Effects of mucosal loading on vocal fold vibration

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A chain model was proposed in this study to examine the effects of mucosal loading on vocal fold vibration. Mucosal loading was defined as the loading caused by the interaction between the vocal folds and the surrounding tissue. In the proposed model, the vocal folds and the surrounding tissue were represented by a series of oscillators connected by a coupling spring. The lumped masses, springs, and dampers of the oscillators modeled the tissue properties of mass, stiffness, and viscosity, respectively. The coupling spring exemplified the tissue interactions. By numerically solving this chain model, the effects of mucosal loading on the phonation threshold pressure, phonation instability pressure, and energy distribution in a voice production system were studied. It was found that when mucosal loading is small, phonation threshold pressure increases with the damping constant R_r , the mass constant R_m , and the coupling constant R_μ of mucosal loading but decreases with the stiffness constant R_k . Phonation instability pressure is also related to mucosal loading. It was found that phonation instability pressure increases with the coupling constant R_μ but decreases with the stiffness constant R_k of mucosal loading. Therefore, it was concluded that mucosal loading directly affects voice production. © 2009 American Institute of Physics. [DOI: 10.1063/1.3120293]

Voice production caused by vocal fold vibrations is a highly nonlinear self-oscillating process. The self-oscillation of the vocal folds results from the interactions between the vocal folds and multiple factors, including glottal airflow, vocal tract acoustics, and subglottal acoustics. The complex coupling between the vocal folds and the surrounding tissue is another important interaction that could affect vocal fold vibration and voice production. However, few studies have noted this effect. In this study, the loading caused by the interaction between the vocal folds and the surrounding tissue is referred to as mucosal loading. A chain model, in which the vocal folds and the surrounding tissue are modeled by a series of oscillators connected by a coupling spring, was proposed to study the effects of mucosal loading on vocal fold vibration. Using this model, the influences of the mucosal loading on the nonlinear dynamical behavior of the vocal fold vibration were predicted.

I. INTRODUCTION

Vocal fold vibration is studied to provide not only a basic understanding of voice production^{1,2} but also information about types of dysphonia caused by laryngeal pathologies.^{3–5} Vibration of the vocal folds results from interactions between the vocal folds and multiple factors, including glottal airflow, vocal tract acoustics, and subglottal acoustics. The interaction between glottal airflow and vocal fold tissue is intrinsic to vocal fold vibration.^{6–10} This tissue-airflow interaction provides the energy necessary to sustain the oscillation of the vocal folds.²

The coupling that occurs between the vocal folds and vocal tract acoustics is another mechanism that influences vocal fold vibration. Titze² predicted that vocal tract inductance reduces the oscillation threshold pressure, whereas vocal tract resistance increases this pressure. Subsequent experiments confirmed the hypothesized effects of this interaction between the vocal folds and the vocal tract acoustics.¹¹ Moreover, vocal tract acoustics may also contribute extremely rich dynamics to vocal fold vibration.^{12–14}

The results of a recent study showed that the interaction between subglottal acoustics and the vocal folds also plays an important role in vocal fold vibration.¹⁵ Using a physical model of the vocal folds and tracheal tube, it was found that nonlinear vocal phenomena are potentially related to strong laryngeal interactions with the acoustical resonances of the subglottal system.¹⁵

Besides the three aforementioned interactions, the coupling that occurs between the vocal folds and the surrounding tissue is another kind of interaction existing in the voice production system. It is established that the vocal fold is not an isolated organ. The trachea is attached to the inferior side of the vocal folds, while the false vocal folds and the vocal tract are attached to the superior side of the vocal folds. The mucosa also covers these organs and connects to the mucous membrane of the vocal folds. The coupling between the vocal folds and the surrounding tissue could produce additional loading on the vocal folds during phonation. This loading caused by the surrounding tissue is referred to as mucosal loading in this study. It is anticipated that the interaction between the vocal folds and the surrounding tissue could make an important contribution to vocal fold vibration similar to aerodynamic loading and acoustic loading.^{2,11,15} However, the effects of mucosal loading on vocal fold vibration were not specifically examined in previous studies.

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FIG. 1. The sketch map of the general chain model of the vocal folds and the surrounding tissue, where D_t is d/dt . In this study, the system is assumed to be left-right symmetric; therefore, we omit the superscript (α) to simplify the expression.

In order to study the effects of mucosal loading, a chain model of the vocal folds was proposed. In this model, the vocal folds and the surrounding tissue were represented by a series of oscillators connected by a coupling spring. The lumped masses, springs, and dampers of the oscillators represented the mass, stiffness, and viscosity properties of the tissue. Bernoulli's relationship was used to describe the airflow-tissue interaction in the glottis.¹ This chain model not only included the vocal folds themselves but also described the surrounding tissues as an oscillator chain. Therefore, this model has the ability to predict the interactions between the vocal folds and the surrounding tissue. By numerically solving this chain model, the energy propagation in a voice production system can be predicted. The effects of mucosal loading on phonation threshold pressure and irregular vibration of the vocal folds are studied in Sec. III. Finally, conclusions are drawn in Sec. IV.

II. THE CHAIN MODEL OF THE VOCAL FOLDS

Figure 1 is a sketch map of the chain model of the vocal folds and the surrounding tissue. The dynamic behavior of this chain model can be described by the equations of two-way coupled oscillators,

$$m_i \ddot{x}_i + r_i \dot{x}_i + k_i x_i + \mu_i (x_i - x_{i-1}) + \mu_{i+1} (x_i - x_{i+1}) = f_i, \quad (1)$$

where i is the oscillator site index and the variables $\ddot{x}_i$, $\dot{x}_i$, and x_i represent the acceleration, velocity, and displacement of the oscillator i , respectively. The coefficients m_i , r_i , and k_i are the mass, damping constant, and spring constant of the oscillator i , respectively. The coefficient μ_i is the coupling

spring constant between the oscillator ($i-1$) and the oscillator i . The right side of Eq. (1) represents the force f_i applied to oscillator i due to tissue collision and tissue-airflow interaction. f_i is formulated as follows:

$$f_i = P_i L d_i + Q_i L d_i, \quad (2)$$

where P_i represents the action of the airflow pressure, Q_i is the left-right tissue impact pressure, d_i is the thickness of the mass i , and L is the length of the glottis.

This study focused on the effects of mucosal loading on voice production; therefore, for comparison with previous models, the chain model is interrupted into N dimensions, and two oscillators (oscillators 1 and 2) are used to represent the vocal folds,

$$m_0 \ddot{x}_0 + r_0 \dot{x}_0 + k_0 x_0 + \mu_1 (x_0 - x_1) = f_0, \quad (3)$$

$$m_i \ddot{x}_i + r_i \dot{x}_i + k_i x_i + \mu_i (x_i - x_{i-1}) + \mu_{i+1} (x_i - x_{i+1}) = f_i, \quad (4)$$

$$m_{N-1} \ddot{x}_{N-1} + r_{N-1} \dot{x}_{N-1} + k_{N-1} x_{N-1} + \mu_{N-1} (x_{N-1} - x_{N-2}) = f_{N-1}, \quad (5)$$

where $i=1, 2, \dots, N-2$. In addition, it is assumed that the tissue-airflow interaction mainly occurs at the glottis and that the airflow in the glottis is a steady, laminar, and incompressible fluid which follows Bernoulli's relationship,

$$P_1 = P_s \left[1 - \Theta(a_{\min}) \left(\frac{a_{\min}}{a_1} \right)^2 \right] \Theta(a_1) \quad \text{and} \quad P_i = 0 (i \neq 1) \quad (6)$$

with

$$\Theta(x) = \begin{cases} \tanh(50x/x_0), & x > 0 \\ 0, & x \leq 0, \end{cases} \quad (7)$$

where $a_{\min} = \max[0, \min(a_1, a_2)]$, the term $a_i = a_{0i} + 2x_i L$ is the lower glottal area ($i=1$) and the upper glottal area ($i=2$), a_{0i} is the prephonatory lower glottal areas ($i=1$) and upper glottal area ($i=2$), and P_s is the subglottal pressure.

The trachea and the vocal tract are usually wide, and left-right tissue collision seldom happens in this region. However, the glottis is narrow, and strong collisions between the left and right vocal folds could occur in this region. Therefore, the impact pressure between the right and left tissues can be formulated as

$$Q_i = -\Theta(-a_i) 3k_i a_i / (2L^2 d_i) \quad (i=1, 2), \quad (8)$$

$$Q_i = 0 \quad (i \neq 1, 2).$$

It is evident in the above description of glottal airflow and collision [Eqs. (6) and (8)] that the vocal fold part of this chain model is similar to a two-mass model.^{1,3} The following parameters constitute our standard parameter configuration.

For the vocal folds (oscillators 1 and 2),

$$m_1 = 0.125, \quad r_1 = 0.02, \quad k_1 = 0.08, \quad m_2 = 0.025,$$

$$r_2 = 0.02, \quad k_2 = 0.008, \quad \mu_2 = 0.025, \quad d_1 = 0.25,$$

$$d_2 = 0.05, \quad a_{01} = 0.05, \quad a_{02} = 0.05.$$

For the false vocal folds (oscillator 10),

$$m_{10} = 0.06, \quad r_{10} = 0.02, \quad k_{10} = 0.03, \quad d_{10} = 0.2.$$

For the other oscillators,

$$m_i = 0.005R_m, \quad r_i = 0.004R_r, \quad k_i = 0.002R_k,$$

$$d_i = 0.05, \quad \mu_i = 0.002R_\mu.$$

In the study, the parameters of the vocal folds (oscillators 1 and 2) are chosen according to Ishizaka and Flanagan's work.¹ The surrounding tissues are smaller than the true vocal folds. Therefore, we used relatively small mass, damping, and spring constants to represent the typical parameters for these surrounding tissues. However, the variation in the tissue is very large in *in vivo* laryngeal systems. Therefore, in this study, we also introduce the loading factors R_m , R_r , R_k , and R_μ . Larger loading factors represent a heavier mucosal load. In this study, these loading factors are variable rather than constant. Therefore, we can study the effect of mucosal loading within a broad parameter range. Clearly, if $R_\mu = 0$, the vocal folds will be separated from the surrounding tissue. In this situation, the chain model can be simplified to a two-mass model. All parameters are given in units of centimeters, grams, milliseconds, and their corresponding combinations.

III. RESULTS AND DISCUSSION

By numerically solving a 20-dimensional chain model (20 masses are included in the chain) using the fourth-order Runge-Kutta routine with a time step of 0.01 (10 μ s), we studied the effects of the surrounding mucosal loading on vocal fold vibration.

A. Energy propagation

Figure 2(a) illustrates the waveform of the oscillation of the proposed chain model, where $R_m = R_r = R_k = R_\mu = 1$ and $P_s = 0.008$ (≈ 8 cm H₂O). The initial conditions are $x_1 = 0.001$, $\dot{x}_1 = 0$, $x_i = 0$, and $\dot{x}_i = 0$ ($i \neq 1$). With the above model parameters and initial conditions, the oscillation of the chain model gradually grows, which suggests that the energy introduced into the vocal fold system due to the tissue-airflow interaction is larger than the energy lost due to the tissue viscosity.² The increased vibratory amplitude enlarges the energy consumption due to viscosity. Finally, the energy income and loss are brought into balance, and the vocal fold is sustained in a stable oscillation. There exists a phase delay between the downstream and upstream oscillators, which indicates that the mucosal wave and energy travel from the vocal folds to the downstream tissue. For comparison, the waveform of the oscillation of the chain model with the $R_\mu = 0$ is presented in Fig. 2(b), where the other parameters are identical to those used to predict Fig. 2(a). Clearly, for $R_\mu = 0$, the vocal folds and the surrounding tissue are uncoupled. In this situation, the chain model is degenerated to a two-mass model.^{1,3} It can be observed that the surrounding tissue does not vibrate, and the propagation of the mucosal wave and energy stops at the upper edge of the vocal folds.

FIG. 2. (Color online) The vibratory waveform of the vocal folds and the surrounding mucosa, where $R_m = R_r = R_k = 1$ and $P_s = 0.008$ (≈ 8 cm H₂O): (a) $R_\mu = 1$ and (b) $R_\mu = 0$.

From Fig. 2, it is also notable that the strongest oscillation occurs at the vocal folds (oscillators 1 and 2). This is because the strongest airflow-tissue interaction occurs at this location. Figure 3 illustrates the peak-to-peak amplitude of the sustained vibration of each oscillator, with $R_m = R_r = R_k = R_\mu = 1$ and $P_s = 0.008$ (≈ 8 cm H₂O). It is seen that since the downstream oscillators are essentially driven linear damped oscillators, the oscillation amplitude of the surrounding tissue decreases approximately exponentially with the increase in distance away from the vocal folds. The vibratory amplitude of oscillator 1 (0.080 18 cm) is almost 5.5×10^6 times larger than that of the last oscillator 19 (1.45×10^{-8} cm). Moreover, there is a significant decrease in amplitude from oscillator 9 to oscillator 10 because oscil-

FIG. 3. The peak-to-peak amplitude of the sustained vibration of the vocal folds and the surrounding mucosa, where $R_m = R_r = R_k = R_\mu = 1$ and $P_s = 0.008$ (≈ 8 cm H₂O).

FIG. 4. (Color online) The energy consumed in the voice production system with $R_m=R_r=R_k=R_\mu=1$ and $P_s=0.008$ (≈ 8 cm H₂O), where W_i represents the average power loss in the oscillator i due to the damping r_i .

lator 10, which represents the false vocal folds, has larger mass, damping, and stiffness constants than the other oscillators.

To illustrate energy propagation in the chain model, we calculate the average power consumed by each oscillator and present the results in Fig. 4, where the average power consumption W_i of the oscillator i during the time interval $[t_1, t_2]$ is integrated by

$$W_i = \frac{1}{(t_2 - t_1)} \int_{t_1}^{t_2} r_i(\dot{x}_i)^2 dt. \quad (9)$$

The average power W_{air} converted into the vocal fold due to tissue-airflow interaction during the time interval $[t_1, t_2]$ is also calculated according to

$$W_{\text{air}} = \frac{1}{(t_2 - t_1)} \int_{t_1}^{t_2} P_1 L d_1 \dot{x}_1 dt. \quad (10)$$

For $R_\mu=0$, the energy converted from the glottal air stream to the tissue has an average power of 2.46 N m/s. The average powers consumed by oscillators 1 and 2 are 1.18 and 1.28 N m/s, respectively. Since the other oscillators did not vibrate, their energy consumption is zero. Clearly, $W_{\text{air}}=W_1+W_2$ indicates that all energy converted into the tissue will be used to overcome frictional energy losses in the vocal folds. For $R_\mu=1$, the energies consumed by the vocal folds are only 1.19 and 1.15 N m/s for oscillators 1 and 2, respectively. The leftover energy 0.12 N m/s $= W_{\text{air}} - W_1 - W_2$ is propagated into the surrounding tissue and consumed by them, i.e., $W_{\text{air}} = \sum W_i$. These results suggest that the surrounding tissue changes the energy distribution and consumes additional energy in a voice production system. Moreover, the energy consumption of the surrounding tissue decreases approximately exponentially with the increasing distance from the vocal folds.

B. Phonation threshold pressure

Phonation threshold pressure (P_{th}) is defined as the minimum subglottal pressure required to initiate vocal fold oscillation.² Much attention has been paid to this parameter^{16,17} because it could provide considerable information about speech system dysfunctions due to the abnormalities in tissue tension, viscosity,^{2,18–20} glottal gap,^{21,22} asymmetry,³ laryngeal size,²³ pitch,^{24–26} and so on. Moreover, it has been demonstrated that downstream loading, including aerodynamic loading and acoustic loading,^{2,11} sig-

FIG. 5. (Color online) Phonation threshold pressure (P_{th}) as a function of the surrounding mucosal properties. (a) The effect of the surrounding mass on P_{th} with $R_r=R_k=1$, where P_{th} increases with the surrounding mass in the left side of the dotted line. (b) The effect of the damping constant on P_{th} with $R_m=R_k=1$. (c) The effect of the stiffness constant on P_{th} with $R_m=R_r=1$.

nificantly influences phonation threshold pressure. However, the effects of downstream tissue loading on phonation threshold pressure have not been well studied.

In this subsection, the relationship between downstream tissue loading and phonation threshold pressure is studied using the chain model. Figure 5 presents phonation threshold pressure as a function of the surrounding mucosal loading. Without the surrounding tissue ($R_\mu=0$), phonation threshold pressure is about 0.234 kPa. When the surrounding tissue is coupled with the vocal folds ($R_\mu=1$), phonation threshold pressure increases to 0.25 kPa. Moreover, when the coupling constant R_μ continues to increase to 2 and 3, P_{th} increases to 0.26 and 0.27 kPa, respectively. The influence of independent parameters, including mass, damping, and stiffness, were also investigated, respectively. It is seen that the tissue damping R_r increases P_{th} , as shown in Fig. 5(b); however, the stiffness R_k decreases P_{th} , as shown in Fig. 5(c). The mass loading R_m shows complex effects on phonation threshold pressure, as shown in Fig. 5(a). P_{th} is undulated with the increase in mass within the interval of $0.0 < R_m \leq 10$. For example, for $R_\mu=2$, P_{th} increases with mass loading as R_m increases from 0 to 2.1. After P_{th} reaches its maximum value at $R_m=2.1$, P_{th} decreases with R_m from $R_m=2.1$ to $R_m=3.9$. Then, P_{th} increases with R_m again from $R_m=3.9$ to $R_m=5.9$. Finally, P_{th} decreases within the interval $R_m \in [5.9, 10.0]$. This resonancelike structure in this figure could be related to the resonance of the surrounding tissue. Substituting $x_{i\pm 1} = x_i e^{\pm j\alpha}$ ($\alpha_i = 2\pi d_i/\lambda$, with λ as the mucosal wavelength) into Eq. (1) and letting $\mu_i = \mu_{i+1}$, we have $m_i \ddot{x}_i = -r_i \dot{x}_i - [4\mu_i \sin^2(\alpha/2) + k_i]x_i$ and the resonance frequency is

$f_0 = (1/2\pi)\sqrt{[4\mu_i \sin^2(\alpha/2) + k_i]/m_i}$. For $R_m=1$, $R_k=1$, and $R_\mu=3$, we have resonance frequency of about 100–362 Hz ($0 \leq \alpha \leq \pi$). If the vibratory frequency is closer to the resonance, more dissipation occurs. The phonation onset pressure could be increased. In general, P_{th} increases with mass loading when R_m is small [left side of the dotted line in Fig. 5(a)].

In a recent study, Alipour *et al.*²⁷ carried out a detailed study of the effect of the epiglottis and false vocal folds on vocal fold vibration during phonation. In their experiment, the excised larynx with intact false vocal folds and epiglottis was subjected to a series of pressure-flow experiments with longitudinal tension and adduction as major control parameters. Then, the epiglottis and the false vocal folds were removed and the experiment was repeated. They found that the presence of false vocal folds resulted in changes in trans-laryngeal flow resistance and sound intensity level. Their experiments provide primary evidence of the influence of the surrounding tissue on vocal fold vibration. However, these experiments did not directly examine the relationship between P_{th} and the surrounding tissue. In further studies, the P_{th} before and after the surrounding tissue is removed should be measured. These measurements might provide experimental evidence for the current theoretical study.

C. Chaotic vibration

Substantial evidence has shown that vocal fold vibration is a highly nonlinear process.²⁸ Rich irregular vibratory behaviors, such as bifurcation and chaos, can be found in a voice production system.^{4,5,29–34} Some studies have investigated the generation of nonlinear dynamic properties in voice. It has been found that irregular vibratory patterns are related to left-right asymmetry of the vocal folds.^{3,34} Jiang *et al.*³⁵ predicted that bifurcations and chaos could be found in a symmetric vocal fold model with tissue parameters obviously deviating from normal values. Resultant to the source-filter acoustic interaction, delayed feedback of reflected sound in the vocal tract has been shown to contribute to extremely rich dynamics, such as biphonation,³⁶ period doubling bifurcation, and nonperiodic oscillation.^{12–14}

In this subsection, we study the effects of the downstream tissue on irregular vibration of the vocal folds using the chain model. Figure 6(a) shows the spatiotemporal pattern of this chain model, with $P_s=0.05$ (5 kPa), $r_1=0.02$, $r_2=0.01$, $\mu_2=0.09$, and $R_m=R_r=R_k=R_\mu=1$. In this figure, the different colors represent the normalized displacement $\tilde{x}_i$ of the oscillator i calculated by

$$\tilde{x}_i = (x_i - \bar{x}_i)/\sigma(x_i), \quad (11)$$

where $\bar{x}_i$ and $\sigma(x_i)$ represent the mean value and the standard deviation of x_i , respectively. It can be seen that this chain model shows complex dynamic characteristics both in the time domain and the spatial domain. Moreover, the diagonal pattern suggests that the energy travels from the vocal folds to the downstream tissue. The trajectories of oscillators 1 and 5 in the x - v plane are illustrated in Figs. 6(b) and 6(c). Strange attractors suggest that both the vocal folds and the downstream tissue behave in a chaotic manner.

FIG. 6. (Color) Spatiotemporal pattern and the attractors of the chain model with $P_s=0.05$ (5 kPa), $r_1=0.02$, $r_2=0.01$, $\mu_2=0.09$, and $R_m=R_r=R_k=R_\mu=1$. (a) The spatiotemporal pattern of the chain model, where the different colors represent the values of the normalized displacement of the oscillator i [see Eq. (11)]. (b) The attractor of the oscillator 1 in the x_1 - v_1 plane. (c) The attractor of oscillator 5 in the x_5 - v_5 plane.

Previous experiments^{17,37} consistently demonstrated that when the subglottal pressure increases and surpasses a certain level, irregular vibrations are produced. This minimum subglottal pressure producing irregular phonation is defined as phonation instability pressure.³⁸ Surrounding tissue loading could affect phonation instability pressure. Figure 7 gives the bifurcation diagrams of the chain model with various coupling constants of $R_\mu=1.0$, 2.0, 2.5, and 3.0 and $R_m=R_r=R_k=1$. When $R_\mu=1.0$, the phonation instability pressure is 3.63 kPa, as shown in Fig. 7(a). When R_μ is increased to 2.0

FIG. 7. Effect of the coupling constant R_μ of mucosal loading on the phonation instability pressure, where $r_1=0.02$, $r_2=0.01$, $\mu_2=0.09$, and $R_m=R_r=R_k=1$: (a) $R_\mu=1.0$, (b) $R_\mu=2.0$, (c) $R_\mu=2.5$, and (d) $R_\mu=3.0$.

FIG. 8. One-parameter bifurcation diagram for $P_s=0.04$, $r_1=0.02$, $r_2=0.01$, and $\mu_2=0.09$. (a) The output x_1 vs mass parameter R_m , where $R_r=R_k=1$ and $R_\mu=2$. (b) x_1 vs R_r , where $R_m=R_k=1$ and $R_\mu=2$.

and 2.5, the phonation instability pressure increases to 3.90 and 4.88 kPa, respectively, as shown in Figs. 7(b) and 7(c). When $R_\mu=3.0$, the chain regularly vibrates within $P_s \leq 6.0$ kPa. We also studied the bifurcation diagrams of the chain model with various stiffness constants of $R_k=1.0, 2.0, 3.0$, and 4.0 and $R_m=R_r=R_\mu=1$. It was found that when R_k is increased to 2.0, 3.0, and 4.0, the phonation instability values decrease to 3.35, 3.25, and 3.16 kPa, respectively. Therefore, these results suggest that an increase in the coupling constant R_μ may increase phonation instability pressure, but an increase in the stiffness constant R_k decreases phonation instability pressure.

In addition, the above figure also shows that the system gets out of chaotic dynamics as the driving is increased. This is because the bifurcation and chaos of the nonlinear system significantly depend on the control parameters. This phenomenon has been broadly observed in previous experiments and model simulations. Using an excised larynx experiment, Jiang *et al.*³⁷ observed that the chaotic pattern of the excised larynx could transiently return to a regular pattern when the subglottal pressure is increased above the phonation instability pressure. Tokuda *et al.*³² used the longitudinal tension of the vocal fold as the control parameter. They found that when the longitudinal tension is monotonically and slowly decreased, the regular chestlike vibration jumps to irregular vibrations, then switches to regular falsettolike vibration again several seconds later. Berry *et al.*²⁹ also found that when the elastic coefficient is increased from 0.35 to 0.65 kPa, transitions from a subharmonic regime to chaos to a periodic regime characteristic of normal phonation can be found in the outputs of their finite-element vocal fold model.

The effects of the mass and damping constants of the surrounding tissue on phonation instability pressure were also examined in this study. The relationship between these constants and phonation instability pressure is not clear. Figures 8(a) and 8(b) illustrate the one-parameter bifurcation diagram of R_m ($R_k=1$, $R_r=1$, $R_\mu=2$) and R_r ($R_m=1$, $R_k=1$, $R_\mu=2$), where $P_s=0.04$ (4 kPa), $r_1=0.02$, $r_2=0.01$, and $\mu_2=0.09$. When $R_r < 0.815$, the vocal folds produce a regular vibration. When R_r exceeds 0.815, the vocal folds produce chaotic vibration, which suggests that a larger R_r tends to decrease the phonation instability pressure. However, when

R_r surpasses 1.55, the vocal folds return to regular vibration, which suggests that a larger R_r tends to increase the phonation instability pressure. This inconsistency indicates a non-monotonic relationship between phonation instability pressure and the damping constant R_r . A similar phenomenon can also be observed in the bifurcation diagram of the mass constant R_m . The relationship between phonation instability pressure and the mass constant R_m is also nonmonotonic.

IV. CONCLUSION

In this study, a chain model of the vocal folds was proposed to study the effects of mucosal loading on the vocal fold vibration. This model treated the vocal folds and the surrounding tissue as a series of oscillators connected by a coupling spring. The lumped masses, springs, and dampers of the oscillators represented the mass, stiffness, and viscosity properties of the tissue, respectively. The coupling spring represented the tissue interaction.

By numerically solving this chain model, we studied the effects of mucosal loading on the energy distribution in a voice production system, phonation threshold pressure, and phonation instability pressure. It was predicted that the energy converted from the glottal air stream would be transported to downstream tissue. The surrounding tissue consumed additional energy to sustain vibration in the voice production system. When mucosal loading was small, the phonation threshold pressure increased with the damping constant R_r , the mass constant R_m , and the coupling constant R_μ of the mucosal loading but decreased with the stiffness constant R_k . The phonation instability pressure was related to mucosal loading. It was found that the phonation instability pressure increased with the coupling constant R_μ but decreased with the stiffness constant R_k of mucosal loading. In summary, this study suggested that mucosal loading is one important factor that could affect vocal fold vibration.

Some of the theoretical predictions in this study, such as the relationship between P_{th} and the surrounding tissue loading, lack direct experimental evidence. This is a limitation of the current theoretical study. Therefore, further studies should measure and compare the P_{th} of each larynx before and after the surrounding tissue is removed, which could provide the experimental evidence for the current theory study.

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