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Role of gradients in vocal fold elastic modulus on phonation

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ABSTRACT

New studies show that the elastic properties of the vocal folds (VFs) vary locally. In particular strong gradients exist in the distribution of elastic modulus along the length of the VF ligament, which is an important load-bearing constituent of the VF tissue. There is further evidence that changes in VF health are associated with alterations in modulus gradients. The role of VF modulus gradation on VF vibration and phonation remains unexplored. In this study the magnitude of the gradient in VF elastic modulus is varied, and sophisticated computational simulations are performed of the self-oscillation of three-dimensional VFs with realistic modeling of airflow physical properties. Results highlight that phonation frequency, characteristic modes of deformation and phase differences, glottal airflow rate, spectral-width of vocal output, and glottal jet dynamics are dependent on the magnitude of VF elastic modulus gradation. The results advance the understanding of how VF functional gradation can lead to perceptible changes in speech quality.

1. Introduction

There is evidence that the vocal fold (VF) state of health influences the spatial distribution of VF elastic properties. Kelleher et al. (2012) show that gradients in elastic modulus are smaller in cover and ligament specimens excised from subjects associated with tobacco use than specimens excised from non-smokers. Kelleher et al. (2010) show that in vacuo eigenmodes of VF tissue are dependent on gradients in elastic modulus. Zhang et al. (2007) show that in vacuo eigenmodes are playing an important role in the onset of flow–structure interaction (FSI). These findings lead to the hypothesis that functional gradients in VF tissue modulus influence VF dynamics during self-sustained FSI. Answering this hypothesis would contribute to understanding why several studies report perceptible differences between speech quality of smokers and non-smokers.

A very limited number of studies conduct the simulation of VF self-oscillation under conditions of three-dimensional (3D) geometry and physically reasonable air flow and VF tissue properties. These conditions impose significant computational modeling challenges. Bhattacharya and Siegmund (2014b) demonstrate the use of commercially available dedicated solvers for flow and structural domains to solve problems of VF FSI including vibration and contact, VF dehydration (Bhattacharya and Siegmund, 2014a) and surface adhesion (Bhattacharya and Siegmund, 2015). Bhattacharya and Siegmund (2014c) validated this framework against experiments on physical replicas.

This study aims to obtain insights into the role of gradients in VF elastic modulus on VF dynamics during phonation. FSI simulations are conducted using a partitioned approach, whereby segregated solvers for the governing equations of the solid and fluid domains exchange information after every time increment. The investigation is limited to a linear elastic isotropic description of VF tissue properties situated within a 3D model of the glottal tract. The influence of gradation is quantified by analyzing VF surface dynamics during phonation.

2. Method

2.1. Computational model

The VF model comprises separate continuum region definitions for the glottal airflow and the pair of VFs. The FSI model describes the interaction between each VF and the airflow (Bhattacharya and Siegmund, 2014b).

The M5 description (Scherer et al., 2001) defines the geometry of the airflow domain (Fig. 1a) with a rectangular $x_{is}-x_{ml}-x_{ap}$ coordinate system aligned with inferior–superior (*is*), medial–lateral (*ml*) and anterior–posterior (*ap*) directions. The sub- and supra-glottal tracts have uniform rectangular cross-sectional dimensions (*ml*: $W=17.4$ mm and *ap*: $L=20.0$ mm) but unequal *is* dimensions ($T_{entry}=10.0$ mm and $T_{exit}=20.0$ mm respectively). The

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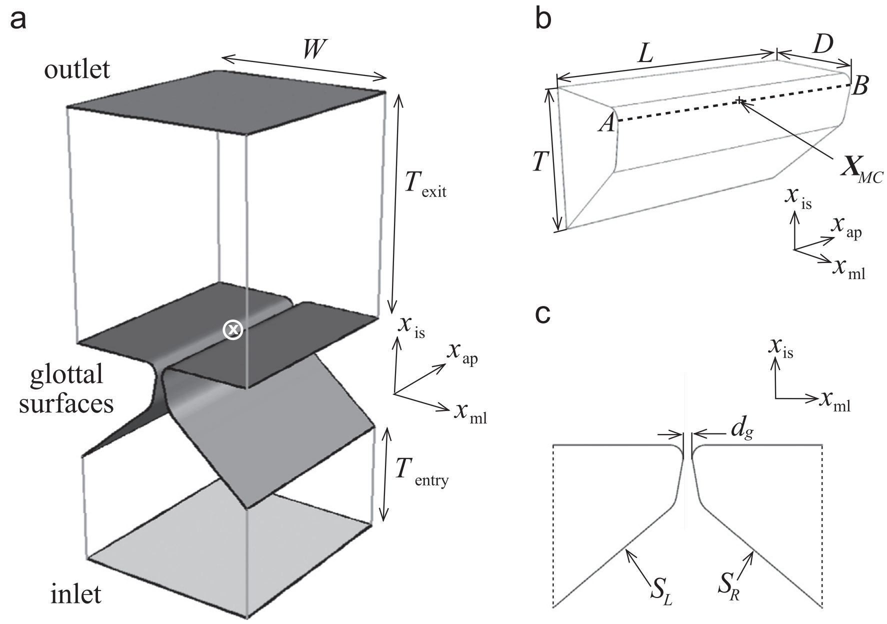

Fig. 1. (a) Geometry of the glottal airflow domain: the inlet, outlet and glottal surfaces are shaded, the coordinate origin (at the intersection of the mid-coronal plane, the mid-saggital plane and the VF superior surface) is ⊗; (b) geometry of the left half of the solid VF model: line *AB* and point $\mathbf{X}_{MC}$ are reference regions at which the VF motion is characterized in this paper; and (c) mid-coronal section showing both pairs of VFs and rigid planes: coordinate axes are offset from the origin for clarity.

is dimension of the glottal region is $T = 10.7$ mm. The fluid medium has properties of air (constant density $\rho_f = 1.23\ \text{kg/m}^3$, dynamic viscosity $\mu = 1.79 \cdot 10^{-5}$ kg/m, etc.) modeled as a Newtonian fluid with fluid stress $\boldsymbol{\tau}_f$ and fluid velocity $\vec{v}$ related by

$$\boldsymbol{\tau}_f = \mu[\nabla\vec{v} + (\nabla\vec{v})']. \tag{1}$$

The continuity and momentum conservation equations are

$$0 = \oint_{\partial(V^f)} (\vec{v} - \vec{v}_g)\cdot \mathrm{d}\vec{S} \tag{2}$$

$$\text{and} \quad 0 = \rho_f \frac{\mathrm{d}}{\mathrm{d}t}\int_{V^f} \vec{v}\ \mathrm{d}V + \rho_f \oint_{\partial(V^f)} \vec{v}(\vec{v} - \vec{v}_g)$$

$$\cdot \mathrm{d}\vec{S} + \oint_{\partial(V^f)} p\boldsymbol{I}\cdot \mathrm{d}\vec{S} - \oint_{\partial(V^f)} \boldsymbol{\tau}_f \cdot \mathrm{d}\vec{S}, \tag{3}$$

along with boundary conditions:

$$p(x_{\text{is}} = -T_{\text{entry}} - T) = p_{\text{in}}(t) \tag{4}$$

$$p(x_{\text{is}} = T_{\text{exit}}) = 0, \tag{5}$$

$$\vec{v}(x_{\text{ap}} = \pm L/2) = \vec{v}_g(x_{\text{ap}} = \pm L/2) = 0, \tag{6}$$

$$\text{and} \quad \vec{v}(x_{\text{ml}} = \pm W/2) = \vec{v}_g(x_{\text{ml}} = \pm W/2) = 0, \tag{7}$$

with p the fluid pressure, $\vec{v}_g$ the discretized grid velocity and $p_{\text{in}}(t)$ the time-varying pressure at the inlet:

$$p_{\text{in}}(t) \equiv p_{\text{max}} \begin{cases} (t/t_0)^2[3 - 2(t/t_0)] & \forall\, t \in [0, t_0] \\ 1 & \forall\, t \in [t_0, \infty) \end{cases} \tag{8}$$

where $p_{\text{max}} = 400$ Pa and $t_0 = 0.150$ s. Zero pressure at the outlet and no-slip and no-penetration at all bounding surfaces except the inlet and outlet are enforced. Here $\vec{v}$ represents the fluid velocity, V^f the volume of the fluid domain, $\partial(V^f)$ its bounding surface, p the fluid pressure, $\boldsymbol{I}$ the second-order identity tensor, and $\boldsymbol{\tau}_f$ the surface traction vector on the fluid boundary. The operator $\cdot$ represents a tensor contraction and the operator ∇ the gradient vector. The motion of the moving–deforming glottal surface given by the grid velocity $\vec{v}_g$ is determined by the FSI model (described later). The fluid volume is discretized using tetrahedral cells, with a minimum cell size of 0.050 mm near the glottis ensured throughout the computation. The fluid model is implemented in ANSYS/Fluent (ANSYS Fluent Release 12.0 User Guide, 2009). The solution is advanced in time following the implicit PISO (Pressure Implicit with Splitting of Operator) algorithm with neighbor and skewness correction (Issa, 1986).

The VF domain comprises identical and disjoint left and right solid parts (Fig. 1b shows the left VF). Both VFs have a depth $D = 8.40$ mm separated initially by $d_g = 0.600$ mm. VF mechanics is governed by the principle of virtual work (Zienkiewicz et al., 2005):

$$\int_{V^s} \boldsymbol{\sigma} : \delta\boldsymbol{D}_v\ \mathrm{d}V = \oint_{\partial(V^s)} \boldsymbol{\tau}_s \cdot \delta\vec{u}_v\ \mathrm{d}S - \int_{V^s} \rho_s \ddot{\vec{u}} \cdot \delta\vec{u}_v\ \mathrm{d}V \tag{9}$$

with $\boldsymbol{\sigma}$ the Cauchy stress, V^s the solid volume, $\boldsymbol{\tau}_s$ the traction applied on the boundary $\partial(V^s)$, ρ_s the uniform solid density, $\vec{u}$ the solid displacement, $\boldsymbol{D} = \nabla\vec{u}$ the displacement gradient, δ a variation of the virtual variables (subscripted 'v'), operator: the double-contraction of two tensors, accent-marks $\dot{}$ and $\ddot{}$ respectively the first- and second-order time-derivatives and ν the Poisson ratio. The VF constitutive behavior is isotropic linear viscoelastic with $\boldsymbol{\sigma}$ depending on the history of the deviatoric strain rate $\dot{\boldsymbol{e}}$ and bulk strain rate $\dot{\epsilon}$:

$$\boldsymbol{\sigma}(t) = \int_0^t 2G(t - t')\dot{\boldsymbol{e}}\ \mathrm{d}t' + \boldsymbol{I}\int_0^t K(t - t')\dot{\epsilon}\ \mathrm{d}t' \tag{10}$$

The time dependence of the shear and bulk moduli are

$$G(t) = \frac{E}{2(1+\nu)}[1 - g_1 + g_1 \mathrm{e}^{-t/\tau_1}], \tag{11}$$

$$\text{and} \quad K(t) = \frac{E}{3(1-2\nu)}[1 - k_1 + k_1 \mathrm{e}^{-t/\tau_1}] \tag{12}$$

The viscoelastic relaxation is modeled by shear and bulk relaxation factors $g_1 = 0.100$ and $k_1 = 0.100$ respectively and relaxation time-