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Coherent entropy induced and acoustic noise separation in compact nozzles

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ABSTRACT

A method to separate entropy induced noise from an acoustic pressure wave in an harmonically perturbed flow through a nozzle is presented. It is tested on an original experimental setup generating simultaneously acoustic and temperature fluctuations in an air flow that is accelerated by a convergent nozzle. The setup mimics the direct and indirect noise contributions to the acoustic pressure field in a confined combustion chamber by producing synchronized acoustic and temperature fluctuations, without dealing with the complexity of the combustion process. It allows generating temperature fluctuations with amplitude up to 10 K in the frequency range from 10 to 100 Hz. The noise separation technique uses experiments with and without temperature fluctuations to determine the relative level of acoustic and entropy fluctuations in the system and to identify the nozzle response to these forcing waves. It requires multi-point measurements of acoustic pressure and temperature. The separation method is first validated with direct numerical simulations of the nonlinear Euler equations. These simulations are used to investigate the conditions for which the separation technique is valid and yield similar trends as the experiments for the investigated flow operating conditions. The separation method then gives successfully the acoustic reflection coefficient but does not recover the same entropy reflection coefficient as predicted by the compact nozzle theory due to the sensitivity of the method to signal noises in the explored experimental conditions. This methodology provides a framework for experimental investigation of direct and indirect combustion noises originating from synchronized perturbations.

1. Introduction

Turbulent flames give rise to fluctuations of pressure, temperature and velocity in the vicinity of the combustion zone. This generates acoustic, entropy and vorticity waves travelling at different speeds and directions in the combustion chamber. Acoustic waves propagate upstream and downstream the flame region, while entropy and vorticity waves are convected by the mean flow in the downstream direction. Coupling mechanisms between these waves are well known [1,2], and their interactions may contribute to increase noise emission or may dangerously increase resonant pressure oscillations in the combustion chamber [3]. For the noise generation process, one generally makes the distinction between direct combustion noise and indirect combustion noise.

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Direct combustion noise results from the unsteady heat release in the reaction zone [3–5]. Mechanisms at the origin of indirect combustion noise are more subtle. In aero-engines or ground based turbines, the flame and secondary air injection also produce entropy disturbances, which are convected through downstream flow-accelerating elements such as turbine blades or a converging nozzle. In these cases, a conversion of accelerated entropy waves into acoustic waves takes place, which has two possible consequences depending essentially on the outlet impedance of the combustor [1].

When the combustor exhaust reflection coefficient is small enough, indirect acoustic waves feature a relatively large spectral low frequency content and are essentially transmitted out of the chamber. This can be considered as an open-loop mechanism where entropy perturbations are converted into sound, which is then radiated in the surrounding environment. This contribution corresponds to the so-called indirect combustion noise. Different numerical strategies were developed to compute simultaneously the two types of noise in a combustion chamber and compare the relative sound pressure levels from both sources (see for example [6,7]). The corresponding experiments remain however a great challenge. To study indirect combustion noise alone, it is necessary to generate temperature fluctuations without any other acoustic source. Attempts have been made in early investigations [8] with clever setups generating entropy fluctuations by periodical heat addition to the air flow. The more recent Entropy Wave Generator (EWG) [9] uses an electrical heating module to produce a hot air column that is transported downstream through a convergent-divergent nozzle. The amplitude and spectral content of the entropy induced pressure wave propagating in the downstream direction through the nozzle was found in agreement with theoretical predictions. Numerical simulations of the EWG setup in supersonic cases [10] and subsonic cases [11,12] however also revealed that reflections from the EWG outlet and direct noise generated by the electrical heating system both contribute to pressure fluctuations in the discharge flow. It appears to be very difficult to generate pure indirect noise without introducing any additional acoustic disturbance. It is then worth examining experimental methods aiming at characterizing entropy noise when other noise contributions are present at the same time. This type of problem has only been addressed in a limited number of investigations, that generally rely on a separation of incoherent contributions to the noise field [13,14]. An alternative method is presented in this article based on the use of synchronized coherent harmonic pressure and entropy fluctuations. The validation of this method represents one of the motivations for the present study.

When the reflection coefficient of the combustor outlet increases, a coupling mechanism between the acoustic field and entropy fluctuations may also take place leading to amplified entropy disturbances at specific discrete tones. This feedback results often in a resonant loop, called rumble, where synchronized pressure and temperature oscillations increase in the chamber until a limit cycle is reached [15,16]. The role of entropy waves on the development of combustion instabilities has been investigated in many studies, but without providing definitive conclusions as will be emphasized below. Gaining insight into the coupling between acoustic and entropy waves during self-sustained thermoacoustic oscillations constitutes the second motivation for the development of a methodology and a setup allowing the separation of synchronized acoustic and entropy harmonic disturbances.

The following section makes a review of the state of knowledge on indirect combustion noise, i.e. entropy induced noise. In Section 3, the theoretical formalism is introduced together with definitions of the transmission and reflection coefficients used in this study. The experimental test bench is then presented in Section 4 together with a parametric analysis delimiting the domain of operation of this system. In Section 5, the separation technique is presented and validated with numerical simulations. Experimental results are presented in Section 6 and are discussed in Section 7 with the support of theoretical and simulation results.

2. Entropy induced noise

Since late 1960, efforts have been made to compute or measure impedances of nozzles and turbine blades. Tsien [17] first characterized analytically nozzle responses to one dimensional axial pressure and velocity perturbations by a transfer function defined as the ratio of mass flow perturbations to pressure perturbations at the entrance of the nozzle, or equally by the ratio $(\rho'/\rho + u'/u)/(p'/p)$ where ρ, u and p are the density, velocity and pressure while the prime subscript denotes the corresponding fluctuating part, as a function of the oscillation frequency. Crocco and Cheng [18] later examined the specific admittance ratio $\alpha = (u'/u)/(\rho'/\rho)$ for studying the role of nozzle in combustion instabilities. They obtained an analytical solution for a subsonic nozzle in the entire frequency range under the hypothesis of isentropic small-amplitude perturbations and determined experimentally the admittance of a choked nozzle from pressure and velocity measurements made at the nozzle inlet. Bell et al. [19] examined experimentally the admittance of a nozzle mounted on a classical impedance tube facility. The standing-wave pattern that was superimposed on a mean flow velocity in the impedance tube was measured by a 10-microphone array to calculate the nozzle admittance using a linear regression method of the measured pressure amplitudes. Marble and Candel [1] simplified the problem by considering the nozzle as compact, with respect to the acoustic and entropy disturbance wavelengths. They considered incoming one-dimensional small perturbations of pressure and temperature, and compute analytically the reflection and transmission coefficients of a compact nozzle with jump conditions. Results show that, at the nozzle location, the incident acoustic wave is transmitted and reflected and an additional acoustic disturbance is generated due to the acceleration of entropy waves convected through the nozzle. In this compact approximation limit, the nozzle transfer function only depends on the nozzle inlet and outlet Mach numbers. In the same study, they also worked out on finite-length supercritical nozzles by assuming a one-dimensional linear velocity distribution in the nozzle [17]. Moase et al. [20] gave an analytical expression for the forced

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