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Measurement of density fluctuations using digital holographic interferometry in a standing wave thermoacoustic oscillator

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ABSTRACT

This paper describes an optical set-up for measuring density fluctuations associated to acoustic oscillations in a thermoacoustic prime-mover. A time-resolved, full-field holographic interferometry technique is used, which enables to measure the optical phase difference between a reference beam and a probe beam passing through the acoustic resonator. The paper first presents the experimental set-up and the processing of holograms from which the instantaneous variations of the gas density along the line of sight of the probe beam are obtained. Then, the measurement technique is applied to the analysis of density fluctuations in the neighborhood of the heated side of a stack in a standing wave thermoacoustic prime mover during the transient regime of wave amplitude growth. The experimental results reveal that there exists very significant entrance effects, which lead to the generation of higher harmonics as well as mean (time-averaged) mass rarefaction in the vicinity of the stack termination. Finally, a short discussion is provided, based on a simplified modeling of higher harmonics generation in temperature associated to the oscillations of an inviscid gas through the stack, but the model fails in explaining the magnitude of the phenomena observed.

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1. Introduction

A first approach of acoustical phenomena in fluids usually involves considering the wave process in terms of pressure and velocity fluctuations around an equilibrium state, and there exists different means to measure those quantities, such as microphones, Laser Doppler Velocimetry or Particle Image Velocimetry. However, density (as well as temperature) fluctuations always accompany pressure fluctuations, and it is sometimes worth considering to measure those density fluctuations, notably when analyzing unsteady heat and mass transfer phenomena involved in thermoacoustic engines.

The operation of thermoacoustic engines is governed by the thermoviscous interaction between gas oscillations and the solid frame of a porous material, referred to as a stack [1,2]. This stack is usually connected to heat exchangers, and inserted within an acoustical resonator. When the thermoacoustic engine is operated as a prime-mover, the application of a temperature gradient along the stack axis leads to the generation of self-sustained acoustic oscillations at the frequency of the most unstable mode; when the thermoacoustic engine is operated as a heat pump, the sustain of resonant gas oscillations by an adequate source leads to advective heat transport by sound along the stack axis. The design and the development of thermoacoustic engines already has a three-decade history [3] and there exists several examples of devices able to reach high performances [4–9]. However, despite their simplicity in terms of geometry, thermoacoustic engines are not very well understood due to the complexity and the variety of the phenomena saturating the acoustic wave amplitude. Among these nonlinear phenomena are the ones impacting unsteady heat and mass transfer through the thermoacoustic core, such as acoustic streaming [10], or hydrodynamic/thermal entrance effects occurring notably at the stack termination (vortex shedding [11], transitional turbulence [12], nonlinear temperature fluctuations [13]).

Because of the complexity of the phenomena involved in thermoacoustics, it is useful to develop adequate measurement techniques allowing to get more information than the one a microphone could provide. Laser Doppler Velocimetry and Particle Image Velocimetry provide information about the gas parcel velocity and have been used previously to characterize acoustic streaming [14–17] or vortex shedding processes [18–20], while cold wire anemometry [21] has been used to characterize the nonlinear temperature fluctuations in the vicinity of the stack termination. In this paper, attention is focused on the development of another measurement method allowing to get information about density

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fluctuations from the variations of the optical index of the gas. This technique basically consists of an interferometer in which optical phase variations are obtained from a full-field, time-resolved digital holography technique.

Thanks to the development of high resolution CCD cameras and the increasing power of computers, digital holographic/interferometric measurements are nowadays under development and have already been used to analyze various processes of vibration kinematics [22,23] or fluid mechanics [24], but only a few works have been made to characterize the density fluctuations associated to an acoustic process. There exists pioneering works performed fifteen years ago by Wetzel and Herman [25–27], in which analog holography has been used to measure temperature fluctuations at the end of a couple of parallel plates submitted to a high amplitude acoustic field. Interferometric techniques have also been used recently to characterize different classes of thermoacoustic phenomena, like sound generation by unsteady heat release within a flame [28], or the so-called piston effect generated in a small cell filled with critical CO_2 [29], but these techniques only allowed the analysis of local (i.e. non full-field) density fluctuations. It is therefore worth considering to pursue the development of these techniques to get further information about various thermoacoustic phenomena, and more generally about some physical processes in which the derivation of density from pressure is not straightforward.

The device under consideration in this paper (see Fig. 1(a)) is a quarter-wavelength thermoacoustic prime-mover, which simply consists of a straight duct, closed at one end, and equipped with a stack submitted to a temperature gradient. In the following, the measurement of density fluctuations by digital holography are performed in the vicinity of the hot side of the stack, during the transient regime of wave amplitude growth. The experimental set-up and the data processing are presented in Section 2. Experimental results are presented in Section 3, which enable to confirm that complicated heat and mass transfer processes are involved near the stack end. A discussion is provided in Section 4, based on the comparison between experimental results and a simplified model developed by Gusev et al. [13].

2. Experimental apparatus and data processing

2.1. Experimental apparatus

A sketch of the thermoacoustic device under consideration in this study is presented in Fig. 1(a). It is composed of a glass tube (49 cm in length, inner diameter $D_i = 52$ mm, outer diameter $D_o = 60$ mm) open at one end and closed by a rigid plug at the other end. Inside the tube is inserted the cylindrical stack (48 mm in length), whose diameter fits the inner diameter of the tube. This stack is made up of a 600 CPSI (cells per square inch) ceramic catalyst with numerous square channels of section 0.9×0.9 mm. The side of the stack facing the plug is heated using an electrical resistance wire (Nichrome wire, 36 cm in length, 0.25 mm in diameter, resistivity 7 Ω/ft) regularly coiled through the stack end, and connected to a DC electrical power supply. Sound is captured using a 1/4-in. condenser microphone (model GRAS, type 40BP) flush-mounted through the plugged end of the resonator. Note that a photograph of this device can also be found in Ref. [30]; it is worth mentioning that the presence of heater does not affect the optical measurements presented in the following, because the Nichrome wire is mounted flush *inside* the stack so that the laser beam used for digital holography does not pass through the heater.

In this study, the position of the stack along the resonator's axis is fixed at a distance $d = 24$ cm from the rigid plug. For this configuration, the onset of self-sustained thermoacoustic oscillations occurs as soon as the heat power supplied by the Nichrome wire exceeds the critical value $Q_{onset} \approx 20$ W (note that this value of Q_{onset} depends on the stack position [31]). The frequency $f \approx 171$ Hz of acoustic oscillations corresponds to the quarter wavelength resonance, which means that $f \approx c_0/4L$, where $c_0 \approx 344$ m/s stands for the adiabatic sound speed at room temperature. Previous studies of the same device [30–32] have clearly shown that, despite of its very simple geometry, this thermoacoustic oscillator can exhibit complicated dynamics of wave amplitude growth/saturation which are not reliably reproduced by theoretical/numerical modeling. It is therefore the objective of this study to perform holographic interferometry to analyze the refractive index variations in a window localized near the stack, where the temperature gradients are the highest, and to gain further insight on the physical processes controlling the saturation of the thermoacoustic instability.

A sketch of the optical set-up used to perform the measurement of density fluctuations close to the heated side of the stack is presented in Fig. 1(b). This set-up basically consists of a Fresnel interferometer enabling to measure the optical phase difference between a reference beam and a measurement beam passing through the acoustic resonator. This phase difference is caused by the variations of the refractive index within the resonator, due to both heat transport (notably the slow variations of the temperature field caused by heating) and acoustic (onset of self-sustained oscillations) processes. The light source is a laser source (Cobolt Flamenco, optical wavelength λ = 660 nm). The laser beam is split into a reference beam and a probe beam, and both beams are then expanded and bundled to parallel rays by a collimating lens. The probe beam passes through the acoustic resonator next to heated side of the stack, as indicated in Fig. 1(a). Then, the interference between the reference and the probe beam are captured by two CCD sensor (thanks to a 50/50 cube), namely a CCD camera and a high speed CMOS sensor (see Fig. 1(b)). The CCD camera (model Hamamatsu ORCA-3CCD C7780-10) is used for analyzing slow temperature variations preceding the onset of self-sustained oscillations: the CCD sensor samples the interferogram at a rate of 1 im./s with 1344×1024 pixels sized 6.45 μm. The high speed CMOS sensor (Phantom V5.1) is used for analyzing the rapid fluctuations of the density occurring after the onset of self-sustained oscillations. This sensor is triggered when the peak amplitude of acoustic pressure exceeds the threshold value of 100 Pa, thanks to the signal provided by the microphone. Interferograms are then sampled during 4 s at 1000 im./s with 1024×1024 pixels sized 14.8 μm. Note that the above mentioned choice is intrinsically related to the performance of the high speed camera, which sets the bounds of both time and space resolution, so that a compromise has to be found to get the best sampling rate with a maximum number of pixels. Here, the sampling frequency of 1 kHz has been chosen so as to satisfy the Shannon-Nyquist criterium up to the second harmonic of thermoacoustic oscillations.

2.2. Data processing

The quantity of interest given by the optical set-up is the optical phase between the probe beam and the reference beam, which is related to the refractive index variation near the stack. From the optical set-up and adjustment of the beam splitter cube, digital holograms including spatial carrier frequencies (off-axis holography) are recorded and processed. The introduction of the spatial carrier frequency by the cube leads to the recording of one hologram at each instant, since there is no need for phase shifting [33]. This provided a single-shot and real-time capability to the experimental set-up to investigate acoustic phenomena. Fig. 2

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