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Study of the acoustic damping in a nonreactive pressurized chamber combining experiments, simulations and modeling

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Abstract Acoustic damping, a key element for the accurate prediction of combustion instabilities, is studied in this work through the combined analysis of the NPCC test bench. This gaseous non-reactive test bench, developed for the study of acoustic damping in a coupled-cavity configuration, is composed of a dome, a chamber and 3 injectors. It mimics the geometry of a LRE in a simplistic way. An acoustic modulation at three different frequencies - corresponding to acoustic modes of the system - is achieved using a perforated wheel. Large Eddy Simulation (LES) properly reproduces the experimental pressure signal for the 3 cases. Then, a Reduced Order Modeling (ROM) approach is presented with a modal expansion, which retrieves numerical results in a linear framework.

Keywords Thermoacoustic · High-frequency · Instability · Liquid Rocket Engine · Large Eddy Simulation · Reduced Order Modeling · Damping

1 Introduction

Thermoacoustic instabilities within liquid rocket engines (LRE) result from a coupling between the dynamics of the injection, the combustion process and the propulsive system's acoustics. This long-standing issue [1] affects engine performance and may lead to its destruction. Several approaches exist to counter the appearance and growth of instabilities. Experimental tests on real-size engines make it possible to iteratively modify the combustion chamber's geometry to shift the modes' frequency or modularize their structures, as during the development of the F-1 engine [2]. Large Eddy Simulation (LES) allows an analysis of the phenomena at stake to understand the flame response under acoustic perturbation, the coupling between the combustion chamber and the injection system [3]. A first try to characterize the acoustic damping in a 2D LES has been presented in [4]. Nevertheless, although having made significant progress, LES still requires time and resources, ill-suited for engine design loops. Thus, reduced order modeling (ROM) strategies have emerged in recent years, aiming to reduce the need for long and costly hot-fire tests or LES [5]. However, mechanisms and coupling involved in combustion instabilities being still not well understood, experimental lab-scale tests and LES are still required to study the engine dynamics as a prerequisite and in order to feed the ROM solvers.

Although combustion models exist accounting for the unsteady rate of heat release under transverse acoustic solicitations, few studies offer a precise analysis of the mechanisms underlying the damping process. Within the New Pressurized Coupled Cavities (NPCC) experimental setup developed by Laboratoire EM2C in the framework of a collaboration with CNES and ArianeGroup, a three-injector cold-flow test rig mimicking the geometry of a LRE [6] presented in Sec. 2, the competition between damping and excitation is first reproduced using LES computations (see Sec. 3). Then a reduced-order representation of this test bench using a Galerkin modal expansion methodology proposed in the StaHF code (Stability High Frequency) [7] is derived (see Sec. 4).

2 Experimental setup

Geometry The NPCC test rig is the latest evolution of the setups developed at EM2C to investigate acoustics in cavities and injector dynamics, conceived and operated during the PhD thesis of Manuel Gonzalez-Flesca [6]. The rig was designed to mimic the geometry of a LRE in a simplistic but well-controlled manner. It is composed of a dome and a chamber linked by three injectors, 6 mm in diameter. The chamber features three sections that can be assembled or removed to modulate the length and therefore the acoustic eigenfrequencies of the rig. The dimensions were set to allow for a coupling between the dome and the chamber. The air flow enters the system by a pipe located on the side of the dome, perpendicular to the injectors. Two nozzles at the end of the chambers allow the flow to exit the rig. It is brought to an operating pressure of 3.5 bar. The total mass flow rate is $\dot{m}_{tot} = 3.1g/s$. Fig. 1 presents a transverse cut of the rig, with the location of the pressure sensors. The probes are located to be either at a node or an antinode of pressure, depending on the excited mode.

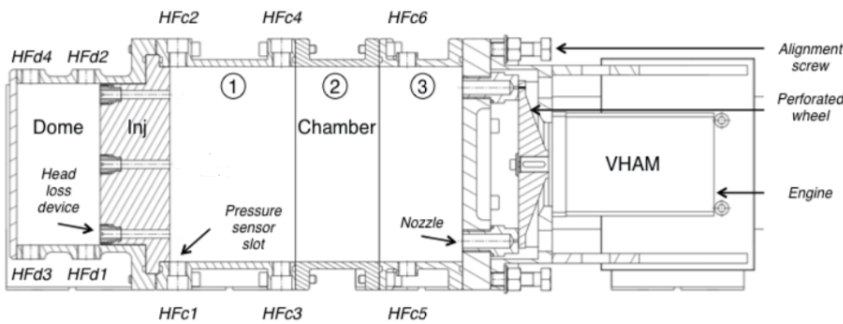


Fig. 1: Schematic cut of the NPCC test rig equipped with the VHAM

Mode	1T	1T1L	1T2L
Experiment	1227 Hz	1465 Hz	2002 Hz
AVSP	1226 Hz	1469 Hz	2036 Hz

Table 1: Modal frequencies found in the experiment and using the Helmholtz solver AVSP from Cerfacs

The acoustic modulation is achieved using the Very High Amplitude Modulator (VHAM) [8]. A fully perforated wheel is used for continuous modulation of the eigenmodes of the rig. The VHAM is placed at the system's exit, for the wheel to block alternatively one nozzle or the other.

Cases studied Three experimental cases are reproduced here with LES: continuous modulation of mode 1T (fully transverse), 1T1L (transverse and longitudinal components with coupled dome and chamber) and 1T2L (transverse and longitudinal components, uncoupled). It is critical to pinpoint precisely the eigenfrequencies (Table 1). The experimental results were obtained by Gonzalez-Flesca [6] using a sweep over the excitation frequency. The frequencies retained for the numerical study were obtained with the Helmholtz solver AVSP from Cerfacs [9]. They are close to the one found in experiments.

3 Large Eddy Simulation

Setup The AVBP code from Cerfacs and IFPEN is used [10]. A dissipative Two-Step Taylor-Galerkin (TTGC) numerical scheme, third order in time and space, is used [11]. Subgrid-scale momentum fluxes are modeled by the Wall Adapting Large Eddy (WALE) model [12], well suited for shear flows, with eddy-viscosity vanishing in purely strained region of the flow. Compared with the experimental geometry (Fig. 1), the exit nozzles are smoothed to avoid sharp corners in zones of high velocity. Two meshes (labeled coarse and fine) are used for modulated cases which require a long physical time (at least 150ms) to reach the limit-cycle (Fig. 2). Table 2 summarizes the mesh details.

At the inlet, speed and temperature are imposed in a soft way with a relaxation method. At the outlet, pressure is imposed in a soft way, with a superimposed sinusoidal acoustic wave to represent

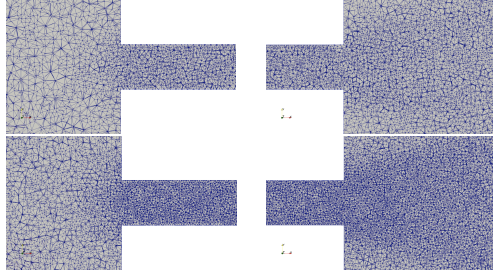


Fig. 2: Meshes used, transverse cut, zoomed-in around the central injector. Left: Injector inlet; right: injector outlet. Top: coarse mesh, bottom: fine mesh

Mesh	Coarse	Fine
Nb. of nodes ($\times 10^6$)	2.1	6.7
Min. cell vol. [m^3]	5.37×10^{-12}	1.03×10^{-12}
Time step ($\times 10^{-6}$ [s])	0.27	0.18
CPU [h] for 10ms	750	3700

Table 2: Mesh information

the excitation by the VHAM for modulated cases. An analytic study (not detailed here to limit the paper length) determines with a reasonable precision the amplitude of the acoustic modulation as a function of the mean chamber pressure : $p'_{max} = 0.45$ bar. The mean pressure at the outlet, 2.95 bar, represents the situation when both nozzles are half-opened. The nozzles are equipped with slippery walls to limit the headloss in the vicinity of the outlet where the excitation takes place. Two boundary conditions are tested for the injectors: adiabatic no-slip walls with zero velocity and walls equipped with an adiabatic wall function for imposing the wall shear stress.

Influence of the grid resolution and injector's boundary condition is tested by computing a case without modulation on the coarse and fine meshes. In addition, the mesh adaptation strategy described by Davillier et al. [13] is used to obtain local mesh refinement in critical places such as the inlet and outlet of each injectors. It is found that the coarse grid equipped with law of the wall boundary conditions was able to retrieve jet topology and injector head loss close to the ones found on finer grids.

Results Mode shapes are correctly retrieved by the LES compared to the AVSP results (Fig. 4). The LES signals are very close to the experiments (Fig. 3), highlighting the capacity of the LES to reproduce the competition between excitation and damping in this configuration, without any adjustments from the user. Very similar results are found when computing the case on the fine mesh, ensuring grid independence. The implementation of disturbance energy budgets [14] in the AVBP code gives insight on the contribution of each phenomena responsible for the acoustic damping in this configuration. The final goal is to develop damping models for the reduced-order approach presented below.

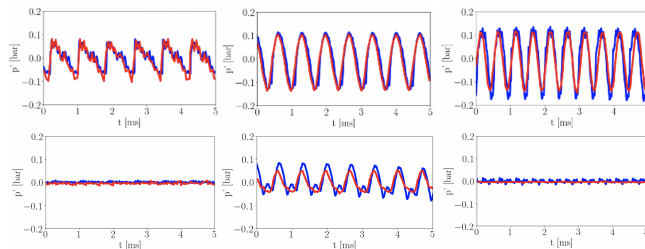


Fig. 3: p' at HFc1 (chamber, top) and HFd1 (dome, bottom), LES on coarse mesh (high-pass filtered); Experiment (high-pass filtered). Left: 1T, Mid: 1T1L, Right: 1T2L

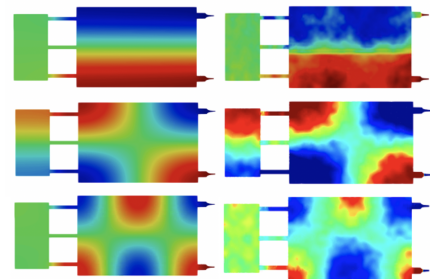


Fig. 4: p' , Transverse cut, LES on a coarse mesh (left) and AVSP solution (right), red: +0.1 bar, blue: -0.1 bar. Top: 1T, mid: 1T1L, bot: 1T2L

4 Reduced Order Modeling

Galerkin modal expansion StaHF (Stability High Frequency)[7], the reduced order modeling tool developed at EM2C, is based on a Galerkin modal expansion, first introduced by [15] and extensively discussed in [16]. The acoustic pressure variations $p'(\mathbf{x}, t)$ are projected onto the acoustic eigenmodes orthogonal base $(\Psi_n)_{n \geq 1}$ such that, considering N modes, $p'(\mathbf{x}, t) = \sum_{n=1}^N \eta_n(t) \Psi_n(\mathbf{x})$.

The projection allows to handle the geometry complexity and offers modularity. Using this decomposition in the acoustic equation, Eq. (1) is obtained for each mode. Once solved, this set of ordinary differential equations provides access to pressure variations by recomposition. Driving, damping and combustion source terms are expressed in the right hand side. The VHAM is modeled through a driving term (see [6]),

$$\ddot{\eta}_n(t) + \omega_n^2 \eta_n(t) = -2\sigma_n^{damp} \dot{\eta}_n(t) + \frac{\dot{m}_{tot}}{2A_n} \omega_e c^2 (\Psi_n(\mathbf{x}_1) - \Psi_n(\mathbf{x}_2)) \sin(\omega_e t) \quad (1)$$

with ω_n the n^{th} mode pulsation, $A_n = \int_S \Psi_n^2(\mathbf{x}) dV$ the mode norm, m_{tot} the mass flow rate modulated by the VHAM, c the mean sound velocity and ω_e the VHAM modulation pulsation. The damping coefficient σ_n^{damp} has to be evaluated based on experimental or numerical results.

Experimental and numerical comparison To compare to experimental results, a ramp modulation of the VHAM is made, varying ω_e linearly from $0Hz$ to $3000Hz$ over a $100s$ period. The modal expansion is performed over the first four transverse modes, see Fig. 4. Damping coefficients and modulated mass flow rate are obtain from [6]. The StaHF code is able to retrieve the experimental pressure signals from the ramp test, see Fig. 5, while noting some differences coming from the uncertainty on the damping coefficients and mass flow rate value.

A comparison with LES is performed in the linear regime, obtained by lowering the modulation amplitude to 10% of its nominal value. This means only the excited eigenmode responds and no energy transfer is made to the harmonics. LES provides $m_{tot} = 5.1 * 10^{-5} kg/s$ and $\sigma_n^{damp} = 3s^{-1}$, and result is shown Fig. 6. Due to mass flow rate variations during the initial transient phase in LES, differences are noted in the first part of the signal. Anyway, StaHF remarkably retrieves the limit cycle LES pressure level, clearly showing the potential of this kind of approach.

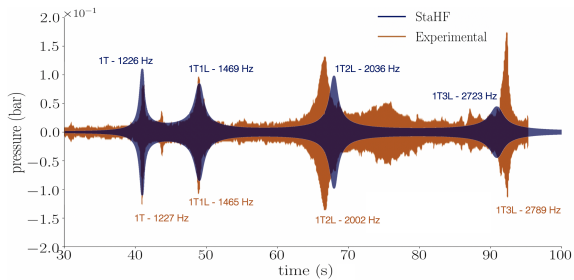


Fig. 5: HFc1 pressure sensor under the ramp excitation from experiment and computed with StaHF

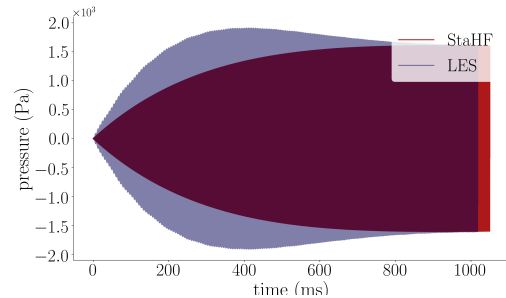


Fig. 6: Pressure variation in the chamber (HFc1) for a 1T1L modulation, from LES and StaHF

5 Conclusion and perspective

First, a LES of a gaseous non-reactive coupled cavity test bench is performed on the 1T, 1T1L and 1T2L eigenmodes on the NPCC testrig. LES reproduces the experimental data without any adjustment of parameters and allows a damping rate characterization. Then, a ROM strategy is proposed based on the modal projection of the pressure variations. This low-order representation, while using LES input parameters as the damping rate, retrieves the limit cycle pressure amplitude in the chamber, i.e. the competition between the damping phenomena and the excitation module (VHAM). Future work will focus on studying the damping mechanisms involved, such as viscous damping and acoustic/flow coupling at the injection units' outlets, and deriving models to account for these phenomena in StaHF.

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