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Analysis of flow-structure coupling in a mechanical model of the vocal folds and the subglottal system ☆

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Abstract

An analysis is made of the nonlinear interactions between flow in the subglottal vocal tract and glottis, sound waves in the subglottal system and a mechanical model of the vocal folds. The mean flow through the system is produced by a nominally steady contraction of the lungs, and mechanical experiments frequently involve a 'lung cavity' coupled to an experimental subglottal tube of arbitrary or ill-defined effective length L, on the basis that the actual value of L has little or no influence on excitation of the vocal folds. A simple, self-exciting single-mass mathematical model of the vocal folds is used to investigate the sound generated within the subglottal domain and the unsteady volume flux from the glottis for experiments where it is required to suppress feedback of sound from the supraglottal vocal tract. In experiments where the assumed absorption of sound within the sponge-like interior of the lungs is small, the influence of changes in L can be very significant: when the subglottal tube behaves as an open-ended resonator (when L is as large as half the acoustic wavelength) there is predicted to be a mild increase in volume flux magnitude and a small change in waveform. However, the strong appearance of second harmonics of the acoustic field is predicted at intermediate lengths, when L is roughly one quarter of the acoustic wavelength. In cases of large lung damping, however, only modest changes in the volume flux are predicted to occur with variations in L.

Keywords: Phonation; Voiced speech; Vocal folds; Vortex sound

1. Introduction

Titze (1988) has argued that feedback coupling of sound waves in the upper and lower sections of the vocal tract on the motion of the vocal folds must generally be relatively weak. Such coupling is likely to be at its strongest at higher frequencies when the voicing frequency approaches the first formant (Joliveau et al., 2004). Then voicing sources can interact with resonances to produce undesirable, involuntary and abrupt changes in frequency; this has been observed during phonation, particularly for resonances of the lower (or subglottal) section of the vocal tract (Titze and Story, 1995; Austin and Titze, 1997; Titze, 2008).

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Experimental studies of phonation that involve either an excised larynx or a laboratory model of the larynx are frequently designed to avoid unwanted coupling with the subglottal region by use of a long subglottal duct whose resonance frequencies are very much smaller than voiced frequencies of interest (Titze and Story, 1995; Alipour and Scherer, 2001; Thomson et al., 2005; Zhang et al., 2007a). On the other hand, some experiments are performed using physical models that replicate more closely the human subglottal system [e.g. Zhang et al. (2007b, 2009)]. The length of the subglottal tube upstream of the larynx is then typically between 17 and 20 cm and it usually terminates in a large reservoir or plenum. The whole arrangement is intended to provide a simplified mechanical model of the trachea, bronchi, and lungs (Flanagan, 1958; Ishizaka et al., 1976).

Many reports of these experiments omit completely important details of the laboratory subglottal region, so that likely influences on voicing of subglottal geometry and mechanical properties cannot easily be ascertained, even when these influences could play a prominent role in determining measured output acoustics (Zhang et al., 2007a). Similarly, numerical investigations frequently proceed on the assumption that the subglottal region is a constant pressure source, without resonances. Indeed, these difficulties were recognized by Zhang et al. (2007a) who concluded, from detailed measurements supported by linearized analysis of the coupled motion of the vocal folds and the subglottal sound, that the results of many experiments reported in the literature are actually a consequence of the action on the vocal folds of unreported or unmeasured feedback from subglottal resonances.

Estimates of feedback strength and its influence on glottis oscillations have generally involved *ad hoc* representations of the coupling between the acoustic field and surface tissue in the glottis (Flanagan and Landgraf, 1968; Gupta et al., 1973; Zanartu et al., 2007; Titze, 2008). In particular, according to an analysis of Zanartu et al. (2007), using a single-mass model of the glottis, the back reaction of acoustic pressures strongly control the maintenance of self-sustaining oscillations. When the vocal folds are coupled only to the lower vocal tract no self-sustained oscillation is observed for any subglottal configuration, apparently in contradiction to the simple single-mass models suggested by Zhang et al. (2007b). Thus the properties of the subglottal tract can strongly affect phonation, although according to Zanartu et al. (2007) the influence of acoustic feedback from the upper tract is more important. Many of these conclusions may be a consequence of the properties of the particular single-mass model of the vocal folds used in their analysis because, for example, the one-mass model of Howe and McGowan (2009) exhibits self-sustained oscillations even in the absence of acoustic feedback. However, a number of experimental studies [e.g. Austin and Titze (1997), Zhang et al. (2007a,b)] record variations of the fundamental frequency with changes in the subglottal and supraglottal tracts.

In this paper subglottal feedback is examined in detail for a mechanical model of the glottis whose fluid mechanical characteristics can be specified precisely, and where the acoustic and aerodynamic pressures associated with vortex shedding during jet formation are calculated with proper account taken of the local geometry of the moving boundaries. A nonlinear analytical model is developed in terms of the theory of aerodynamic sound (Howe, 1998; Howe and McGowan, 2007) for a subglottal system often used in experiments. The system consists of a rigid tube of constant cross-section joining a mechanical model of the vocal folds and terminating at its remote end at a reflectionless plenum or duct of much larger cross-section, henceforth referred to as the 'lungs'. A self-sustaining model, requiring no empirical input, is investigated that makes use of a simple, but aerodynamically consistent single-mass model of the vocal folds [described in detail by Howe and McGowan (2009)] in accordance with the notion of nonlinear excitation propounded by Fant (1960, Section A.21). The theory determines (for this particular model) the details of the influence of subglottal acoustics on the unsteady volume flux through the glottis, and the dependence of the wave profile on the length of the subglottal tube, and on conditions at the interface with the lungs, where the absorption of sound within the lung complex is shown to strongly influence the acoustic-vocal fold interaction. The whole motion is driven by a steady contraction of the lung cavity. The investigation complements the linearized study of the same problem by Zhang et al. (2007a).

The analytical problem is formulated and formally solved in Sections 2 and 3, with the help of an aeroacoustic Green's function derived in the Appendix. The calculation of the glottal volume flux is discussed in Section 4, and numerical predictions of the coupled motions of the vocal folds and the subglottal acoustics are then presented (Section 5).

2. Coupling of the subglottal tract and the vocal folds

2.1. The overall model

We consider a simplified, analytical model of the subglottal vocal tract and vocal folds, illustrated overall in Fig. 1. In this model the upper tract is absent, so that sound generated at the glottis radiates directly into free space.