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On the jet formation through a leaky glottis

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ABSTRACT

The present experimental study aims at analyzing the jet formation of the glottal jet flow using a model of a leaky glottis. Experiments were performed in a flow channel with dynamic models of the vocal folds in order to measure the glottal waveform and the velocity distribution in the supraglottal region using High Speed Particle Image Velocimetry (HSPIV). Proper Orthogonal Decomposition (POD) of the vortex Q-criterion was performed in order to detect the energetically most significant large-scale vortex structures and their appearance in the jet flow. The spectral analysis of the glottal waveforms results in an increased spectral decay with more prominent peaks at higher frequencies in the case of a leaky glottis compared to a completely closing reference case. Vortex induced fluctuation frequencies have similar spectral content in both cases as they appear as trains of vortex packets in a regular manner over the glottal cycle. However, when removing the false vocal folds in the leaky glottis model, coherence of vortex generation is lost over the motion cycle. Thus, the presence of the false vocal folds retains most of the vortex induced characteristics in the source spectrum even when the vocal folds do not close fully.

1. Introduction

Investigations of the characteristic flow field downstream of the glottis are an important step towards understanding human voice production and speech quality. Our voice is the result of a complex interaction of different processes in the larynx: an airflow from the lungs forces the adducted vocal folds to open a gap and a glottal jet flows through the supraglottal region, Fig. 1. The opening of the glottis due to the gap reduces the air pressure of the lungs and the laryngeal muscles force the vocal folds to close the gap. This process repeats and the flow-induced vibrations of the vocal folds generate a pulsatile glottal jet with a significant sound spectrum.

Most people have a healthy speech production but at least 20% of the population develop a voice production disorder, Mittal et al. (2011). One of these disorders is characterized by an incomplete glottal closure which is comparable with a leaky valve. The investigation of the differences between complete and leaky glottal closure is the motivation of the present study.

Voice quality in normal speech can be classified into pressed, modal, and breathy, Laver (1980) and Titze (1995). The breathy phonation is characterized by an incomplete closure of the vocal folds during the closing phase of the glottal cycle. Consequently, the glottal waveform consists of two components: one component is the periodic pulsating flow and the other is a considerable steady flow, which corresponds to the size of the open gap. The acoustic consequence of glottal

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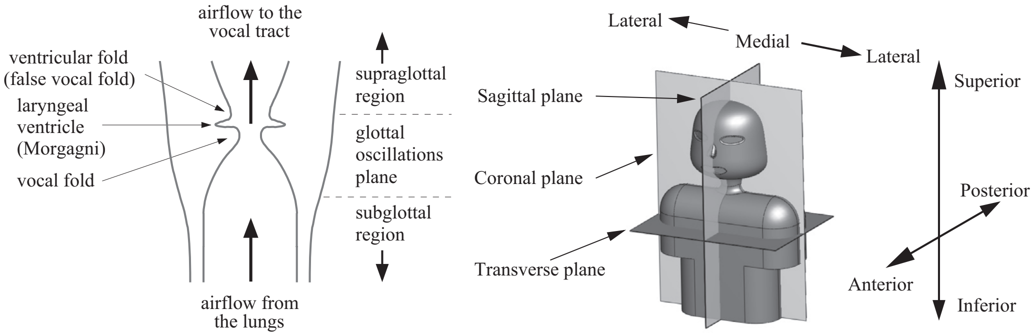

Fig. 1. Sectional view of the human larynx (left) and definition of physiological data planes by Mittal et al. (2013) (right).

leakage is a modification of the spectrum of the glottal waveform: (1) increased bandwidth of the first peak in the frequency spectrum; (2) increased tilt of the glottal spectrum at higher frequencies; and (3) appearance of a turbulent noise source near the glottis with considerable spectral amplitudes, Båvegård and Fant (1994), Hanson (1997) and Chen et al. (2011).

There have been few quantitative investigations of the acoustic consequences of glottal leakage: the influence of an incomplete closure of the vocal folds during speech production has been examined by Cranen and Schroeter (1995, 1996) by means of a computer simulation. The authors analyzed the changes of the glottal waveform due to leakage caused by two different types of leaks: a linked leak (triangular chink at one side of the glottis) caused by abduction and a parallel chink (rectangular chink between the vocal folds) in addition to the time-varying glottal gap. The spectra of the derivative waveforms show a major difference in their spectral slopes: in the case of a parallel chink, the slope is similar to the case without leakage. In the case of a linked leak, the slope decays more rapidly.

More recently, Park and Mongeau (2008) investigated the influence of a posterior gap on glottal flow and sound production experimentally. They used a driven air model with a vibrating orifice. For simulation of the vocal tract a confinement was added. Models of the ventricular folds were not applied. Due to the posterior gap they found an increase of the broadband radiated sound pressure level at higher frequencies within the human frequency range. The energetic source of this jet noise is turbulent fluid motion within the supraglottal region.

The last decade saw the publication of several studies on the influence of vortical structures in the glottal jet flow on speech production. Numerical investigations were carried out for example by Zhao et al. (2002), Zhang et al. (2002a), Horáček and Švec (2002), Horáček et al. (2005), Krane (2005), Suh and Frankel (2007), Chouly et al. (2008), Mihaescu et al. (2010), Zheng et al. (2011) and Smith and Thomson (2013). Experiments were performed for example by Zhang et al. (2002b, 2004), Zhang and Mongeau (2006), Zhang and Neubauer (2010), Krane et al. (2007), Neubauer et al. (2007) and Khosla et al. (2007, 2008a,b, 2009). A comprehensive summary of the state of knowledge about the fluid dynamics of human speech production was published by Mittal et al. (2013).

Following is a very short explanation of the main sound sources:

1. The unsteady volume flow rate due to the oscillation of the vocal folds is a monopole source, Zhang et al. (2002a).
2. Vortical structures develop within the intraglottal and supraglottal regions of the vocal tract due to Kelvin–Helmholtz instabilities along the shear layer of the glottal jet. These structures can change the trajectory of the jet, e.g. by interaction with geometrical structures in the supraglottal region. This unsteady vortex shedding produces dipole sources with the greatest strength of all sources, Mittal et al. (2013).
3. Quadrupole sound sources exist and are determined by turbulent motion of the glottal flow, Zhao et al. (2002), Zhang et al. (2002b) and Mittal et al. (2013).

This paper describes experimental investigations of the hydrodynamic sound sources of a leaky glottis model in comparison to a completely closing glottis model. Both models were investigated with and without models of the ventricular folds. This led to an increase of the data volume, but the presence of ventricular folds in the supraglottal space is still subject of controversial discussion on their relevance for human voice and speech quality, Alipour and Karnell (2014) and Farahani et al. (2013). Even in surgical treatment of pathological voice disorders there is still no clear answer to what extend and if at all a resection of the false vocal folds changes the behavior of the vocal folds. Thus it has not been studied how far a leaky glottis as a typical disorder is affected when the false vocal folds are removed. This is a question of great physical interest from a fluid-interaction point of view and of therapeutic relevance. Therefore, we studied the leaky glottis in two experiments, the first in the natural situation with false vocal folds and compared those results with the case after resection.

The used method was an analysis of the vortex induced source spectra of the glottal jet flows through the models in a pressure driven water duct. The experimental investigations were performed using High Speed Particle Image Velocimetry (HSPIV) and the snapshot method of Proper Orthogonal Decomposition (POD), Triep et al. (2005), Triep and Brücker (2010) and Kirmse et al. (2010). Furthermore, the glottal waveform was measured optically with high accuracy using the