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Modeling and validation of auto-oscillation onset in a constricted tube with application to phonation

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ABSTRACT

An experimental study of the auto-oscillation onset is performed for airflow in a rigid tube containing a constriction downstream from a deformable portion as a function of the constriction degree. A quasi-one dimensional laminar flow model in combination with a reduced order mechanical model (symmetric two mass model) provides a physical fluid–structure interaction model of the deformable portion. Mechanical, geometrical and flow model parameters are chosen to match the experimental setup. Modeled as well as experimental results show that a severe constriction ($>80\%$) at first hinders ($\geq 89\%$) and eventually inhibits ($\geq 95\%$) auto-oscillation. Constrictions of different severity occur naturally in voiced speech sound production (phonation) due to articulation. The current study provides quantitative evidence of the role of the vocal tract constriction degree as a control parameter for phonation (voiced speech sound production) since increasing the constriction degree decreases the vocal folds oscillation frequency (decrease by 25%) and increases the minimum pressure needed to initiate oscillation (increase by 80%).

1. Introduction

Normal speech production involves a series of successive transitions between open (*e.g.* neutral vowel or schwa) and obstructed vocal tract configurations (*e.g.* oral occlusive or stop) so that the corresponding area constriction ratio varies between 0 (no constriction) and 1 (total closure).

Since the pioneering work by the late 1960s (Lisker and Abramson, 1964, 1971), a large amount of ongoing literature reports on the crucial role of the vocal tract configuration in laryngeal and articulatory adjustment for voicing and devoicing (see *e.g.* Ohala and Riordan, 1980; Westbury, 1983; Bickley and Stevens, 1986; Lofqvist et al., 1995; Svirsky et al., 1997; Koenig et al., 2008; Pinho et al., 2012). As a result, semi-occlusives are an established tool for voice training and semi-occluded vocal tract exercises are commonly used in speech therapy (see *e.g.* Laukkanen et al., 2008; Cielo et al., 2013).

In contrast to the cited papers on phonetic properties of the phonological voicing contrast, physical and mathematical studies aiming to understand the possible effect of the vocal tract configuration on the vocal folds dynamics are mostly limited to the impact of acoustical coupling for a uniform open vocal tract configuration (Laje et al., 2001; Zhang et al., 2006; Zanartu et al., 2007; Lucero et al., 2012) or to vocal tract acoustics with (Davies et al., 1993) or without (Arnela and Guasch, 2013; Blandin et al., 2015) accounting for convective flow effects. Therefore, the aim of this work is to contribute to the modeling and experimental validation of the impact of a vocal tract constriction on the outcome of a physical phonation

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model, *i.e.* auto-oscillation of the vocal folds. Such a model approach allows us to express key phonation parameters, such as the pressure threshold at phonation onset, as a function of a limited number of physiologically meaningful parameters to which the vocal tract constriction degree is added. This is a necessary step towards a more extensive study of laryngeal or articulatory adjustment from a physical point of view.

In the following, the impact of a vocal tract by varying constriction degree downstream from a glottal replica (Ruty et al., 2007; Ruty, 2007) on vocal folds auto-oscillation onset is systematically explored using an experimental setup to measure pertinent physical quantities. It was shown (Ruty et al., 2007; Ruty, 2007) that the glottal replica was capable to reproduce phonation pressure thresholds (200–1000 Pa) and auto-oscillation frequencies (100–180 Hz) relevant to the ones observed on human speakers. The streamwise length of a uniformly constricted segment is held constant at 20 mm which corresponds to an order of magnitude of a vocal tract constriction between the tongue and the hard palate (Daniloff et al., 1980; Stevens, 2000). The tube length downstream from the glottal replica has a length of 50 cm which is larger than a human vocal tract (typically 18 cm Daniloff et al., 1980; Stevens, 2000). This is done to avoid secondary noise sources. A simple flow model based on Euler equations is applied to describe the pressure distribution within the vocal tract and to model the influence of the vocal tract constriction on the glottal pressure drop driving phonation. The flow model is then applied to a physical model of speech sound production (van Hirtum et al., 2014) in order to address the impact of a vocal tract constriction from basic fluid dynamical principles for a given vocal tract constriction degree. Acoustical coupling with a downstream pipe representing the supraglottal vocal tract is accounted for in the phonation model. The possible influence of the flow on the wavenumber (Davies et al., 1993) is neglected in the applied model approach as well as the influence of acoustic energy losses along the downstream pipe (Atig et al., 2004; Guilloteau et al., 2014). Moreover, a short upstream pipe is considered in both the model as the experiments. Hence the potential impact of acoustical coupling with an upstream pipe representing the subglottal trachea (Zhang et al., 2006) is not accounted for as well.

2. Method

2.1. Flow model

The onset/offset of vocal fold auto-oscillation is governed by the pressure drop across the glottis. From classical flow studies, it is easily understood that the presence of a constriction in the vocal tract downstream from the glottis alters the pressure distribution within the vocal tract and hence the glottal pressure drop. A simplified vocal tract geometry is schematized in Fig. 1. It consists of a uniform channel with cross-sectional area A_t placed between two constrictions – one at the glottis containing the vocal folds and the other one between the tongue and the hard palate somewhere further downstream with cross sectional area A_{1s}. The total pressure drop ΔP_{tot} yields approximately the imposed subglottal pressure P_{sub}, *i.e.* the pressure immediately upstream from the glottis. The glottal pressure drop ΔP_0 driving vocal folds auto-oscillation is then obtained from the difference of the subglottal pressure P_{sub} and the pressure drop at the constricted vocal tract portion ΔP_1. The pressure drop at the constricted vocal tract portion ΔP_1 is expected to increase as the constriction degree $(1-A_{1s}/A_t)$ increases. Therefore, a pressure recovery immediately downstream from the glottis is expected to occur, which will reduce the pressure drop across the glottis ΔP_0 and hence potentially affects the onset of vocal folds auto-oscillation or phonation.

Based on a non-dimensional analysis of the governing Navier–Stokes equations (Schlichting and Gersten, 2000) and typical values of geometrical and flow characteristics observed for a male adult (Daniloff et al., 1980), the pressure driven flow within the channel is assumed to be laminar (Reynolds number, $\mathrm{Re} \sim O(10^3)$), steady (Strouhal number, $\mathrm{Sr} \ll 1$), incompressible (squared Mach number, $\mathrm{Ma}^2 \ll 0.1$) and two-dimensional (channel aspect ratio or width-to-height ratio, $Ar \gg 4$). The assumption of a two-dimensional flow implies a rectangular glottal cross-section shape for which the height (along the medial–lateral direction) varies along the flow direction $h(x)$ whereas the glottal width (along the anterior–posterior direction) w is fixed. The varying cross-sectional area in the channel can thus be written as $A(x) = h(x) \times w$. Using

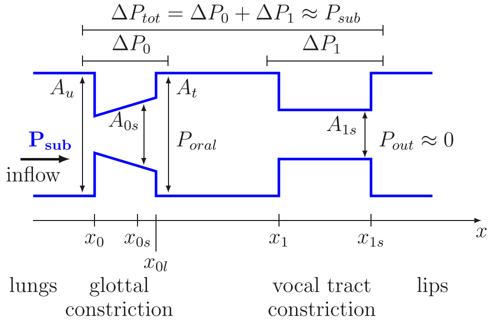

Fig. 1. Schema of glottal and vocal tract geometry enveloping airflow in the streamwise direction (x): pressure $P_\cdot$ (subglottal $\cdot = sub$, oral $\cdot = oral$, outlet $\cdot = out$), pressure drop $\Delta P_\cdot$ (glottal $\cdot = 0$, oral $\cdot = 1$, total $\cdot = tot$), cross sectional area $A_\cdot$ (subglottal $\cdot = u$, glottal flow separation $\cdot = 0s$, downstream end of glottal constriction $\cdot = 0l$, unconstricted vocal tract $\cdot = t$ and uniform vocal tract constriction $\cdot = 1s$).