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Exploration of combustion instability triggering using Large Eddy Simulation of a multiple injector liquid rocket engine

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ABSTRACT

This article explores the possibility of analyzing combustion instabilities in liquid rocket engines by making use of Large Eddy Simulations (LES). Calculations are carried out for a complete small-scale rocket engine, including the injection manifold thrust chamber and nozzle outlet. The engine comprises 42 coaxial injectors feeding the combustion chamber with gaseous hydrogen and liquid oxygen and it operates at supercritical pressures with a maximum thermal power of 80 MW. The objective of the study is to predict the occurrence of transverse high-frequency combustion instabilities by comparing two operating points featuring different levels of acoustic activity. The LES compares favorably with the experiment for the stable load point and exhibits a nonlinearly unstable transverse mode for the experimentally unstable operating condition. A detailed analysis of the instability retrieves the experimental data in terms of spectral features. It is also found that modifications of the flame structures and of the global combustion region configuration have similarities with those observed in recent model scale experiments. It is shown that the overall acoustic activity mainly results from the combination of one transverse and one radial mode of the chamber, which are also strongly coupled with the oxidizer injectors.

1. Introduction

Combustion dynamics phenomena arise in many applications and in most cases have serious consequences on the operation of the system. When they occur in high performance devices like gas turbines, aero-engines or liquid rocket propulsion stages they often lead to failure and in extreme cases to the destruction of the system. In many situations, these dynamical phenomena result from a coupling between combustion and the resonant acoustic modes of the system. High frequency oscillations coupled by transverse modes enhance heat fluxes exceeding the nominal heat transfer rates and leading to melting of the chamber walls with a subsequent failure and in some cases, spectacular explosions of the propulsion system [1–3].

The fundamental understanding of the process leading to a combustion instability is attributed to Rayleigh [4] who indicated that the sign of the product of pressure fluctuations and unsteady heat release rate, integrated over a period of oscillation, defined the stability of the system. Unstable behavior may be obtained when this sign is positive. It was later shown that the Rayleigh index represented a source term in the balance of acoustic energy but that the practical use of this equation required an additional knowledge on the unsteady response of combustion. The instability problem became of considerable technical interest during the early development of high performance devices like jet engines, ramjets and liquid rocket engines. Much effort was expanded during that period to develop analytical tools in parallel with model scale and real engine investigations. It was soon discovered that instability was linked with delays that are inherent to the combustion process. This led to the sensitive time lag (STL) theory most notably developed by Crocco [5,6], Crocco and Cheng [7], Tsien [8], Summerfield [9], Marble and Cox [10] and their colleagues. In this theoretical framework the time lag is sensitive to the pressure and other state variables and this in turn translates in a dependance of the unsteady heat release rate with respect to the pressure which is usually expressed in terms of an interaction index n and a time delay τ. This "$n - \tau$" modeling has been widely used to examine the linear stability of engines but has remained essentially phenomenological because the values of n and τ are not known *a priori* so that the model only provides a global description of the underlying physical mechanisms driving unstable combustion.

The necessity to understand and control combustion instabilities in rocket engines led to many further studies generating a

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large amount of knowledge. Much of what was learnt was gathered in NASA's SP-194 report edited by Harrje and Reardon [11]. This document gives a comprehensive summary of the main findings and highlights the key parameters influencing the occurrence of combustion instabilities in liquid rocket engines such as the geometry of the thrust chamber which determines the resonant mode structures, the evaporation rate of the propellant droplets, the pressure loss through the injectors which governs the coupling with the propellants feed system *etc*. Much of the more recent effort in this field has been focused on gaining a better understanding of the fundamental processes controlling instabilities. A major difficulty in the prediction of combustion instabilities is that they are quite sensitive to minute geometric parameters such as lip thickness or recess for coaxial injectors. Small variations in operating conditions such as the mixture ratio, the momentum flux ratio, the temperature of propellants, the chamber pressure also have a first-order impact on stability. This is exemplified in a book edited by Yang and Anderson [3], in the monograph written by Culick [12] and in many further investigations. In the recent period, many studies pursue the analytical modeling of the driving mechanisms as for example [13–19] while new model scale experiments and scaling methods are reported in [20–31]. These experiments have provided novel information on the interaction between the combustion region and acoustic modes with much attention focused on transverse modes which are only weakly damped in thrust chambers and are consequently the most dangerous (the detrimental effect of transverse modes was already well recognized during the early period [11,32]). Much work has also concerned control methods involving damping enhancement with quarter wave cavities or Helmholtz resonators or baffles to modify the structure of resonant modes in the vicinity of the thrust chamber backplane and reduce its sensitivity to pressure and velocity perturbations (see for example [2,33–35]).

All these investigations provide new data and help engineering design but cannot be used at this stage for instability prediction. This is so because: (1) the fundamental processes driving combustion instabilities are still not well understood, underlining the need to identify them, (2) there is lack of numerical tools providing a high fidelity representation of the dynamical phenomena leading to instability and allowing predictive studies applicable in engineering design.

As the problem involves interactions between a range of physical mechanisms operating over multiple time and length scales the development of computational tools raises difficult challenges. The present article reports progress made in this direction on the basis of high-performance Large-Eddy Simulation in combination with computational acoustics. There are several original aspects in the present investigation:

- It is based on Large-Eddy Simulations (LES) of flows under supercritical conditions, *i.e.* operating at pressures exceeding the critical pressure of the injected propellants.
- Calculations are carried out in a representative configuration comprising a dome feeding a thrust chamber through multiple injectors.
- The system is investigated for both linearly-unstable and triggered self-sustained oscillations.

Moreover, a joint analysis with computational acoustics allows further interpretation of the LES data.

The study considers an experimental thrust chamber designated as the BKD comprising a large number of injectors and operated at the P8 test facility at DLR Lampoldshausen [28,29,36]. Self-excited combustion instabilities (CI) develop for selected load points at frequencies corresponding to the transverse acoustic modes of the chamber. The objective of the present investigation is to analyze the instability affecting the BKD by making use of a Large Eddy Simulation of the full engine, from the injection domes to the nozzle outlet. The calculations are also intended to provide an understanding of the physical mechanisms that lead to this transverse instability. The full 3D simulation provides insight on interactions between acoustics, turbulent eddies and combustion that could not be deduced from a simulation of a single injector or by simulating only a sector of this configuration.

At this point one may note that several studies of LES of unstable configurations can be found in the literature, which mainly consider longitudinal instabilities in liquid rocket engines (LRE) and azimuthal instabilities in aeronautical combustion chambers [37–42]. There are also studies of the coupling between transverse acoustic modes and single or multiple cryogenic flames [43–45], as well as 2D simulations of multiple-injector engines [46,47]. However, to the authors' knowledge, there are no LES studies on LRE transverse self-excited instabilities, in a full configuration. The present simulations are carried out with AVBP-RG a real gas version of the AVBP code in combination with the computational acoustics Helmholtz solver AVSP allowing a detailed identification of the system modes. Many combustion dynamics simulations have already been carried out with AVBP to investigate longitudinal or azimuthal instabilities (see [38,48–51] for some recent examples). Liquid rocket engine applications relying on AVBP-RG are less common. Calculations have been carried out to analyze the structure of cryogenic jets [52,53], the response of cryogenic jets and cryogenic flames submitted to transverse acoustic modulations [43,44] or to investigate the response of a multiple injector configuration modulated by an external actuator [45]. In this context, the present investigation constitutes the first attempt to analyze the possible triggering of self-excited transverse instabilities in a full LRE configuration. Beyond the scientific challenge, this computation also constitutes a high performance computation challenge because of the multi-scale nature of the configuration.

This article begins with a presentation of the engine configuration (Section 2), together with the set of operating conditions considered in the simulations. The two solvers used in this analysis are described in Section 3. The first (AVBP-RG) allows LES calculations including real gas effects while the second (AVSP) provides the acoustic eigenmodes of the system. Section 4 is devoted to the comparison of the two load points under well established steady state operation. The two operating points are then submitted to a perturbation in the form of a transverse mode to analyze the possible nonlinear triggering of the system (Section 5). This leads in one case to a sustained cycle of oscillation, which is analyzed in Section 6.

2. Configuration

The BKD is an experimental model liquid rocket engine developed at DLR Lampoldshausen, which operates under conditions representative of a liquid propellant rocket engine. The thrust chamber comprises 42 shear coaxial injectors and has a diameter of 8 cm and a length of slightly more than 20 cm. Geometrical details are given in Fig. 1, which also shows the injector pattern and the location of the experimental pressure transducers, C_1 to C_8 (Fig. 1(b)) and also displays a close-up view of one injector (Fig. 1(c)).

It is useful to recall that the critical properties of oxygen and hydrogen are respectively $p_{cr,O_2} = 50.4$ bar, $T_{cr,O_2} = 155$ K, $p_{cr,H_2} = 13$ bar, $T_{cr,H_2} = 33$ K. The chamber operates above the critical pressure of oxygen but the injection temperature of this propellant is well below the critical value so that the oxygen is in a transcritical form and its density is high and of the order of 1000 kg m^{-3}. On the other hand, the hydrogen injection temperature is above its critical value and it is injected in the chamber in a supercritical gaseous state. The two reactants, oxygen and