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VARIATION OF ACOUSTIC ENERGY ACROSS A SUDDEN CROSS SECTION AREA INCREASE SUSTAINING A SUBSONIC MEAN FLOW

R. Gaudron[1] **J. Guzman-Iñigo**[1] **A. S. Morgans**[1]

[1] Department of Mechanical Engineering, Imperial College London, London, UK
r.gaudron@imperial.ac.uk

ABSTRACT

The variation of acoustic energy across a given geometry can be quantified using the acoustic absorption coefficient. A quasi-steady analytical model predicting the absorption coefficient across an axisymmetric sudden area expansion sustaining a subsonic mean flow is derived in this study. This dimensionless parameter is shown to depend on the inlet Mach number M_u, cross section area ratio θ, and upstream acoustic reflection coefficient $\mathcal{R}_u$. Numerical simulations are then used to validate the analytical model for a wide range of parameters. It is found that depending on $(M_u, \theta, \mathcal{R}_u)$, the acoustic energy can be either completely damped, partially damped, unaffected, or even amplified across the sudden area expansion.

1. INTRODUCTION

Acoustic waves propagating within suddenly expanding ducts containing a subsonic mean flow are of interest in many practical applications such as gas turbines, ventilation ducts, and domestic appliances [1–3]. It is known that the presence of a mean flow might be responsible for a transfer of energy between the acoustic waves and the vorticity fluctuations generated at the rim of the area expansion [4–6]. The objective of this work is to characterize the acoustic energy source/sink behavior of an axisymmetric sudden area expansion sustaining a subsonic mean flow. An analytical model predicting the acoustic absorption coefficient of sudden area expansions is first derived in Sec. 2. Numerical simulations covering a wide range of parameters are then presented in Sec. 3. The validity of the analytical model is finally discussed in Sec. 4.

2. ANALYTICAL MODEL

The analytical model predicting the acoustic energy source/sink behavior of axisymmetric sudden area expansions sustaining a subsonic mean flow is now derived. The fluid is assumed to be a perfect gas. All mean flow variables are assumed to be one-dimensional far away from the sudden area expansion. Body forces and heat transfers are neglected. Viscous effects are assumed to be negligible except close to the rim of the area expansion. The area expansion is further assumed to be acoustically compact. Under these assumptions, the compact conservation of mass, momentum and stagnation enthalpy are given by the following equations:

$$\nabla \cdot (\rho \mathbf{u}) = 0 \tag{1}$$

$$\nabla \cdot (\rho \mathbf{u} \otimes \mathbf{u}) = -\nabla p + \nabla \cdot \boldsymbol{\tau} \tag{2}$$

$$\nabla \cdot (\rho \mathbf{u} H) = \nabla \cdot (\boldsymbol{\tau} \cdot \mathbf{u}) \tag{3}$$

where ρ is the fluid density, $\mathbf{u}$ the velocity, p the pressure, $\boldsymbol{\tau}$ the viscous stress tensor, and H the stagnation enthalpy. Equations (1)-(3) are then integrated over a control volume enclosing the area expansion and linearised. The zeroth (respectively first) order terms lead to jump conditions for the mean (respectively fluctuating) variables across the sudden area expansion. The corresponding dimensionless equations indicate that both the mean flow and the linearised fluctuations are fully characterised by the inlet Mach number M_u and the cross section area ratio $\theta = A_u/A_d$ where A_u and A_d are the cross section area of the upstream and downstream ducts respectively.

The acoustic absorption coefficient is then defined as:

$$\Delta = 1 - \frac{|W_d^+| + |W_u^-|}{|W_u^+| + |W_d^-|} \tag{4}$$

where $W_{u/d}^{\pm}$ is the time-averaged surface-averaged acoustic energy flux associated with the wave propagating in the positive/negative direction upstream/downstream of the area expansion. The acoustic absorption coefficient compares the average amount of acoustic energy entering and leaving the system. Based on the previous equations, the absorption coefficient of a sudden area expansion is shown to be a function of M_u, θ and $\mathcal{R}_u$, the upstream acoustic reflection coefficient.

3. NUMERICAL SIMULATIONS

The predictions according to the analytical model are now examined using numerical simulations. Nine reference cases, corresponding to a large ($\theta = 0.01$), medium ($\theta = 0.1$) and small ($\theta = 0.5$) sudden area expansion sustaining a low ($M_u = 0.1$), moderate ($M_u = 0.5$) and high ($M_u = 0.9$) Mach number flow, are defined. The mean flow is first obtained using 3D compressible RANS simulations performed with OpenFOAM. The momentum and

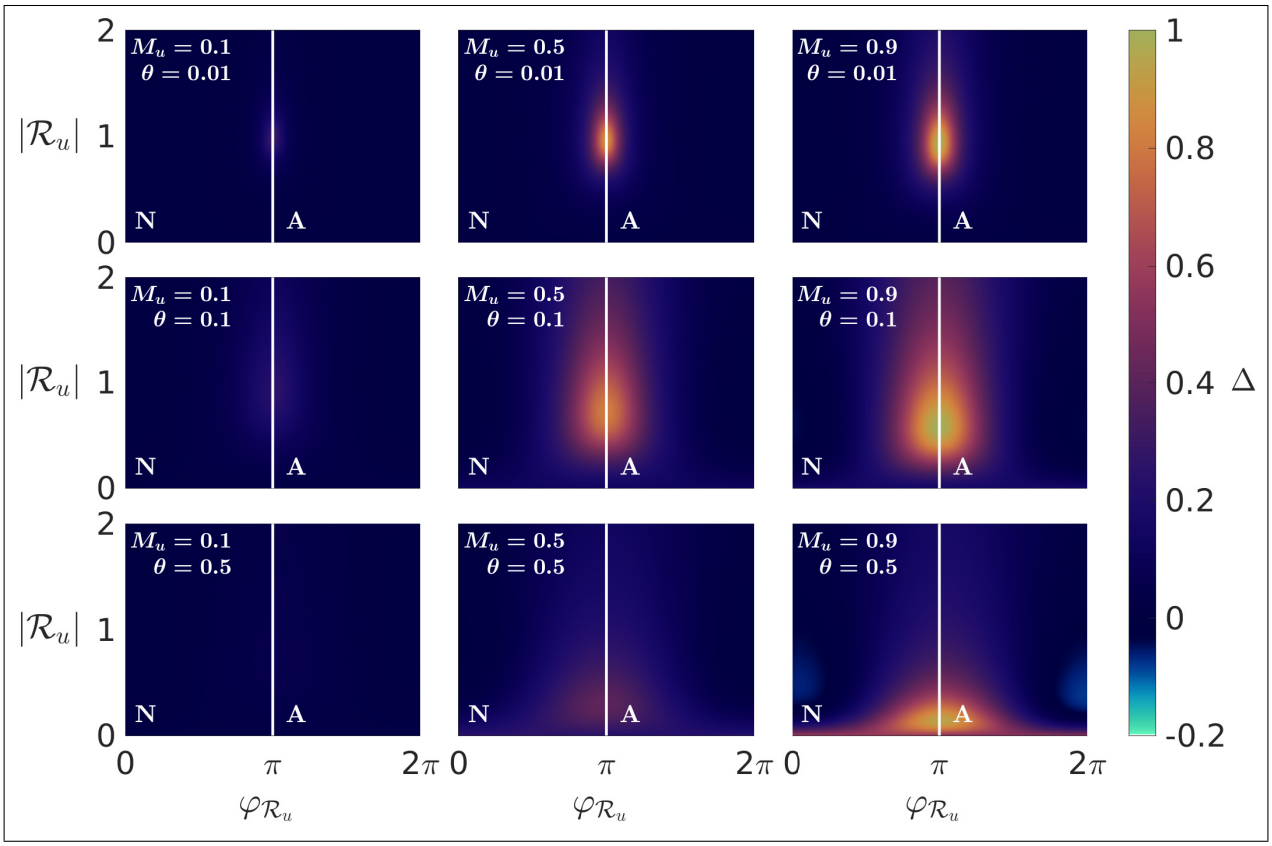

Figure 1. Acoustic absorption coefficient of a sudden area expansion as a function of the modulus (y-axis) and phase (x-axis) of the upstream acoustic reflection coefficient for three different upstream Mach numbers and cross section area ratios. (Top) $\theta = 0.01$. (Center) $\theta = 0.1$. (Bottom) $\theta = 0.5$. (Left) $M_u = 0.1$. (Middle) $M_u = 0.5$. (Right) $M_u = 0.9$. The left (respectively right) part of each subplot corresponds to the numerical solution (respectively the analytical prediction).

pressure equations are solved using a SIMPLE algorithm. The effects of turbulence are described using a $k - \omega$ SST model. A structured mesh is designed for every reference case such that the viscous sublayer is fully resolved. The acoustic flow field variables are then obtained using a Linearised Navier-Stokes Equations (LNSE) solver where the linearised conservation of energy is solved [7]. The ingoing Riemann invariants are set at the boundaries of the geometry. Vortical and entropy fluctuations are allowed to be generated inside the system, thus affecting its acoustic energy balance. The acoustic absorption coefficient is finally computed using the Riemann invariants extracted from the numerical solutions.

4. DISCUSSION

Figure 1 depicts the analytical and numerical acoustic absorption coefficient as a function of the modulus and phase of the upstream reflection coefficient for all nine reference cases. The agreement between the analytical model and the numerical simulations is excellent for all inlet Mach numbers M_u and cross section area ratios θ investigated. The analytical model is thus validated over a wide range of parameters.

Figure 1 also demonstrates that the acoustic absorption coefficient remains close to zero at low Mach numbers whatever the upstream acoustic reflection coefficient. As the inlet Mach number is increased, the impact of the upstream reflection coefficient becomes progressively larger. For instance, a narrow sudden area expansion ($\theta = 0.5$) sustaining a high Mach number mean flow ($M_u = 0.9$) has a unity absorption coefficient for $\mathcal{R}_u \sim -0.15$ but a slightly negative absorption coefficient for $\mathcal{R}_u \sim 0.5$. The first case corresponds to a very strong sink of acoustic energy while the second case corresponds to a limited source of acoustic energy.

5. CONCLUSION

In this study, an analytical model predicting the acoustic absorption coefficient of an axisymmetric sudden area expansion sustaining a subsonic mean flow has been derived. The analytical absorption coefficient was shown to be a function of the inlet Mach number M_u, cross section area ratio θ, and upstream acoustic reflection coefficient $\mathcal{R}_u$. This analytical model was then validated using numerical simulations for a wide range of parameters. The acoustic energy was found to be completely damped, partially damped, not affected at all, or even amplified across the area expansion depending on the exact value of $(M_u, \theta, \mathcal{R}_u)$. It was also found that the upstream acoustic reflection coefficient had a large impact on the acoustic absorption coefficient at high Mach numbers.

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