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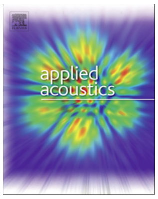

Technical Note

A setup to study aero-acoustics for finite length ducts with time-varying shape

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ABSTRACT

Elastic ducts with time-varying geometry are a recurrent issue in many engineering and physiological flow or sound production problems. In this study, we present and characterize a setup to study aero-acoustic phenomena through a deformable duct with time-varying geometry. The setup is designed in such a way that experimental control parameters relate directly to input parameters of a quasi-analytical geometrical model (Van Hirtum, 2015). We focus on low Mach number and moderate Reynolds number applications pertinent to physiological problems for which geometrical model input parameters can be related to well defined physiological quantities. Therefore, data gathered using the presented setup allow to study underlying physical phenomena and in addition favor comparison with high performance computational simulations as well as with analytical models for which a limited number of physiological meaningful input parameters are essential. Typical measurements illustrate the impact of geometrical control parameters on the acoustic pressure field in absence and in presence of flow, respectively.

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1. Introduction

Sound production and propagation through ducts is well studied when considering ducts with a constant shape [17,4,15]. Whereas such ducts are essential for many applications – *e.g.* industry (applications related to liquid/gas transport [6,18]), musical acoustics (flute resonators or organ pipes [10]), *etc.* – much less research considers sound production and propagation through ducts with a time-varying shape. Nevertheless, physiological phenomena related to noise production and propagation often occur in ducts with a time-varying shape related to blood flow or air flow [12,5,7,8,3,2,16].

Human speech production is a common example of such a phenomenon, naturally associated with sound production, for which the duct's, *i.e.* upper airway, shape varies voluntary during articulation of different phoneme utterances [13,19,1,9]. In this case, sound through a finite duct is generated either aerodynamically somewhere in the upper airway or is due to a fluid–structure interaction resulting in auto-oscillation at the duct's inlet, *i.e.* at the larynx [9]. Obviously, the detailed geometry of a time-varying human upper airway – or more in general physiological flow or sound systems – is extremely complicated and is subject to intra- and inter-subject variability. In addition, measurement of geometrical, flow and acoustic properties on human subjects is limited and therefore not suitable for studies aiming physical understanding of sound production and propagation. Consequently, systematic physical studies often rely on simplified geometries to enhance understanding [12,9,19].

In the current work, a setup is presented to study aero-acoustics of finite ducts for moderate Reynolds numbers and low Mach numbers as suitable for physical studies of physiological flow and sound systems such as the human upper airway. It is aimed to control the duct's geometry using a limited amount of control parameters related to constriction degree, duration and position for up to two constrictions. Systematic variation of these parameters is expected to enhance model validation since most studies consider a limited amount of static geometrical configurations which hinders general conclusions [22]. In addition, new insights in transient phenomena related to controlled time-varying geometries are expected to be gained since such data are few in literature. Consequently, quantitative measurements in relation to a controlled time-varying duct geometry potentially increases understanding of the impact of the duct's geometry on the flow and sound field.

Besides possible applications related to physiological flow or sound systems the proposed setup can be used to contribute to active vibration and noise control strategies. As an example, the impact of varying the constriction degree on *e.g.* fluid–structure

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interaction somewhere in a duct has been show to be a simple way to fine-tune the associated auto-oscillation frequency and instability onset pressure [22] whereas other studies focus on the impact of the duct geometry on sound scattering for engine exhaust silencers [14].

In the following, the design and realization of the setup is detailed and characterized. Next, examples of quantitative measurements are discussed in order to provide evidence to what extent complex aero-acoustic phenomena, including transient regimes, can be produced, reproduced and hence studied. The impact of the duct geometry is shown.

2. Setup

2.1. Design

The design is inspired on recent work on the deformation of an a priori uniform circular (diameter $D = 2b_0$, with b_0 the radius of the undeformed circular cross-section) elastic duct by pinching it between two parallel bars [20]. A quasi-analytical geometrical model was proposed and validated to describe the pinched duct portion based firstly on the assumption of a constant perimeter ($P \simeq 2\pi b_0$) and secondly on the assumption that each cross-section can be described as a stadium ring. The internal shape of the duct is modeled as a function of the imposed pinching effort $\mathcal{P} = 1 - b_{x_c}/b_0$ with $b_{x_c} \leqslant b_0$ corresponding to the minimum radius of the compressed duct. The approach results in an characteristic error of less than 4% of the duct's diameter for pinching efforts between 40% and 95%. Besides the low computational cost, the quasi-analytical duct model has the advantage to depend on a single parameter b_{x_c} defining the imposed pinching effort at position x_c. Moreover, the model holds regardless the importance of the applied constriction effort $\mathcal{P}$ (small, modest or severe pinching efforts). A pinched circular duct of length L oriented along the x-direction is illustrated in Fig. 1(a). Main geometrical parameters are indicated: undeformed circular internal radius b_0 defining perimeter P, wall thickness d, pinching position x_c, major $a(x)$ and minor $b(x)$ axes of the cross-section.

The design of the setup exploits these features by aiming to control as a function of time t the position of pinching along the duct's main axis $x_c(t)$ as well as the pinching effort $\mathcal{P}$ by imposing $b_{x_c}(t)$. Consequently, the pinched duct's geometry can be approximated from the time-dependent parameter set $\{b_{x_c}, x_c\}(t)$ using the geometrical duct model following the flowchart indicated in Fig. 2 and its outcome is illustrated in Fig. 1(b). The instantaneous input parameter set $\{b_{x_c}, x_c\}$ consists of the constriction position (x_c) and the minor axis at this position (b_{x_c}). Besides time-varying parameters, two constant geometrical duct parameters are given – unpinched internal radius and duct's length $\{b_0, L\}$ – as well as the internal diameter and length $\{D_l, l\}$ of the attachment portion which geometry is determined by the way the duct is mounted to the remaining of the setup (see realization in Section 2.2). Therefore, the geometry is modeled for longitudinal x-positions in the range $-L + l < x \leqslant 0$.

Concretely, for a pincer consisting of two parallel round bars and a duct with internal radius b_0, the minor axis at each longitudinal position $b(x)$ at time instant t is then estimated from the known input parameters as [20]:

$$b_{(x_c, b_{x_c})}(x) = b_0 - b_0 \cdot \left(1 - \frac{b_{x_c}}{b_0}\right) \cdot \left(\frac{(x - x_c)^2}{\alpha_b^2} + 1\right)^{-1}, \tag{1}$$

with in the case of a pincer with parallel round bars of diameter 6.4 mm

$$\alpha_b(1 - \beta(x_c)) = 48 \cdot (1 - \beta(x_c))^2 - 70 \cdot (1 - \beta(x_c)) + 39, \tag{2}$$

$$\beta(x) = b(x)/b_0. \tag{3}$$

Once minor axis $b(x)$ is known at each longitudinal x-position, the corresponding duct's cross-section in polar coordinates (r, θ) is modeled as a piecewise function of $\theta \in [0, 2\pi]$:

$$r_b(\theta) = \begin{cases} \frac{b}{\sin(\theta)}, & \text{for } \varphi \leqslant \theta \leqslant \pi - \varphi, \\ \frac{\pi}{2} b \frac{1-\beta}{\beta} \left[\left(\frac{4}{\pi^2} \left(\frac{\beta}{1-\beta} \right)^2 - \sin^2(\theta) \right)^{1/2} + \cos(\theta) \right], & \text{for } -\varphi < \theta < \varphi, \\ \frac{\pi}{2} b \frac{1-\beta}{\beta} \left[\left(\frac{4}{\pi^2} \left(\frac{\beta}{1-\beta} \right)^2 - \sin^2(\theta) \right)^{1/2} - \cos(\theta) \right], & \text{for } \pi - \varphi < \theta < \pi + \varphi, \\ -\frac{b}{\sin(\theta)}, & \text{for } \pi + \varphi \leqslant \theta \leqslant 2\pi - \varphi, \end{cases} \tag{4}$$

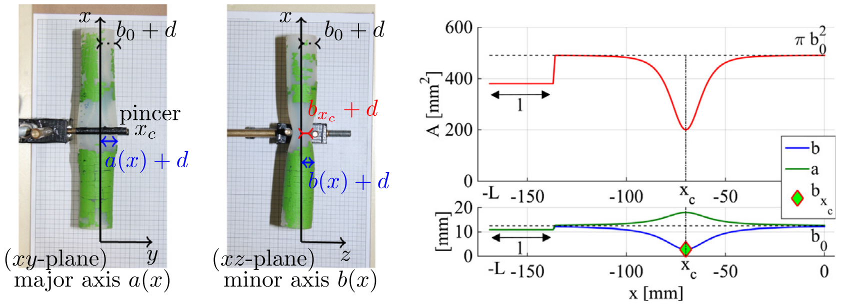
with critical angle $\varphi(b) = \arctan \frac{2}{\pi} \frac{\beta}{1-\beta}$.

Other geometrical variables important for aero-acoustic applications such as the area function $A(x)$ or major axis $a(x)$ can then be expressed as a function of minor axis $b(x)$ as well:

$$A(x) = \pi b^2 + 2\pi b_0^2 \beta (1 - \beta), \tag{5}$$

$$a(x) = b + \frac{\pi}{2} b_0 (1 - \beta). \tag{6}$$

Following this design outlined in Fig. 2, the duct's geometry can be accurately modeled for a duct pinched between two parallel blocks with circular extrema of diameter 6.4 mm enveloping the duct in the plane perpendicular to the duct's longitudinal axis (x-direction) at a known constriction position x_c and for a known minor axis at this position b_{x_c}. Consequently, in the next Section 2.2



(a) principle of pinched elastic duct (b) duct's geometrical features ($\mathcal{P} = 77\%$)

Fig. 1. (a) Main parameters of a pinched duct (unpinched internal radius b_0 or constant perimeter $P \simeq 2\pi b_0$, constant wall thickness d) along the z-direction for pinching effort $\mathcal{P} = 1 - b_{x_c}/b_0$ applied at longitudinal position x_c. (b) Some modeled geometrical quantities (area $A(x)$, major $a(x)$ and minor $b(x)$) for a duct of length L for known input of constriction position x_c and imposed pinching effort $\mathcal{P}$ associated with b_{x_c}. The duct's exit is taken as the origin of the x-axis so that its inlet corresponds to $-L$. Attachment length l is indicated (length corresponding to connection of the duct to remaining of the setup (Section 2.2) for which the diameter is reduced to D_l).

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