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Fourier and wavelet analyses of intermittent and resonant pressure components in a slot burner

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ABSTRACT

In laboratory-scale burner it has been observed that the acoustic excitations change the flame topology inducing asymmetry and oscillations. Hence, an acoustic and aeroacoustic study in non reactive condition is of primary importance during the design stage of a new burner in order to avoid the development of standing waves which can force the flame. So wall pressure fluctuations inside and outside of a novel slot burner have been studied experimentally and numerically for a broad range of geometrical parameters and mass flow rates. Wall pressure fluctuations have been measured through cavity-mounted microphones, providing uni- and multi-variate pressure statistics in both the time and frequency domains. Furthermore, since the onset of combustion-driven oscillations is always presaged by intermittent bursts of high amplitude, a wavelet-based conditional sampling procedure was applied to the database in order to detect coherent signatures embedded in the pressure time signals. Since for a particular case the coherent structures identified have a multi-scale signature, a wavelet-based decomposition technique was proposed as well to separate the contribution of the large- and small-scale flow structures to the pressure fluctuation field. As a main outcome of the activity no coupling between standing waves and velocity fluctuations was observed, but only well localized pressure signatures with shape strongly affected by the neighbouring flow physics.

1. Introduction

Pressure oscillations generated by the coupling of a flow with acoustic standing waves are commonly called *self-sustained* or *self-excited oscillations*. This phenomenon was widely investigated for different geometries in industrial applications, such as T-joints, safety valves, pipes with side branches [1,2], trapped vortex cells [3–5] open cavities [6,7] and combustor (see among many [8]).

Typically, large-scale flow structures or shear layers and their interaction with the walls are identified as the main source of acoustic waves [9–12]. This source can excite the acoustic resonances of a partial enclosure sustaining the *self-excited oscillations*. In self-excited oscillations condition the domain is dominated by high-amplitude pressure tonal components. This feature can affect the flow velocity fluctuations and, for a reactive flow, the flame dynamic. Indeed, it was observed in a laboratory-scale burner that the tonal acoustic excitations of the flame affect the flame topology, the axial velocity and the radical OH^* concentration [13,14]. The present investigation is focused on a slot burner (SB) geometry, a kind of a partial enclosure, characterized

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by an important section contraction.

Kartheekeyan et al. [15] observed that tonal pressure fluctuations induce asymmetry and oscillations in the laminar flame front generated by a slot burner.

The interest for SBs arises thanks to their application in the field of combustion research. In fact this simple test-case produces a two-dimensional laminar premixed flame useful to the aim of basic physical understanding and Direct Numerical Simulation (DNS) validation. With reference to DNS, only a small volume outside the burners is usually simulated in order to reduce the computational costs. This approach is based on two important assumptions:

- the disturbances generated within the burner and propagating through the computational domain are negligible.
- the disturbances radiated by the burner geometry are well known and numerically reproducible.

These external unpredictable disturbances must be avoided with passive control systems or, at least, well characterized to ensure an agreement between experimental and numerical results.

Since standing waves play an important role in flame dynamics, to design a new generation of SBs, an experimental/numerical aeroacoustic study in non-reactive conditions of the burner geometry has to be performed. The discussion above underlines that an acoustic and aeroacoustic study is of primary importance during the design stage of a new burner. This represents the main motivation of the present research activity, where wall pressure fluctuations inside and outside of a slot burner have been studied experimentally and numerically for a broad range of geometrical parameters and mass flow rates. The objective of the research is to provide a complete description of the pressure fluctuations induced in a laboratory-scale SB. The acoustic response of the burner was analysed numerically, whereas the aeroacoustic behavior was studied experimentally for several mass-flow rates. Specifically, the wall pressure fluctuations in the presence of the mean flow were measured using a flush-mounted microphone array. The spectral content and the statistical features of the wall pressure field were deeply characterized. Since intermittency in pressure fluctuations plays a fundamental role in combustion stability [16], a wavelet-based conditional sampling procedure was applied as well in order to detect the flow signatures embedded in the pressure time signals. Finally, a wavelet-based decomposition technique of the pressure fluctuation field into large- and small-scale components was presented. The effect of the large- and small-scale flow structures on the interior aeroacoustics of the slot burner was clearly addressed. Finally the interior acoustics and aerodynamics of the slot burner were characterized through FEM and RANS simulations respectively.

The paper is organized as follows. The advanced wavelet-based techniques adopted to reveal the signatures embedded within the pressure time signals is explained in §2, whereas the description of the experimental set-ups investigated is given in §3. The numerical and experimental characterizations of the feed-line and of the slot burner are presented in §4 and §5, respectively. Conclusions are finally addressed in §6.

2. Wavelet-based techniques

2.1. Wavelet-based auto-conditioning method

An auto-conditioning technique based on the wavelet transform is described in this section. This post-processing technique is applied in order to provide a statistical description of the signatures embedded within a time series. Since intermittent coherent structures in pressure fluctuations are related to combustion instability [16], this preliminary task is important as support for the future interpretation of the flame dynamics and as an input for DNS. According to [17,18], the continuous form of the wavelet transform of a time signal $x(t)$ is:

$$w(r,t) = C_{\Psi}^{-1/2} \int_{-\infty}^{+\infty} x(\tau)\, \Psi^{*}\left(\frac{t-\tau}{r}\right) \mathrm{d}\tau \tag{1}$$

where $C_{\Psi}^{-1/2}$ is a constant which accounts for the mean value of the mother wavelet function denoted as $\Psi(t)$. The integral represents a convolution between the signal $x(t)$ and the complex conjugate of the dilated and translated $\Psi(t)$. The conditional sampling procedure applied herein permits to select events in a time signal based on a dimensionless energy criterion. Indeed, as pointed out by Farge [19], the energy content of a time series can be evaluated by the so-called Local Intermittency Measure (LIM), as defined in the following:

$$\mathrm{LIM}(r,t) = \frac{w^2(r,t)}{\langle w^2(r,t)\rangle_t} \tag{2}$$

where $\langle\cdot\rangle_t$ denotes a time average. This function enhances non-uniform distributions of energy in time, since the quantity $w^2(r,t)$ can be interpreted as the energy contained in the signal at the scale r and the instant t [20]. Hence, the LIM gives a local measure in the $[r,t]$ space of the deviation of the energy from the time-averaged energy content.

As firstly introduced by Ref. [21], the coherent structures identification procedure is based on the idea that the passage of a high-energy event of characteristic scale r_k at the instant t_i, induces a burst in the LIM at the scale r_k and time t_i. The LIM can be thresholded, fixing a proper trigger level T, in order to select a set of relative maxima satisfying the condition:

$$\mathrm{LIM}(r_k,t_i) > T \tag{3}$$