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## Sound generation in a hole-tone configuration

Javier Sierra Ausin<sup>\*1,2</sup>, David Fabre<sup>1</sup>, Vincenzo Citro<sup>2</sup>, and Flavio Giannetti<sup>2</sup>

<sup>1</sup>*Institut de Mécanique des fluides de Toulouse (IMFT), Toulouse 31400, France*

<sup>2</sup>*Dipartimento di Ingegneria (DIIN), Università degli Studi di Salerno, Fisciano 84084, Italy*

**Summary** It is aimed to describe dynamics of a whistling jet in a two hole configuration. The current configuration depicted in Fig. 1 displays tonal noise at low Reynolds numbers. Threshold of instability have been determined with aid of fully compressible linear stability theory and the evolution of the saturated frequency with a compressible weakly nonlinear stability method. The study at larger Reynolds numbers is carried out with an augmented compressibility model, a incompressible flow solver with impedance boundary conditions, whose underlying hypothesis are compacity of acoustic sources and monopolar radiation of sound. The augmented model has confirmed the existence of a region with bistability which was first determined in an experimental campaign.

### INTRODUCTION

The problem of the flow passing through circular holes in a plate is encountered in many practical applications and has been widely studied by experimental and numerical investigations, including human whistling, wind instruments, whistle of a tea kettle, the latter has been studied by Henrywood & Agarwal [1] or birdcalls (devices used by hunters to imitate bird singing) analyzed by Fabre et al. [2].

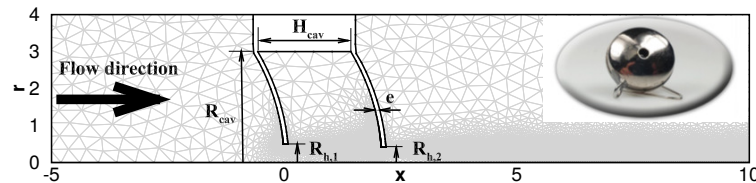


Figure 1: Sketch of the hole-tone configuration, frame of reference and definition of geometrical parameters. An example of computational mesh is also reported in light gray. An actual birdcall is depicted in the upper right corner.  $e$  denotes the thickness of the cavity wall, radius of holes  $R_{h,i}$ ,  $i = 1, 2$ , radius and length of the cavity are denoted by  $R_{cav}$  and  $H_{cav}$  respectively. Values of geometrical parameters can be found in Longordardi et al. [3].

Early attempts to characterise sound generation attracted attention from acoustic researches [4, 5, 6]. These early attempts approached the problem mainly from a purely acoustic point of view, the influence of the mean flow was neglected. Another possibility are the so called lumped models, where the hydrodynamical component of the system is modelled by a system of a limited number of degrees of freedom. Recently, the problem of sound generation has been tackled with linearised Navier Stokes equations. The instability mechanism at the threshold has been analysed on the one hole (see Fabre et al. [7, 8]) and the two hole configuration (see Fabre et al. [2]) using incompressible Navier Stokes equations where the compacity of acoustic sources is assumed and with compressible (see Longobardi et al. [3]) LNSE. These efforts allowed to identify the difficulties associated to boundary conditions which has been addressed by Sierra et al. [9, 10]. An experimental campaign on the hole-tone configuration carried out by Fabre et al. [11] has shown the appearance of complex dynamics such as quasiperiodicity and chaos for low to moderate Reynolds numbers. Theoretical and numerical determinations should provide some answers to the reason behind dynamics and the underlying physical mechanism.

### PRELIMINARY RESULTS

Most of sound generating devices are in essence self-sustained oscillators composed of two parts: An *acoustic system* which acts as a resonator and a *hydrodynamic system* which can be a shear flow. The purpose of this work consists in the analysis of dynamics of the double hole tone configuration with an special emphasis on the hydrodynamic part. The stability of the configuration is analysed via *linearised compressible Navier Stokes equations* (LNSE), which allow the determination of the onset. The saturated tone frequency past the instability onset is determined by a *weakly nonlinear analysis or multiple scales* method. Far beyond the threshold time stepping simulations are employed.

The study of weakly compressible flows with time stepping techniques becomes fast unaffordable when  $M \rightarrow 0$ , which makes an impossible task the parametric study of sound generation. To overcome this issue, augmented compressibility is proposed. This methodology consists in the modellisation of compressibility on the boundary conditions, on the cavity, inlet and outlet. Underlying assumptions of the methodology are compacity of acoustic sources and monopolar

\*Corresponding author. E-mail: javier.sierra@imft.fr

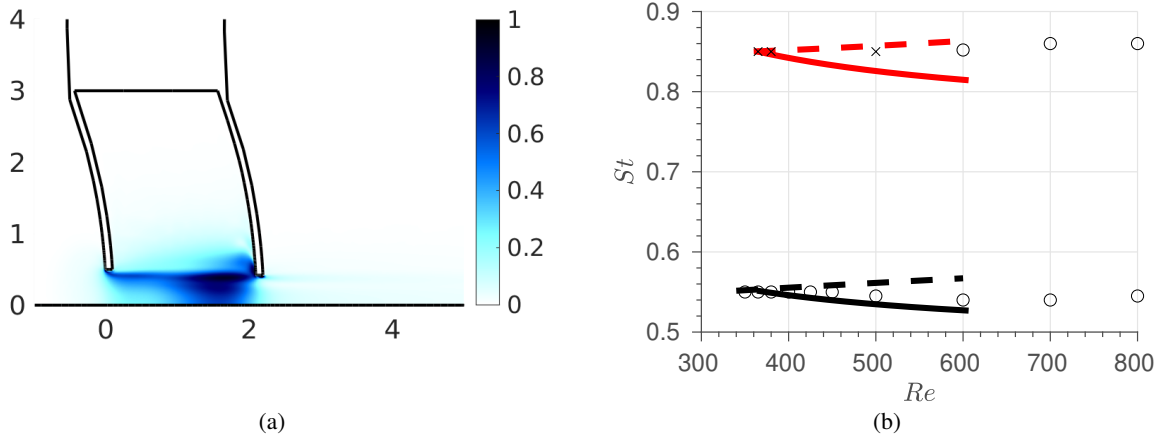


Figure 2: (a) Structural sensitivity of the flow field [12]. (b) Prediction of the whistling fundamental harmonic frequency at  $M = 0.02$ . Dashed lines corresponds to the frequency determined via compressible linearised Navier Stokes equations, solid lines to compressible weakly nonlinear stability, crosses ( $\times$ ) to unstable frequencies and circles ( $\circ$ ) to stable frequencies determined by augmented model

radiation, which have been verified in experiments [11]. The inlet and the cavity are modelled as a Helmholtz resonator whereas at the outlet a radiation boundary condition is imposed.

$$\int_{\Gamma_i} \left[ \frac{\partial p'}{\partial t} + \frac{S_i}{V_i M^2} \mathbf{u}' \cdot \mathbf{n} \right] dS = 0, \quad i = \text{inlet or cavity} \quad (1a)$$

$$\int_{\Gamma_{out}} \left[ \frac{\partial^2 \mathbf{u}' \cdot \mathbf{n}}{\partial t^2} + \frac{8}{M S_{out}} p' \right] dS = 0 \quad (1b)$$

The current model needs to be validated with a fully compressible time stepping simulation. In frequency domain augmented compressibility model has already provided fruitful results, see Longobardi et al. [3]. Augmented compressibility model serves as a tool for parametric exploration of the parametric space in particular in those regions with rich nonlinear dynamics, such as nonlinear periodic or non-periodic regimes. Furthermore, compressible linear and weakly non linear stability show a purely hydrodynamic feedback mechanism localised in the region between the two holes, that is the wavemaker is found in the jet between both holes, see Fig. 2.

Numerical simulations of the augmented model show the existence of a range in Reynolds number  $Re$  of bistability, existence of two stable invariants, i.e. limit cycles. These predictions have been complemented with fully compressible linear and weakly nonlinear stability methods.

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