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Nonlinear indirect combustion noise for compact supercritical nozzle flows

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ABSTRACT

In this paper, indirect combustion noise generated by the acceleration of entropy perturbations through a supercritical nozzle is investigated in the nonlinear regime and in the low-frequency limit (quasi-static hypothesis). This work completes the study of Huet and Giauque (*Journal of Fluid Mechanics* 733 (2013) 268–301) for nonlinear noise generation in nozzle flows without shock and particularly focuses on shocked flow regimes. It is based on the analytical model of Marble and Candel for compact nozzles (*Journal of Sound and Vibration* 55 (1977) 225–243), initially developed for excitations in the linear regime and rederived here for nonlinear perturbations. Full nonlinear analytical solutions are provided in the absence of shock as well as second-order analytical expressions when a shock is present in the diffuser. An analytical evaluation of the shock displacement inside the nozzle caused by the forcing is proposed and maximum possible forcings to avoid unchoke and 'over-choke' are discussed. The accuracy of the second-order model and the nonlinear contributions to the generated waves are then addressed. This model is found to be very accurate for the generated entropy wave with negligible nonlinear contributions. Nonlinearities are more visible, but still limited, for the downstream acoustic wave for large inlet Mach numbers. Analytical developments are validated thanks to comparisons with numerical simulations.

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1. Introduction

Increasingly severe regulations concerning noise emission are a real challenge for the conception of any new aircraft. Engine noise, in particular, is the major contributor to overall aircraft noise and much attention remains focused on its reduction. Considerable efforts have been performed during the last decades to reduce jet and fan contributions, leading to the emergence of other noise sources that were previously considered negligible. The contribution of such additional sources was evidenced in the 1970s, the noise emitted by modern turbofan being higher than the sole contribution of the jet [1]. This noise was first labelled *excess noise* [2], before being associated to the combustion process. At the present time, it is classically referred to as *core noise* [3] or *combustion noise* [4] with the two main contributors being direct and indirect noise. Direct noise is related to the pressure fluctuations generated by the unsteady heat fluctuation of the turbulent flame whereas indirect noise comes from the scattering of entropy or vorticity perturbations generated by the flame as they are accelerated by the mean flow or interact with turbine blades.

The propagation of acoustic waves in nozzles was first studied in the linear regime by Tsien [5] with a quasi-one-dimensional nozzle flow assumption. It was later extended to deal with the acceleration of isobaric entropy perturbations by Marble and Candel [6]. The authors proposed a model to deal with subcritical and supercritical compact nozzles without shock, as well as the particular case of supercritical nozzles with a shock located at the downstream end of the diffuser. The

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compact nozzle hypothesis assumes the nozzle length to be small compared to the entropy and acoustic wavelengths, so that the nozzle can be treated as a discontinuity with the conservation of mass, stagnation temperature and entropy between both extremities. This model is valid for low frequencies solely and does not take the nozzle geometry into account. Analytical developments were also provided for the non-compact supercritical nozzle with a linear velocity profile to illustrate the influence of the frequency on the generated noise. In the same period, different methods have been proposed by Bohn [7] and Bloy [8] to evaluate the noise generated through non-compact subcritical nozzles. Bohn [7] solved the linearized Euler equations in the frequency domain and especially evidenced the importance of the forcing frequency on the nozzle response by evaluating asymptotic high-frequency reflection and transmission coefficients, whereas Bloy [8] used the method of characteristics to evaluate numerically the pressure fluctuations generated by the acceleration of a temperature disturbance in the time domain. More recently, Stow et al. [9] and Goh and Morgans [10] extended the compact solution of Marble and Candel [6] for choked flows to low frequencies using an effective nozzle length correction through an asymptotic expansion and Moase et al. [11], Giauque et al. [12] and Duran and Moreau [13] generalized the non-compact approach of Marble and Candel to deal with any arbitrary nozzle geometry, without frequency limitation. An extension of the compact model to nonlinear perturbation is proposed by Huet and Giauque [14] without shock. The presence of a normal shock in the diffuser is addressed in the general case by Moase et al. [11] in the linear regime but its contribution on noise generation for nonlinear forcings has never been investigated.

It is the objective of the present work to address the indirect combustion noise generation by low-frequency, nonlinear excitations in supercritical nozzles. The linear approach is actually legitimate for mid- to high-frequency excitations which, having small wavelengths, are subject to intense turbulent dissipation in the burnt gas region before the nozzle or turbine stage, but it may reach its limits when low-frequency entropy forcings are considered. Indeed, below a few hundred Hz the wavelength of such fluctuations becomes comparable to the turbulent integral scale in the engine and no significant damping is expected in this case between the flame and the combustion chamber outlet. Recent studies have shown both numerically and experimentally the influence of coherent entropy waves on the onset or sustainability of combustion instabilities [15–20] and it seems reasonable to consider that such entropy perturbations can lie in the nonlinear domain. This work completes the study of Huet and Giauque [14] for nonlinear noise generation in nozzle flows without shock and particularly focuses on shocked flow regimes. The paper is organized as follows. The analytical models are derived in Section 2. The expression of the nonlinear invariants is first recalled and is followed by the full nonlinear models for the supercritical nozzle, without and with a shock. Full nonlinear analytical solutions are provided in the absence of shock, as well as second-order analytical expressions for shocked configurations. A validation of the nonlinear solutions is provided in Section 3 by comparison with numerical simulations. Thorough analyses of the nozzle response to nonlinear forcing are then performed in Section 4, including shock displacement in the diffuser and accuracy of the second-order model. To end, concluding remarks are given in Section 5.

2. Analytical models

In this section, a resolution starting from a modified set of equations is first addressed for the supercritical nozzle to provide exact analytical expressions in the nonlinear regime. Additional developments are then proposed to account for the presence of a shock in the diffuser and numerical full nonlinear and analytical second-order solutions are provided. This approach relies on nonlinear expressions of the flow invariants, whose derivation is presented in detail in Huet and Giauque [14] and expressions given hereafter.

For the sake of simplicity, the coupling between different excitations is not considered in the present paper: for any acoustic or entropy forcing, all other excitations are set to 0. This approach to the study of nonlinearities is legitimate because even thermo-acoustic instabilities can be analysed with success in the linear limit as far as acoustics is concerned [21–24]. In this case, the study of superimposed acoustic and entropy excitations is straightforward because it corresponds to the summation of both linear and nonlinear responses.

For one-dimensional flows, the three invariants present in the flow are the entropy, forward and backward acoustic waves. These invariants write respectively

$$\sigma = s'/c_p \tag{1}$$

$$\Gamma^+ = \frac{1}{2}\left(\frac{2}{\gamma-1}\left(\left(1+\frac{p'}{\overline{p}}\right)^{\frac{\gamma-1}{2\gamma}}-1\right)+\frac{u'}{\overline{c}e^{\frac{\sigma}{2}}}\right) \tag{2}$$

$$\Gamma^- = \frac{1}{2}\left(\frac{2}{\gamma-1}\left(\left(1+\frac{p'}{\overline{p}}\right)^{\frac{\gamma-1}{2\gamma}}-1\right)-\frac{u'}{\overline{c}e^{\frac{\sigma}{2}}}\right) \tag{3}$$

where p', u' and s' are the pressure, velocity and entropy fluctuations, respectively, $\overline{p}$ and $\overline{c}$ the mean pressure and sound speed, respectively, c_p the heat capacity at constant pressure and γ the adiabatic coefficient. The derivation of the acoustic invariants assumes a quasi-static evolution of the entropy perturbation, an hypothesis that is verified throughout the paper. The reader is referred to Huet and Giauque [14] for the detailed derivation of the invariants.

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