus Safran Launchers joint venture. It will lead to bi-national departments and the direct exchange between former Safran and former Airbus methods will lead to a consolidation of approaches in treating HF stability. The French partners have invested great resources in high end numerical simulation. The combination of these CFD methods with hybrid methods like Piano-Sat will be examined. The present network has proven to be efficient and productive. The authors are therefore optimistic about future progress.

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HF Combustion Stability - Research Activities in Germany

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Space Propulsion Conference, Rome, 06.05.2016

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AIRBUS DEFENCE & SPACE

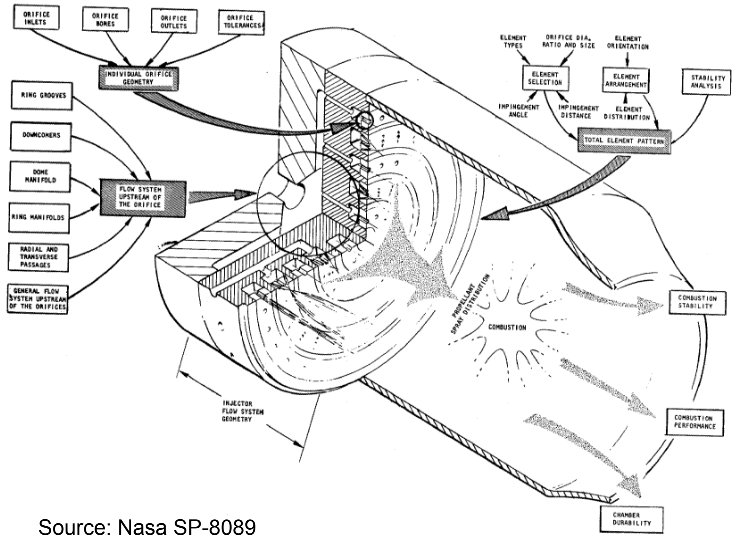
Outline

- Introduction
- Major Institutions
- Activities
- Programs
- Summary

Introduction

What are Combustion Instabilities?

- Are an oscillation fed by combustion heat release and resonating in the combustion system
- Can affect different portions of the combustion system
- HF combustion instabilities are located within the combustion chamber



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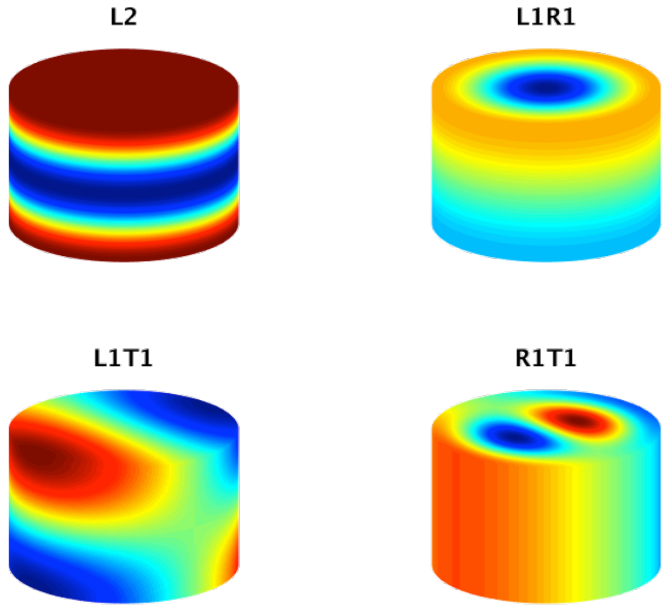


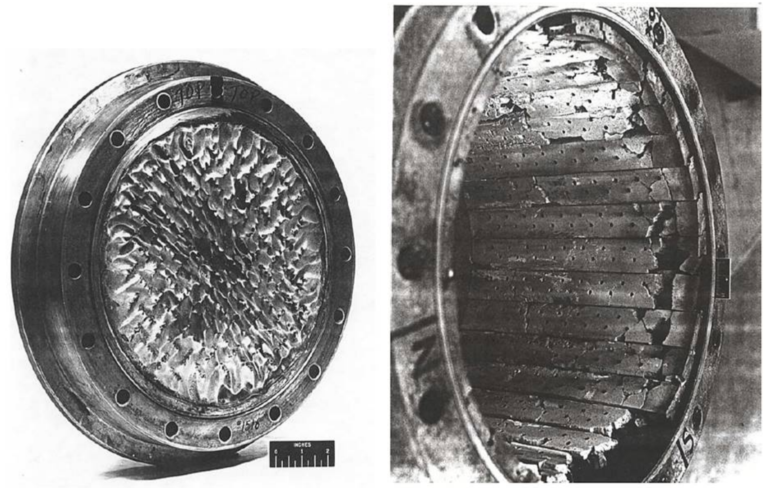
Introduction

Why are Combustion Instabilities of Interest?

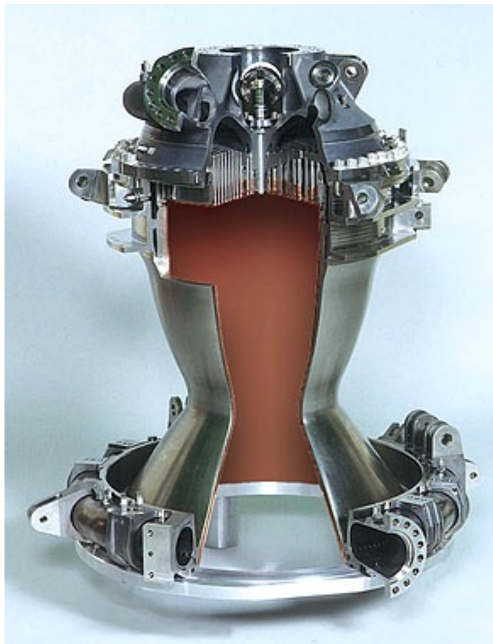
- They can destroy rocket combustion chambers in fractions of seconds
- Combustion Instabilities are still hard to predict
- They usually are detected in tests and therefore eliminating them is costly and time consuming

What is the relevance for Germany?

- Germany is interested in liquid rocket propulsion
- Ariane 5's thrust chambers are manufactured in Germany
- HF Combustion instabilities are inherent thrust chamber issues



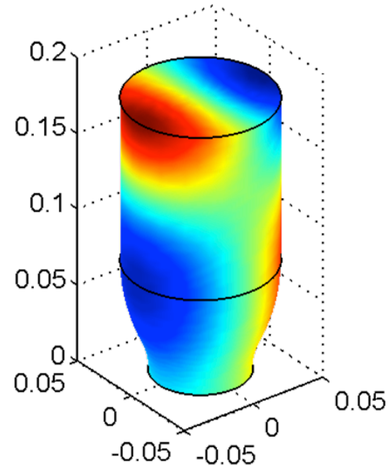
Source: Yang and Anderson 1995

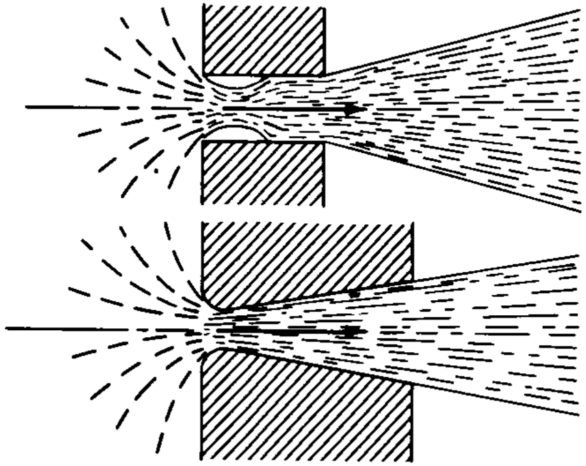


What knowledge do you need

- Acoustics of the combustion chamber
  - Variable temperature
  - Variable composition
- Flame dynamics
  - Atomization
  - Mixing
  - Chemistry
- Data for validation
- Smart approaches for industrial needs

➔ Subject of research





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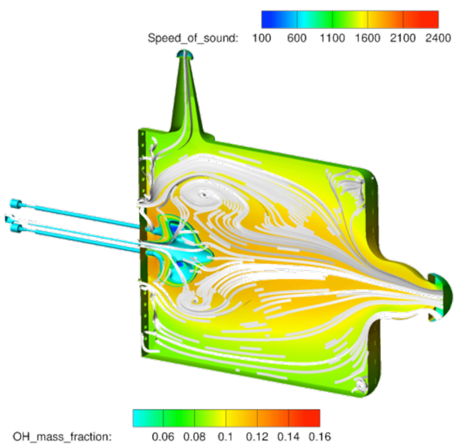
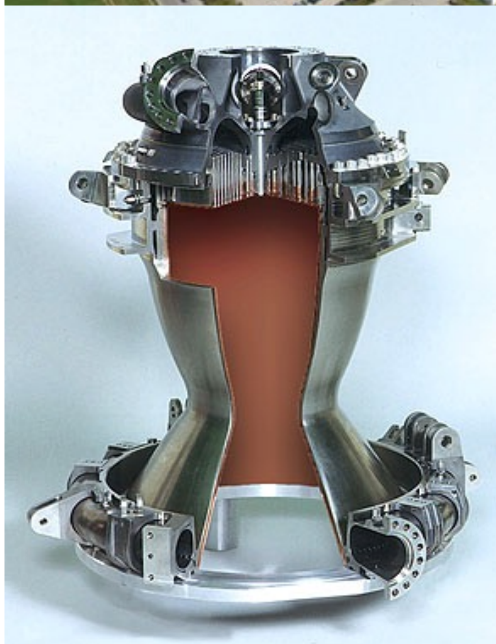


Airbus Defence and Space Ottobrunn

- Part of Airbus an international aerospace and defence company
- Manufactures Thrust chambers for Ariane 5
- Invests in R&D in the field of Liquid Rocket Combustion
- Presents heritage in both storable and cryogenic rocket combustion with valuable data and experience
- Has developed a tool portfolio around HF combustion stability
- To be part of Airbus Safran Launchers



AIRBUS DEFENCE & SPACE

DLR

German national aerospace research institution, space agency, and project management agency
Lampoldshausen site: Institute of Space Propulsion
Rocket Propulsion research department

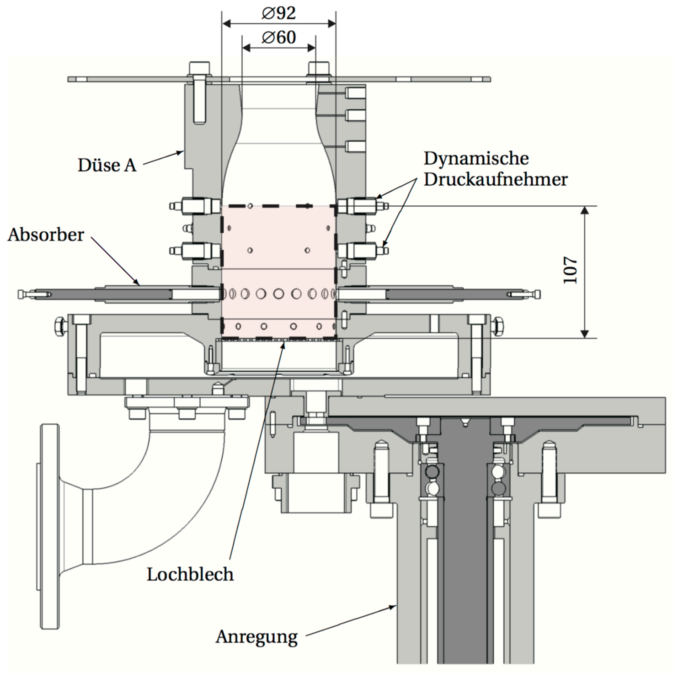
Research portfolio

- High pressure combustion
- Injector performance
- Atomisation and combustion
- Ignition methods and processes
- Heat transfer and cooling methods
- Materials and manufacturing processes
- Transient flow phenomena
- LOX/H_2, LOX/CH_4 propellants
- Nozzle flow
- Combustion instabilities

AIRBUS DEFENCE & SPACE

TUM

- One of the leading technical universities
- Intense and dedicated research in the field of combustion instabilities at School of Thermodynamics (Lehrstuhl für Thermodynamik)
- Heritage from gas turbines and history in liquid rocket propulsion
- Development partner for Piano-Sat combustion stability code
- Laboratory facilities and numerical capabilites
    - Comsol
    - Piano-Sat
    - CFX



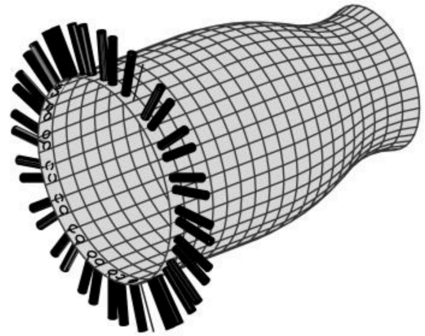
Source: Dissertation R. Kathan, TUM

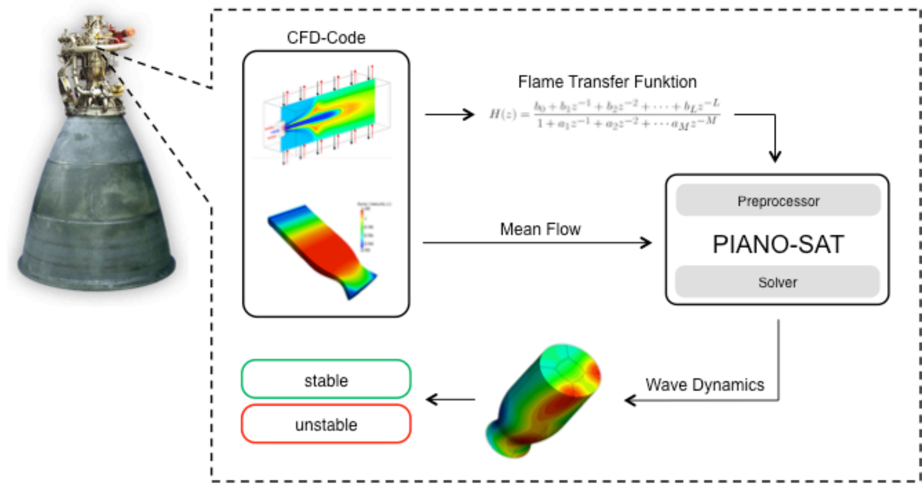
Adapted from: United States Department of Energy - http://www.netl.doe.gov/scng/projects/end-use/at/images/at31176

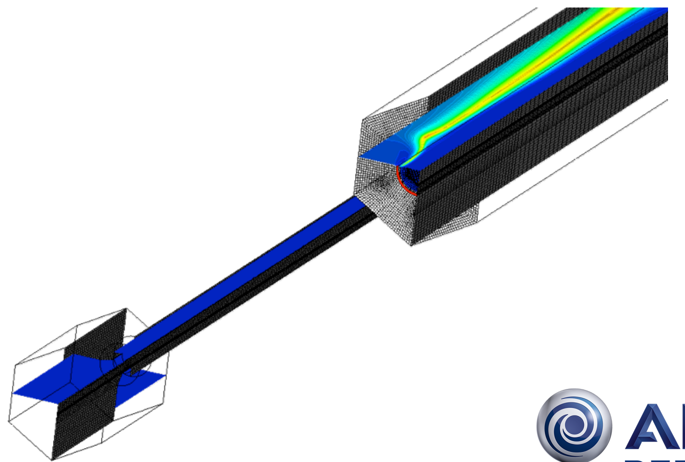
AIRBUS DEFENCE & SPACE

Industrial Activities

- Airbus DS does continuous testing and hosts a large database
- Pre-development tests new technologies and propellant combinations
- Heritage in storable and cryogenic propellant combinations
- Dedicated tool set for the assessment of combustion chamber acoustics
- Tools for the evaluation of stabilization devices
- Tools for evaluating flame dynamics
- Continuous R&T

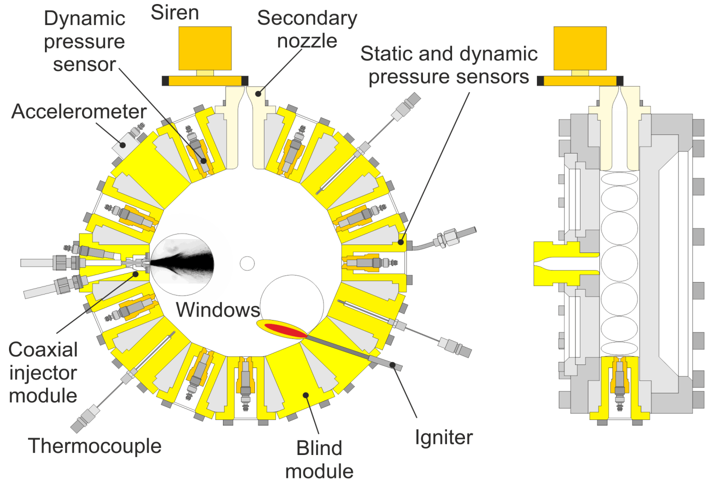




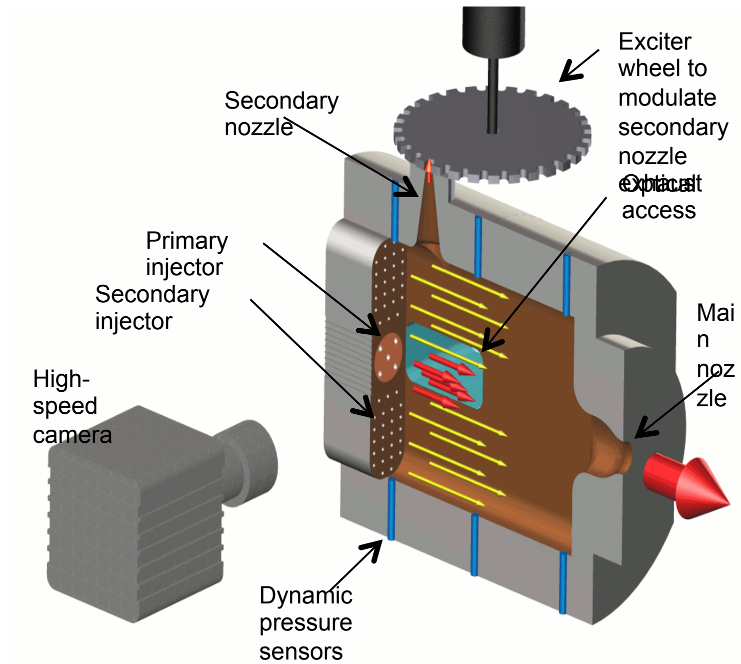


DLR Activities

- Common Research Chamber
  - REST development
  - Lab-scale combustor for visualising flame-acoustic interaction
  - LOX @ 77K, GH2 or CH4 @ 280K, p_c up to 10 bar
  - Radial injection, optical access
  - Secondary nozzle with siren for acoustic excitation



- BK H
  - Extension of CRC flame response visualisation work to representative conditions and multiple injectors
  - LOx/H_2 propellants (H_2 ~ 290 or 50 K)
  - 5 shear-coaxial elements, VINCI scale, matrix pattern, tight spacing
  - Chamber pressure 40 bar (subcritical) to 60 bar (supercritical)

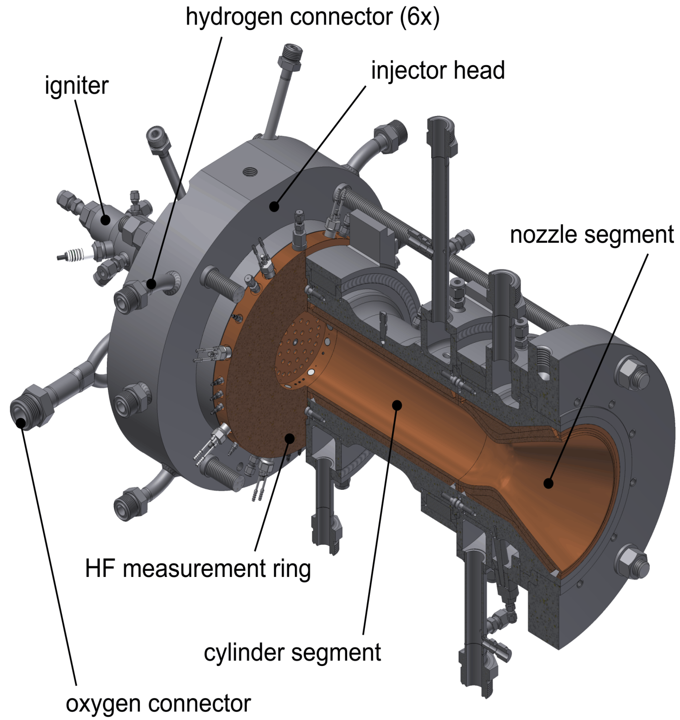


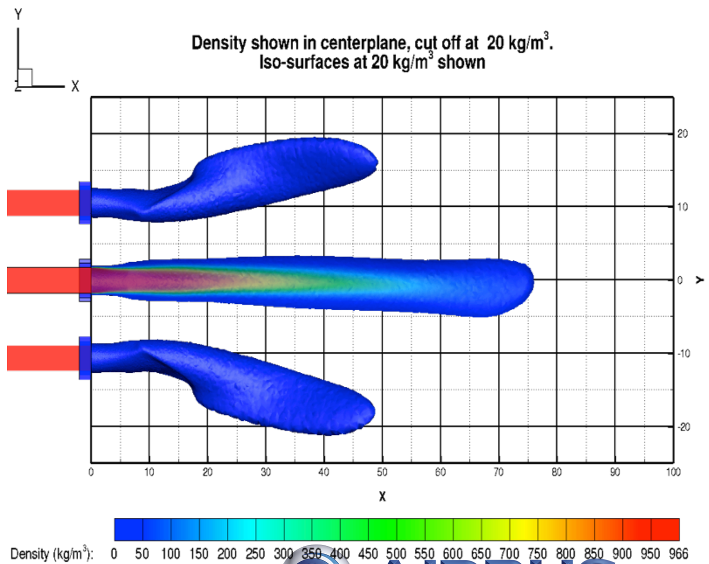
AIRBUS DEFENCE & SPACE

DLR Activities

- BK D
  - Investigation of self-excited instabilities under representative conditions
  - 80 mm diameter, 42 elements
  - LOx/H_2 propellants (LOx ~ 110 K, H_2 ~ 40 - 290 K)
  - Chamber pressure up to 80 bar
    - Mass flow rate up to 6.7 kg/s
    - Thrust 25 kN
    - Power 80 MW
  - Measurement ring with dynamic pressure sensors and optical probes
  - Self-excited 1T mode for particular operating conditions, amplitudes up to 26% of p_c (peak to peak)

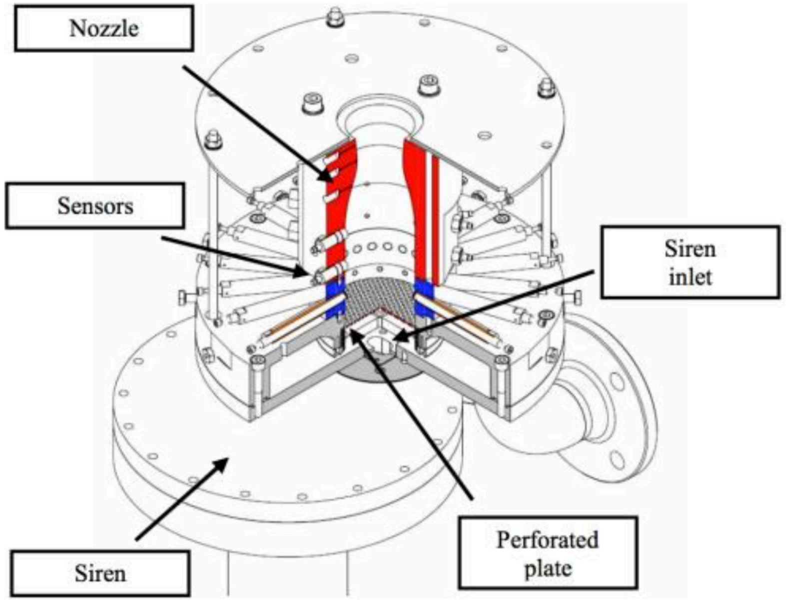
- Modelling
  - Develop DLR TAU code for modelling thermo-acoustic phenomena
  - Use model to explore flame-acoustic interaction
  - BKH as test case for validation
  - Acoustic and optical measurements

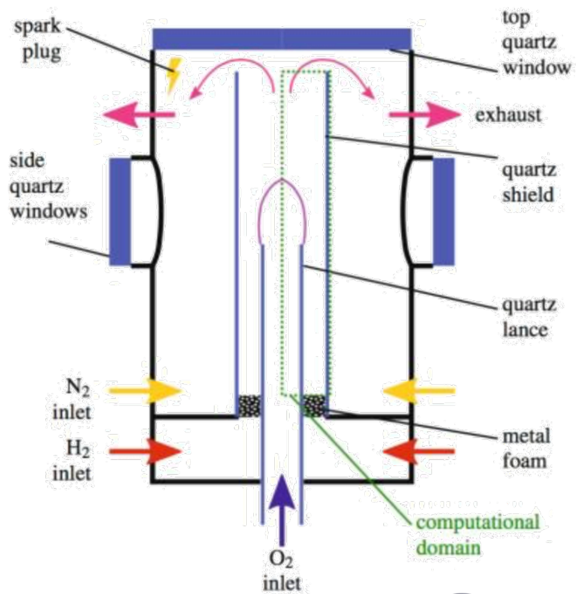




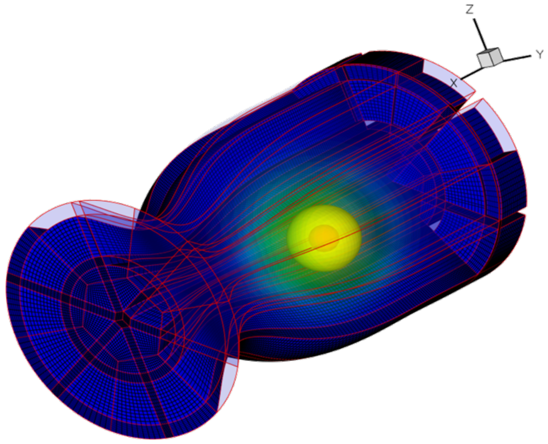
TUM

- The School of thermodynamics (Lehrstuhl für Thermodynamik) has a well developed know how in different field of combustion instabilities
- Provides a research portfolio stretching from non reactive acoustic tests to advanced numerical simulation
- Basic research on flame dynamics quantification in high pressure, high temperature environments
- Development of the Piano-Sat and a Comsol based code for combustion stability modeling





Programs R&T



Piano-Sat

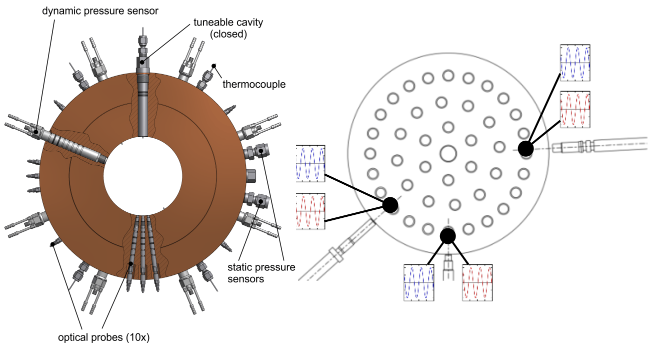
- DLR funded project between TUM and Airbus DS
- Industrialization of a stability prediction code

TARES

- DLR Co-funded R&T Program at Airbus DS for various aspects of LRE issues.
- HF presents one work package of this program

SFB – TRR 40

- Special research initiative
- DFG funded research network comprising various universities for modeling rocket propulsion issues.
- HF combustion is subject to work packages mainly including TUM



AIRBUS DEFENCE & SPACE

Programs – Coordination and Exchange

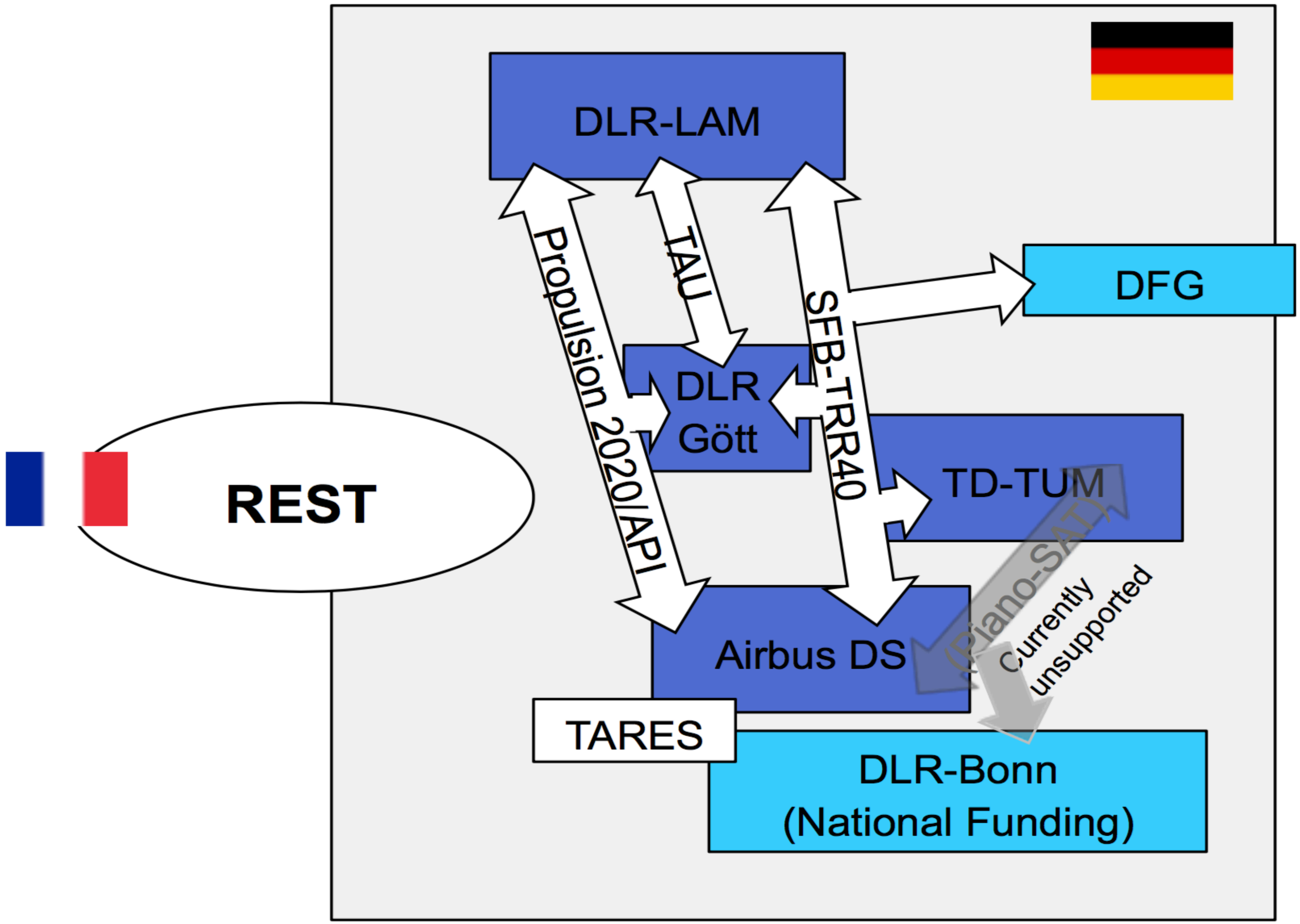
Propulsion 2020

- Exchange platform between DLR and Airbus DS
- Regular meetings
- NDA protected environment also for “hot” topics

REST

- German French instability program
- Forum of coordination and benchmarking
- Regular meetings and workshops

Network overview



Summary

- There is a concentrated research activity in Germany in the field of HF combustion stability
- Several institutions provide input and participate
- The experimental side is well established
- State of the art code development is conducted
- Exchange with the French colleagues is promoted and performed within REST
- The formation of Airbus-Safran Launchers will foster this exchange