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W. Tao, Marek Mazur, M. Huet, Franck Richecoeur. Indirect Combustion Noise Contributions in a Gas Turbine Model Combustor with a Choked Nozzle. Combustion Science and Technology, 2016, Ninth Mediterranean Combustion Symposium, 188 (4-5), 10.1080/00102202.2016.1139374 . hal-01312563

HAL Id: hal-01312563

<https://hal.science/hal-01312563>

Submitted on 24 Aug 2020

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INDIRECT COMBUSTION NOISE CONTRIBUTIONS IN A GAS TURBINE MODEL COMBUSTOR WITH A CHOKED NOZZLE

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Abstract

Direct and indirect combustion noise sources co-exist in combustors. Direct noise results from unsteady combustion. Indirect contributions are associated to entropy fluctuations convected through flow accelerating devices such as a nozzle. Many analytical and numerical studies on combustion noises have been achieved since the late 1970s yet few experimental studies were carried out to discriminate direct from indirect contributions. An experimental method to compute direct and indirect nozzle transfer functions separately has been developed in our previous work presented in 6th European Combustion Meeting [1]. It consist of measuring the direct and indirect noise transfer functions through simultaneous pressure and temperature fluctuation measurements. The method has already been validated in a well-controlled test bench which generates temperature and acoustic fluctuations without the complexity of combustion. This paper discusses the application of the methodology in a pressurized burner based on simulations of acoustic and entropy fluctuations in the combustion chamber.

Introduction

Noise emission from air transportation has rising concern because of the rapid increase of the air traffic. The main noise contributions to a full scale aeroengine identified by [2] using microphone array techniques include the combustion noise and the exhaust jet noise. While jet noise is the dominant noise at full thrust, combustion noise become the main noise emission at low speed such as landing and taxiing.

It is commonly admitted that combustion noise has two different contributions. Direct combustion noise results from the heat release rate fluctuations in the flame [3] and indirect combustion noise is produced by the acceleration of entropy fluctuations convected by the mean flow due to a pressure gradient [4]. For compact nozzles, analytical solutions obtained by [5] may be used to determine the acoustic pressure reflected and transmitted through the nozzle due to entropy fluctuations. [6] numerically compared the direct and indirect combustion noise in the transmitted noise spectrum through the nozzle and found that indirect noise may be dominant at high ratio of outlet to inlet Mach numbers. The reflected indirect noise also contribute to the acoustic feedback to the upstream combustion process, as experimentally investigated by [7]. More recently [8, 9] considered the indirect noise mechanism in thermoacoustic analysis of a model combustor and concluded that the acoustic addition due to entropy fluctuations may influence the stability of the combustor.

From experimental aspects, one challenging issue is to measure the indirect from the direct transfer function of the nozzle. The difficulty lies in the coherence between the acoustic and entropy fluctuations created due to flame dynamics. As reported by [10], the separation of direct and indirect noises from the correlations between pressure fluctua-

tions recorded inside and far away from the engine has to suppose that direct flame noise emission and entropy fluctuations are not correlated in the considered frequency domain. Such coherence has been an important error factor in measuring the response of choked nozzle in a combustion chamber during limit cycle [11], and makes it difficult to separate direct and indirect noise contribution through available diagnostics such as pressure and temperature fluctuations measurements. A clever setup as the Entropy Wave Generator (EWG) [12] uses an electrical heating module to produce a hot air column that is transported to the downstream through a convergent-divergent nozzle. However numerical simulations of EWG in supersonic case [13] and subsonic case [14, 15] showed that reflections from EWG outlet and direct noise from electrical heating may both contribute to pressure fluctuations in the discharge flow. So it is necessary to develop experimental strategies aiming at quantifying entropy noise when other noise contributions are present at the same time. However, such work is few documented in the literature.

An experimental method to separate direct and indirect noises has been developed in our previous work presented in 6th European Combustion Meeting[1]. It consists of simultaneous pressure and temperature fluctuation measurements to identify the direct and indirect nozzle transfer functions. The separation method has been applied to an unique acoustically-controlled test bench capable of generating pressure and temperature fluctuations in a subsonic nozzle. It was also numerically validated by the code Sunday (SimUlation of Noise in 1D flows due to fluctuAtions in entropY) developed at ONERA [15, 16].

The present study aims at applying the method in a more complicated environment encountered in a high pressure combustor and particularly with a choked condition at the outlet of the combustion chamber. The definition of direct and indirect transfer functions in a compact nozzle and the separation method are first presented. The burner with a choked exhaust nozzle and diagnostics are presented in the next section. Then pressure and temperature evolutions in the burner combustion chamber are simulated by the code Sunday with the knowledge of the nozzle shape as well as the acoustic and entropy waves entering the chamber. Finally, nozzle transfer functions are calculated using the separation method from local pressure and temperature evolutions which are the kind of signals can be measured in real experiments.

Nozzle transfer functions

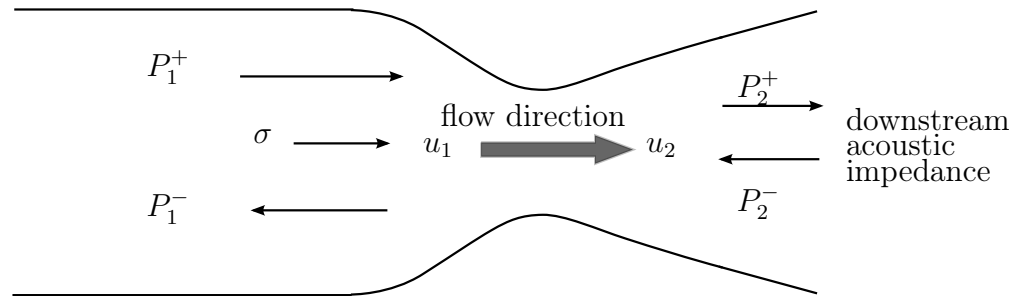


Figure 1: Acoustic and entropy waves propagate in the upstream and downstream a converging-diverging nozzle.

A simple model of the acoustic and entropy waves in a nozzle is illustrated in Fig. 1. The nozzle is submitted to axial acoustic wave P_1^+ and entropy wave σ . In response reflected P_1^- and transmitted P_2^+ pressure waves are generated. Usually due to the reflection from boundary conditions downstream of the nozzle, there exists a wave P_2^- in the discharge flow. For subsonic nozzle such disturbances propagate towards the nozzle and

can also generate direct contribution in the upstream and downstream acoustic field. So waves like P_1^- and P_2^+ have direct and indirect contributions from respectively incident acoustic and entropy waves and can be represented by:

$$P_1^- = P_{1a}^- + P_{1b}^- + P_{1s}^- \quad (1)$$

$$P_2^+ = P_{2a}^- + P_{2b}^- + P_{2s}^- \quad (2)$$

The subscripts 1, 2 designate the regions upstream and downstream of the nozzle, a, b stand for direct contributions due to incoming pressure waves from upstream and downstream side of the nozzle, and s stands for the entropy contribution.

For a compact nozzle, meaning that the length of the nozzle is negligible compared with the wave lengths of acoustic and entropy waves, and if the amplitude of the pressure, velocity and entropy perturbations are within 10% of respective mean values, one dimensional analytical solution (see Eqs. 3) of the noise generation with respect to the sources (acoustic or entropy) can be found in the famous work of [5].

$$R_a = \frac{P_{1a}^-}{P_1^+} \quad T_a = \frac{P_{2a}^+}{P_1^+} \quad R_b = \frac{P_{2b}^+}{P_2^-} \quad T_b = \frac{P_{1b}^-}{P_2^-} \quad R_s = \frac{P_{1s}^-}{\sigma} \quad T_s = \frac{P_{2s}^+}{\sigma} \quad (3)$$

To separate direct and indirect contributions in nozzle response, we define nozzle transfer functions as:

$$H_1 = \frac{P_{1a}^- + P_{1b}^-}{P_1^+} \quad H_2 = \frac{P_{2a}^+ + P_{2b}^+}{P_1^+} \quad (4)$$

$$H_3 = \frac{P_{1s}^-}{\sigma} \quad H_4 = \frac{P_{2s}^+}{\sigma} \quad (5)$$

Thus H_1 and H_2 indicate the reflection and transmission of the perturbing acoustic waves, and H_3 and H_4 the generation of indirect noise due to the entropy perturbations.

The analytical values of the above transfer functions in a subsonic flow can be deduced from Marble and Candel's solutions. If the reflection coefficient R_L at a distance L downstream of the nozzle is known, it allows to write:

$$R_L = \frac{P_2^-}{P_2^+} \cdot e^{-i(k_i + k_r)L} \quad (6)$$

where $k_i = \omega/c(1 + M_2)$, $k_r = \omega/c(1 - M_2)$ are the wave number of the progressive and regressive acoustic waves. Then by combining Eqs. 2, Eq. 6 and Marble and Candel's solutions, we obtain expressions 7 and 8 for the total reflected and transmitted waves P_1^- and P_2^+ as functions of the incident waves.

$$P_1^- = \left[R_a - \frac{R_L T_a T_b e^{ik_i L}}{R_L R_b e^{ik_i L} - e^{-ik_r L}} \right] P_1^+ + \left[R_s - \frac{R_L T_s T_b e^{ik_i L}}{R_L R_b e^{ik_i L} - e^{-ik_r L}} \right] \sigma \quad (7)$$

$$P_2^+ = \left[\frac{T_a e^{-ik_r L}}{R_L R_b e^{ik_i L} - e^{-ik_r L}} \right] P_1^+ + \left[\frac{T_s e^{-ik_r L}}{R_L R_b e^{ik_i L} - e^{-ik_r L}} \right] \sigma \quad (8)$$

These equations show evidently the direct acoustic and entropy contributions on both

side of the nozzle, from which we find solutions for the transfer functions:

$$H_1 = R_a - \frac{R_L T_a T_b e^{ik_i L}}{R_L R_b e^{ik_i L} - e^{-ik_r L}} \quad (9)$$

$$H_2 = \frac{T_a e^{-ik_r L}}{R_L R_b e^{ik_i L} - e^{-ik_r L}} \quad (10)$$

$$H_3 = R_s - \frac{R_L T_s T_b e^{ik_i L}}{R_L R_b e^{ik_i L} - e^{-ik_r L}} \quad (11)$$

$$H_4 = \frac{T_s e^{-ik_r L}}{R_L R_b e^{ik_i L} - e^{-ik_r L}} \quad (12)$$

These transfer functions depend on the nozzle inlet and outlet Mach numbers as well as the acoustic condition at nozzle discharge. In the particular case of a choked nozzle, the direct and indirect transfer functions H_1 and H_3 characterising direct and indirect acoustic feedback to the region upstream of the nozzle are dependant only on the inlet Mach number.

Separation method

A method for measuring response of a choked nozzle to acoustic and entropy perturbations has already been proposed in [11]. This method, also called the 2M1T method, evaluates the transfer functions (Eqs. 13-14) from the auto- and cross-spectral densities of the incident the entropy wave (designated by s), the incident the acoustic wave (designated by a) and the reflected wave (designated by r).

$$H_1 = \frac{S_{sr} S_{as} - S_{ss} S_{ar}}{S_{as} S_{sa} - S_{ss} S_{aa}} \quad (13)$$

$$H_3 = \frac{S_{sa} S_{ar} - S_{aa} S_{sr}}{S_{as} S_{sa} - S_{ss} S_{aa}} \quad (14)$$

In experimental implementations, the spectral densities are calculated from the auto- and cross-spectral density of simultaneous pressure and temperature measurements due to the relation established for small-amplitude perturbations (noted with $'$):

$$\frac{s'}{c_p} = \frac{T'}{T} - \frac{\gamma - 1}{\gamma} \frac{p'}{\bar{p}} \quad (15)$$

However the 2M1T method is not valid if the acoustic and entropy fluctuations are very coherent because in this case $S_{as} S_{sa} - S_{ss} S_{aa} = 0$. An alternative way to measure the nozzle transfer functions H_1 and H_3 is to use the reflection coefficient \mathcal{R} and the complex ratio of entropy wave to acoustic wave $SA = \sigma/P_1^+$ at the entrance of the nozzle following:

$$\mathcal{R} = \frac{P_{1a}^- + P_{1s}^-}{P_1^+} = \frac{H_1 P_1^+ + H_3 \sigma}{P_1^+} = H_1 + H_3 \cdot SA \quad (16)$$

In practice the reflection coefficient \mathcal{R} is measured by the three-microphone techniques [17] and the parameter SA can be estimated by computing cross-corellations $SA = S_{as}/S_{aa}$, following the procedure proposed by [11]. The proposed method is called the diff-R method.

The strategy to calculate the value of transfer functions on each forcing frequency is to compare two operation regimes No.1 and No.2 where the amplitudes of acoustic oscillations are equal but the amplitudes of entropy fluctuations are different. This is

acceptable if we suppose linear perturbations so that the direct and indirect contributions add straightforward to each other. A simple example is to choose for regime No.1 $|\sigma| > 0$ and regime No.2 $\sigma = 0$. In the later case, the reflection coefficient is effectively equal to H_1 . Therefore by conserving the same inlet Mach numbers in two conditions, we have:

$$H_1 = \mathcal{R}(\sigma = 0) \quad (17)$$

$$H_3 = \frac{\mathcal{R} - \mathcal{R}(\sigma = 0)}{SA} \quad (18)$$

Generally in full scale burners it is difficult to have two measurements under the same mean experimental conditions and acoustic amplitudes but different entropy waves. One solution is to consider that the direct transfer function of a compact choked nozzle is well known and can be determined by the inlet flow Mach number. Thus one can use the analytical value

$$H_1 = \frac{1 - \frac{\gamma-1}{2}M}{1 + \frac{\gamma-1}{2}M}; M \text{ is the nozzle inlet Mach number} \quad (19)$$

together with the measured parameters \mathcal{R} and SA to compute the indirect nozzle transfer function H_3 .

Experimental setup

The burner CESAM-HP equipped with a choked nozzle as illustrated in Fig. 2 has been developed at EM2C Lab for investigation of indirect noise. The acoustic boundary condition upstream of the premixing tube is controlled by the impedance control system (ICS) designed by [18], composed of a perforated plate traversed by a bias flow and a Helmholtz back cavity with adaptable length. The bias flow also limits flame flash-back. Lean premixed propane/air swirled flow is generated by tangential injection from the feeding lines into the premixing tube. The combustion chamber is connected to a convergent-divergent nozzle. The nozzle profile has been acoustically optimized to maximize the indirect combustion noise production[19].

Piezo-electric pressure sensors capable of measuring absolute and fluctuating pressure under pressurized condition up to 80 kHz are located in the premixing tube and the combustion chamber. Same sensors are also installed in a pressurized impedance measurement system (PIMS) which is connected to the feeding lines to measure *in situ* and on-the-fly the acoustic properties by a technique already presented in [20]. The mean gas temperature in the premixing tube and near the entrance of the nozzle are measure by isolated R-type thermocouples that are able to measure temperature up to 1 600°C. The positions of the sensors are illustrated in Fig. 3.

When the burner is running on the operating point in Tab. 1, the measured static pressure in the combustion chamber reaches 2.2 bar and the mean gas temperature near the nozzle approaches 1 340°C. The nozzle is choked in this condition. Measurements of pressure and temperature fluctuations can give access to the acoustic and entropy waves impinging the nozzle and thus are necessary to evaluated the nozzle transfer functions. While the four axially distributed pressure sensors in the chamber are sufficient to capture progressive and regressive acoustic waves, instantaneous temperature in the burnt gas flow is difficult to measure. The power spectral density (PSD) of the sensor in position 2 features several peaks between 98 and 2324 Hz (Tab. 2). The present study proposes to numerically mimic the experimental test bench and generate numerical pressure and temperature unsteady signals the same mean condition and geometry. The separation method is then applied with local numerical pressure and temperature signals to evaluate

Table 1: The experimental test bench runs with a lean equivalence ratio, and air mainly entering the chamber tangentially through the injection tube.

Property	Value
Name	op13-5-85
Tangential air flow rate m_a	13 g/s
Tangential fuel flow rate m_f	0.97 g/s
Axial air flow rate m_{ax}	5 g/s
Global equivalence ratio Φ	0.85
Mean chamber pressure	2.2 bar

Table 2: The acoustic wave entering the numerical model for Sunday calculation is composed of several harmonic waves.

Frequency [Hz]	98	195	293	381	487	2324
SPL [dB]	169	156	146	141	133	122

the nozzle transfer functions and compare with analytical solutions. The details for the numerical solver Sunday is present in the next section.

Sunday simulation

The quasi-one-dimensional non-linear Euler equations of the flow passing through a nozzle are solved with the numerical code Sunday (SimUlation of Noise in 1D flows due to fluctuAtions in entropY). With the knowledge of acoustic and entropy forcing waves and the boundary conditions, it gives the evolution of pressure, velocity and temperature in the flow domain. The calculation domain is composed of the combustion chamber and the nozzle. The combustion chamber is represented by a cavity with a length of 140 mm. The reaction zone is not computed in the calculation. Instead, acoustic and entropy waves are injected at the entrance of the combustion chamber. The suppression of combustion maybe insufficient to accurately represent pressure and entropy fluctuations, but it is not the purpose of using the numerical solver, which is to generate the representative pressure and temperature signals related with the nozzle to validate the separation method. However, it maybe interesting to use tools like the flame describing function [21] to determine acoustic and entropy waves eminent from the flame in further studies.

The incident acoustic wave is represented by the superposition of harmonic waves at frequencies and amplitudes corresponding to the peaks identified in the PSD spectrum of the pressure sensor on position 2 which are summarized in Tab. 2. Although there are not yet experimental informations on entropy fluctuations in the flow, but it is assumed that entropy spots are transported at the bulk flow velocity towards the nozzle and that the characteristic convection wavelength of entropy spots equals approximately the chamber length. The frequency of the entropy wave is estimated by this way at 105 Hz. The non-dimensional amplitude of the entropy wave σ is set to 0.05, which refers to a moderate estimation that the amplitude of the temperature fluctuations weights 5% of the mean temperature.

Finally the acoustic upstream boundary condition is characterized by $u' = 0$ to mimic the wall-type condition at the entrance of the chamber while in the numerical calculations acoustic and entropy waves are allowed to leave the domain without much reflections. The calculation is implemented for simultaneous acoustic and entropy wave forcing the nozzle. Signals on the four sensor positions in Fig.3 are recorded at 20 000 Hz during 5 seconds.

The obtained fluctuations of pressure, velocity and temperature on the sensor position 2 are normalised by their mean values ($\bar{p} = 2.2$ bar, $\bar{T} = 1612$ K and $\bar{u} = 8.7$ m/s) and are traced in Fig. 4. It is noted that the fluctuating properties all oscillate within 10% of the mean values (the same on the other three positions) so that the separation method can be used to evaluate the indirect nozzle transfer function H_3 .

Results and discussions

When treating the simulation signals, the incident acoustic and entropy waves are supposed unknown. Combustion noises are only characterized through the pressure signals in the combustion chamber. Firstly 2048 samples are used to compute the PSD of pressure and temperature fluctuations on position 2, which are shown in Fig. 5. Five distinct peaks with SPL higher than 100 dB: 98, 195, 293, 381 and 488 Hz are observed (all corresponding to the input acoustic wave of Sunday calculation). By the same spectral analysis it is found that temperature fluctuations have maximum amplitude on 107 Hz (which differs only slightly from that of the input entropy wave 105 Hz). The frequency resolution of the spectral analysis here is about 10 Hz, so it is probable that direct and indirect noise contributions are most correlated on 107 Hz. Moreover there is a distribution of multiple peaks in the pressure spectrum around 2324 Hz, and the frequency difference between two adjacent peaks is equal to 107 Hz. There maybe a coupling of acoustic and entropy modes but more work needs to be done in order to clarify this phenomenon. The nozzle transfer function H_3 is evaluated on the identified frequencies smaller than 500 Hz.

In the next step, it is necessary to evaluate the coherence between acoustic and entropy waves in order to chose a proper method to calculate the nozzle transfer function. To do so the coherence factor between the incident waves $C_{as} = |S_{as}|^2 / (S_{aa}S_{ss})$ is computed from the pressure signals on position 3 and 4, and the temperature signal on position 4, the maximum of which is also found on 107 Hz in Fig. 6. As a result, the 2M1T method (see Eq. 14) is used to calculate the indirect nozzle transfer function H_3 on the frequencies listed in Tab. 2 on which C_{as} almost vanishes. At 107 Hz, where $C_{as} = 1$, the reflection coefficient \mathcal{R} and the complex ratio $SA = \sigma / P_1^+$ are evaluated. The value of H_3 is then calculated according to Eq. 18 by using the analytical solution in Eq. 19 with $M = 0.01$, $\gamma = 1.29$ (given by Sunday). For comparison purpose the value of H_3 at 107 Hz is also computed by the 2M1T method.

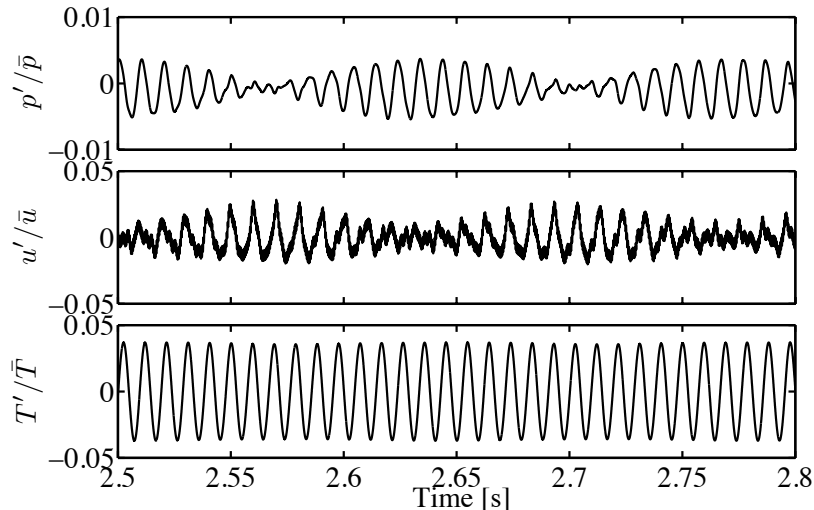


Figure 4: Sunday simulation time signals. Top: Pressure fluctuations. Middle: Velocity fluctuations. Bottom: Temperature fluctuations

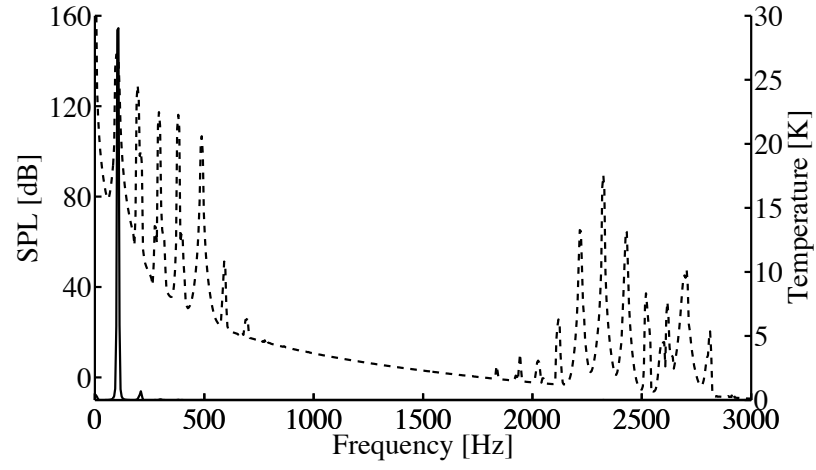


Figure 5: Power spectrum of numerical pressure and temperature fluctuations on position 2. Left axis and dashed-line: Pressure. Right axis and black-line: Temperature.

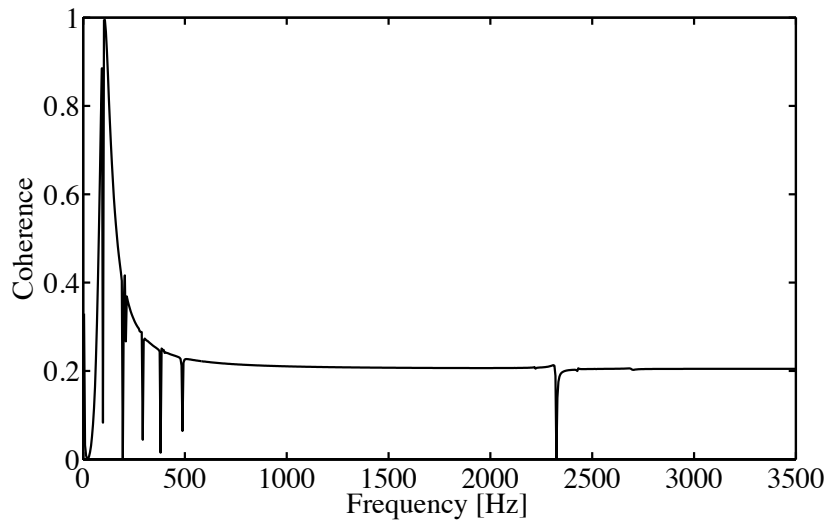


Figure 6: Coherence factor of incident entropy and acoustic waves.

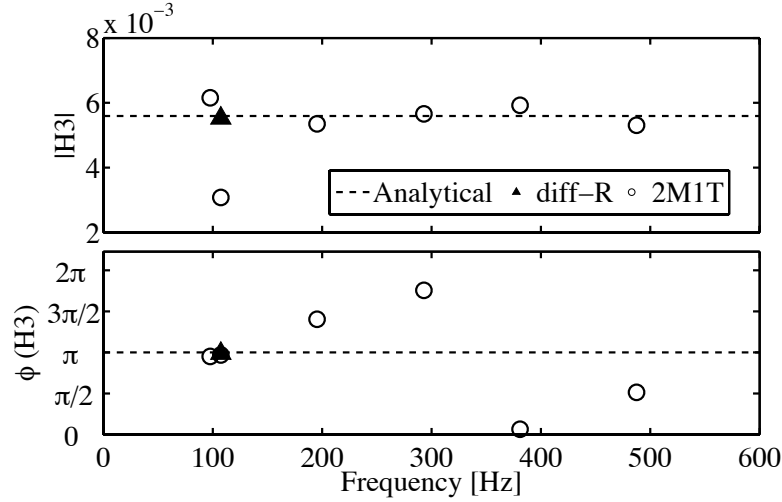


Figure 7: Indirect nozzle transfer function calculated by analytical compact nozzle solution (dashed-line), the diff-R method on 107 Hz (black triangle) and the 2M1T method on 98, 107, 195, 293, 381 and 487 Hz (empty circle).

The results of the indirect transfer function (H_3) from the analytical compact nozzle solution, the 2M1T method and the diff-R method are plotted in Fig. 7. The absolute value of H_3 calculated by the 2M1T method is close to the analytical compact nozzle solution within $\pm 10\%$ of relative errors, except on 107 Hz. And unlike the constant phase in analytical compact nozzle solution, the phase value of H_3 calculated from the 2M1T method is linearly dependant on the frequency. But the value on 107 Hz is correctly calculated using \mathcal{R} and SA .

To conclude, the indirect nozzle transfer function has been measured from numerical temperature and pressure fluctuations that are solved by the code Sunday with representative acoustic and entropy forcing waves in the CESAM-HP burner. It has been shown the diff-R method is able to measure correctly the indirect nozzle transfer function when acoustic and entropy wave are most correlated. In some burners the correlation between acoustic and entropy fluctuation may be broke down as they propagate towards downstream due to turbulence, but it is more likely to sustain in the CESAM-HP burner since the combustion chamber is relatively short. Therefore it is promising to use the diff-R method to evaluate the indirect combustion noise contributions in the combustion chamber if access to the temperature fluctuations are allowed.

Conclusion

This paper discusses the application of an experimental method to measure the indirect nozzle transfer function in a gas turbine model combustor with a choked nozzle. First the transfer functions of a compact nozzle are defined and their analytical solutions have been deduced from a former work by [5]. Then the separation method diff-R has been presented, which uses the link between the transfer functions with the nozzle reflection coefficient \mathcal{R} and the complex ratio SA . The study on the possibility to use the diff-R method in the CESAM-HP burner with a choked nozzle is based on numerical signals generated by the code Sunday. To do so, characteristic acoustic and entropy waves have been injected to the calculation domain composed of the combustion chamber and the nozzle. From the pressure and temperature evolutions in the combustion chamber given by the code Sunday, the diff-R method has been proofed capable of measuring the indirect

nozzle transfer functions when entropy and acoustic waves are very coherent. In the future it maybe interesting to characterize acoustic and entropy waves impinging to the nozzle by the flame dynamics. This approach is likely to provide the numerical solver Sunday with more information on the forcing waves and thus more evidence for the application of the diff-R method.

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