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A NUMERICAL STUDY ON THE ENTROPY NOISE GENERATED IN A SUDDEN AREA EXPANSION

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ABSTRACT

In this work, we investigate numerically the sound generated when incoming entropy waves are decelerated in a sudden area expansion. To this end, we linearise the compressible Navier-Stokes equations around a turbulent mean flow. The mean flow is obtained as a solution of the RANS equations. The linearised equations are then solved in the frequency domain to determine the acoustic variables. Finally, the transmission and reflection coefficients are obtained and compared with the predictions of two different quasi-steady models.

1. INTRODUCTION

Entropy noise refers to the sound generated when advective temperature fluctuations (entropy waves) are accelerated/decelerated by non-uniform mean flows [1]. A number of analytical models [2, 3] are available to predict entropy noise when the flow is accelerated through smooth cross-sectional area changes, i.e. nozzle flows. However, recent experimental studies [4, 5] have shown that such models, which rely on quasi-one-dimensional and isentropic assumptions, are inadequate when the area change is sudden. In these studies, the flow is accelerated/decelerated through a hole, comprising a sudden area contraction followed by an expansion. In the contraction portion, the flow remains essentially attached and isentropic. In the expansion part, on the other hand, the flow massively separates, creating a large recirculation zone which leads to strong mean-entropy gradients at the downstream side.

Using an acoustic analogy, Yang et al. [6] showed that the results for the expansion part significantly differ from the classical theory of Marble and Candel [2]. At low Mach numbers, the mismatch can be explained solely by the existence and extension of the recirculation region. The aforementioned model, however, is based on a Green's function method and is only applicable to low-Mach-number flows. In this work, we study the entropy noise generated in a sudden area expansion at different Mach numbers by numerical means. The results show that the predictions of Marble and Candel [2] significantly deviate from the numerical results and that this deviation becomes more severe when the Mach number is increased.

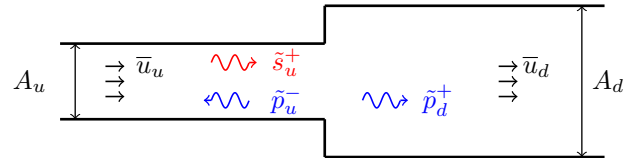


Figure 1. Schematic of the configuration. The subindices $()_u$ and $()_d$ denote variables defined in the upstream and downstream ducts, respectively.

2. METHODOLOGY

We consider an axisymmetric area expansion as depicted in Fig. 1. The geometry is defined by an expansion ratio $A_u/A_d = 0.346$. The area of the upstream duct is given by $A_u = \pi R_u^2$, with R_u the radius of the duct. A uniform flow of normalised speed $M_u = \bar{u}_u/\bar{c}_u$ is imposed at the inlet upstream of the expansion, giving a $Re = \bar{u}_u R_u/\nu = 10^6$. The steady mean flow is then obtained as the solution of the compressible Reynolds-Averaged Navier-Stokes (RANS) equations using the finite volume solver OpenFOAM [7] (version 4.1). The turbulent Reynolds stresses are modelled by the $k-\omega$ SST turbulence model. The mean-flow variables are denoted by $\bar{()}$.

A time-harmonic, small-amplitude entropic fluctuation $s'_u = \tilde{s}_u^+ e^{i\omega t}$ is superimposed at the upstream inlet. $\tilde{()}$ denotes time-harmonic perturbation variables and ω is the angular frequency. The acoustic response is subsequently obtained as the solution of the linearised Navier-Stokes equations (LNSEs). The LNSEs are recast in frequency domain and solved using a finite element method stabilised with a least-squares formulation [8]. The equations are implemented in the open-source computing framework FEniCS [9, 10]. At the inlet and outlet of the domain, non-reflecting boundary conditions are imposed. Finally, the downstream-propagating acoustic wave in the downstream duct \tilde{p}_d^+ , and the upstream-propagating one in the upstream duct \tilde{p}_u^- are computed using the multi-microphone method [11].

The numerical results are compared with the theory of Marble and Candel [2]. This model is valid in the zero-frequency limit and proposes upstream-downstream matching conditions obtained by applying the conservation of mass, stagnation enthalpy and entropy. A second

quasi-steady model is also proposed. This model, hereafter termed Model 2, derives the equivalent jump conditions, but using the conservation of mass, stagnation enthalpy and momentum. An additional unknown term appears in the momentum equation, the pressure at the back-plate, which is assumed equal to the pressure at the upstream duct p_u [12].

3. RESULTS

The reflection and transmission coefficients are defined, respectively, as

$$P_u^- = \tilde{p}_u^- / \gamma \bar{p}_u, \quad P_d^+ = \tilde{p}_d^+ / \gamma \bar{p}_d, \quad (1)$$

where γ denotes the ratio of the specific heat capacities of the gas at constant pressure and constant volume. Fig. 2 shows the reflection and transmission coefficients obtained when a normalised entropy perturbation is imposed at the inlet $\sigma = \tilde{s}_u^+ / c_p$, with c_p the specific heat capacity at constant pressure. Fig. 2(a) shows that the reflection coefficient predicted by the LNSEs is nearly constant at low frequencies ($St < 0.03$), but its value is about 1/3 of the predictions of Marble and Candel. At higher frequencies, non-compact effects cause the coefficient to drop in the form of a low-pass filter. The transmission coefficient Fig. 2(b) also presents a plateau at very low frequencies. However, non-compact effects arise at lower frequencies ($St \approx 0.01$), and a peak is reached at $St \approx 0.1$. After that value the coefficient drops and tends to a small value at higher frequencies. The difference with Marble and Candel is less acute in this case, but it is still quite large.

The predictions of Model 2 are also included in Fig. 2. It is apparent that these values are quite close to the numerical values, showing that this model is more adequate for sudden area expansions than the previous one.

4. CONCLUSION

We have performed numerical simulations of small-amplitude entropy waves decelerated in a sudden area expansion. The results show that quasi-one-dimensional and isentropic modelling is not adequate for this configuration. An alternative quasi-steady model has been proposed based on the conservation of mass, momentum and stagnation enthalpy. This model predicts accurately the reflection and transmission coefficients at low frequencies.

5. ACKNOWLEDGEMENTS

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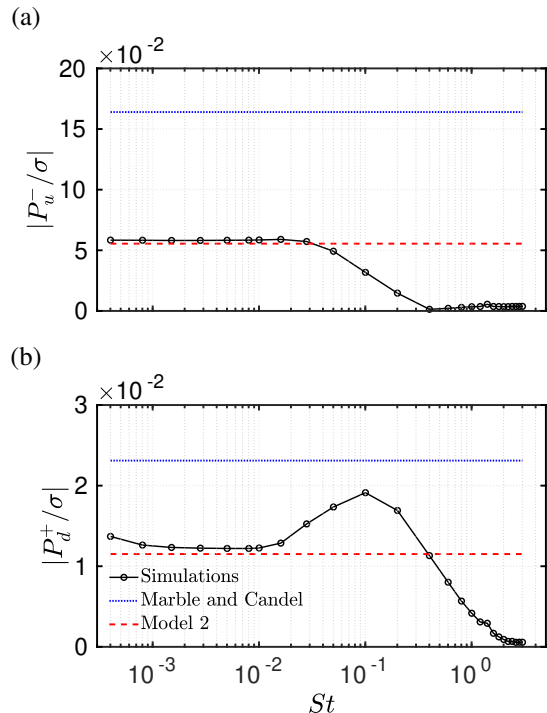


Figure 2. (a) Reflection and (b) transmission coefficients obtained from (black solid) the simulations, (blue dotted) predicted by Marble and Candel [2] and (red dashed) predicted by Model 2. The Mach number in the upstream duct is $M_u = 0.5$. The Strouhal number is defined as $St = \omega R_u / \bar{u}_u$.

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