Acoustic sensitivity of a symmetrical two-mass model of the vocal folds to physiologic control parameters

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Introduction

Low-dimensional models of the vocal folds have proved to reproduce a wide variety of acoustic effects while profiting from their conceptual simplicity as well as from the interpretative power of non-linear dynamics. Recent low-dimensional vocal fold modelling includes dynamic flow separation within the glottal channel and the assumption of a symmetrical glottal structure [1]. A systematic study of the acoustic sensitivity of such production models to the variation of physical parameters has been recently performed to unveil the actions that the modelled glottis employs to produce different acoustic effects in terms of the speaker's (direct or indirect) control of subglottal pressure and vibrating mass, length and thickness [2].

It has often been remarked that the main weakness of this approach lies in the absence of a simple relationship between the parameters in the model and the physiology of the vocal folds. Nevertheless, recent research work has shown that laryngeal muscle activation can be effectively linked to the mechanical properties of simple mass-spring models, by means of empirically derived rules converting laryngeal muscle activity into physical quantities such as mass, thickness, depth, strain and stiffness [3]. Nevertheless, the vocalist controls perceptual parameters, such as loudness, pitch, register, tightness or roughness, rather than vocal fold parameters. It is therefore likely that the thought processes for activation of laryngeal and respiratory muscles are governed by perceptual dimensions. This brings forward acoustic phenomenological models as a powerful tool to test production models in perceptually realistic control spaces. Doval and D'Alessandro have shown that description of glottal-flow waveforms is possible in terms of a unique set of acoustic parameters, closely linked to the physiological aspect of the vocal folds vibratory motion [4]. This article uses such a set of acoustic parameters to quantify the sensitivity of a symmetrical two-mass model to the variation of laryngeal muscle activity, according to the rules derived in [3] with an algorythmic procedure similar to [2].

The symmetrical vocal fold model

A sketch of the symmetrical model is given in Figure 1. Notice that the symmetry assumption sets $m_1 = m_2 = m$ and $k_1 = k_2 = k$. This hypothesis is supposed suitable for non-pathological cases, in which vocal folds have uniform elastic an inertia properties along the $x-$axis [1]. As shown in [2], this assumption has the interesting side effect of reducing the number of control parameters of the dynamical system without hindering reproduction of glottal-flow signals under different laryngeal mechanisms.

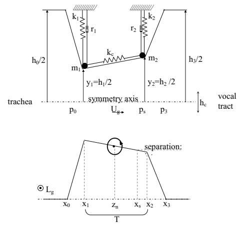

Figure 1: Sketch of the glottal channel geometry in the Niels Lous two-mass model.

The control parameter set

The rules for muscle control of the geometrical and elastic parameters of a symmetrical two-mass model are a particular case of the rules derived in [3] (in the absence of a body-cover distinction). The symmetry assumption implies that the nodal point z_n must be fixed to $1/2T$. This eliminates the nodal point rule (which was qualified as one of the weaker ones in [3]) at the price of fixing the normalized thyroarytenoid activity at $a_{TA} = 1/2$. The reduced set of rules yields:

$$L_g = L_0[1+\epsilon] \tag{1}$$

$$T = \frac{T_0}{[1+0.8\epsilon]} \tag{2}$$

$$m = \frac{\rho L_g T D_c}{2} \tag{3}$$

$$k = \frac{\mu_c L_g T}{D_c} \tag{4}$$

$$k_c = \frac{1}{2}(\mu_c L_g)(\frac{3D_c}{T} - \frac{T}{D_c}) \tag{5}$$

The resting length L_0, the vibrating thickness at resting length T_0, the tissue density ρ and the shear modulus μ_c are empirical constants ($L_0 = 1.4\ cm$, $T_0 = 0.20\ cm$, $\rho = 1.04\ g/cm^3$, $\mu_c = 1500\ Pa$). Finally,

$$\epsilon = G(Ra_{CT} - a_{TA}) - Ha_{LC} \tag{6}$$

$$D_c = \frac{D_{muc} + 0.5 D_{lig}}{1+0.2\epsilon} \tag{7}$$

where a_{CT} and a_{LC} are the normalized cricothyroid and lateral cricothyroid activity respectively. The effect of the interarytenoid muscle is neglected and the effect of the posterior cricoarythenoid muscle is included allowing

a_{LC} to become negative. The gain of elongation G, the torque ratio R, the adductory strain factor H, the depth of mucosa D_{muc} and ligament D_{lig} are set to $G = 0.2$ cm, $R = 3.0, H = 0.2$ cm, $D_{muc} = 0.2$ cm, $D_{lig} = 0.2$ cm in this study. Concerning damping, upper and lower masses are assigned an equal viscous loss fixed at 0.1.

Results

In order to focus on vocal fold characteristics, vocal tract loading is deliberately excluded in this study. The initial resting glottal area is set to zero and subglottal pressure to $P_s = 800$ Pa. In Figure 2, we produce muscle activation plots (MAPs) for a_{CT} and a_{LC} with contour lines for each of the dimensionless acoustic parameters characterizing glottal pulse shape: the open quotient O_q, the speed quotient S_q and the return quotient R_a, which respectively quantify the relative duration of the open phase, the degree of asymmetry of the pulse and the abruptness of glottal closure. MAPs with contour lines for fundamental frequency F_0 and the speed of closure E (whose main perceptual correlate is loudness) are given in Figure 3.

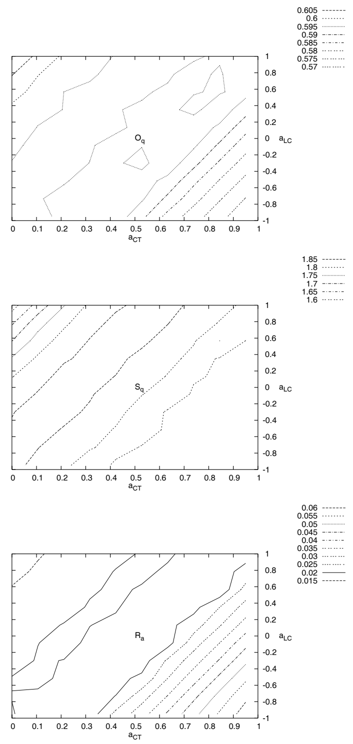

Figure 2: Muscle activation plots for cricothyroid a_{CT} and lateral cricothyroid a_{CT} activity with dimensionless acoustic parameters as contour lines.

Discussion

Perceptual (acoustic) parameters show a smooth variation as a function of muscle activity which is much less complex than their variation as a function of vocal fold physical parameters. Such complexity seems to be well captured by the empirical rules, which constitute a promising tool towards relating neural activities to glottal driving parameters (as has been recently done for the

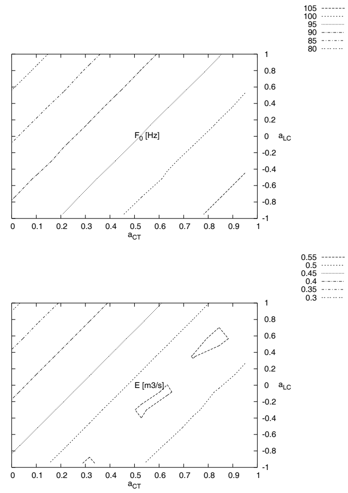

Figure 3: Muscle activation plots for cricothyroid a_{CT} and lateral cricothyroid a_{CT} activity for frequency and intensity control.

syrinx in the case of birds). Notice however that the set of muscle control rules complying with the symmetry hypothesis of this two-mass model strongly reduces the range of variation of vocal fold physical parameters (in particular, $m \in [0.071$ $g, 0.075$ $g]$, $k \in [20$ $N/m, 30$ $N/m]$). This prevents the model from attaining the wide variety of acoustic effects reported in [2] and most probably implies that the simplified mechanics of the symmetrical two-mass model is likely to require even more complicated rules for physiologic control. Ranges can be widened if lung pressure (on which muscle depths would probably depend) is allowed to vary (see Figure 4). It is conceivable that improvements could be made with a symmetrical three-mass model capturing body-cover differentiation.

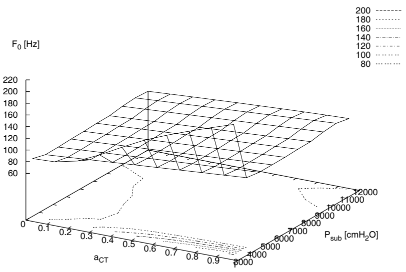

Figure 4: Fundamental frequency F_0 as a function of cricothyroid activity a_{CT} and lung pressure P_s.

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