DOI: 10.61782/fa.2023.0272

EFFECTS OF CONTROLLING CHAOTIC VOCAL FOLD VIBRATIONS ON FINITE ELEMENT GENERATED VOWELS

Oriol Guasch[1*] **Marc Freixes**[1] **Marc Arnela**[1] **Annemie Van Hirtum**[2]

[1] HER group, La Salle, Universitat Ramon Llull, 08022 Barcelona, Catalonia, Spain
[2] CNRS Grenoble Alpes University, LEGI, Grenoble Campus, 38000 Grenoble, France

ABSTRACT

Lumped mass models of the vocal folds have been widely used to analyze the physics of human phonation. This is a strongly non-linear process that results in regular self-oscillations of the vocal folds. However, various factors such as polyps, excessive subglottal pressure, etc., can alter such motion and make it chaotic. Ideally, it would be possible to use a smart material to control the dynamics of the vocal folds and restore its regularity. In this paper, we will see the effects of such a control strategy on the generation of vowels. The chaotic and the controlled train of glottal pulses will be imposed as boundary conditions at the glottis of a three-dimensional model of the vocal tract (VT). Then, the finite element method will be used to solve the wave equation inside the VT and the spectra and sound of the generated vowels will be compared to check the performance of the chaos control strategy on phonation.

Keywords: *phonation pacemaker, vocal fold mass model, chaotic oscillations, vocal tract acoustics, numerical voice production, finite element method*

1. INTRODUCTION

In this paper, we show how a theoretical pacemaker made of a smart material attached to the vocal folds (VFs) could help change the chaotic motion of unhealthy VFs to regular motion again, and see the impact this has on the generation of vowel sounds. It was shown in [1] that even a simple symmetric two-mass model of phonation [2, 3] could give rise to chaotic oscillations by modifying some model parameters, such as the flexural stiffness between the masses, which could represent some kind of injury.

It was first proposed in [4], that it might be possible to regulate the chaotic motion of the VFs by means of a theoretical phonation pacemaker attached to one of the model masses and whose parameters could be tuned to alter the energy of the system appropriately [5, 6]. In this work

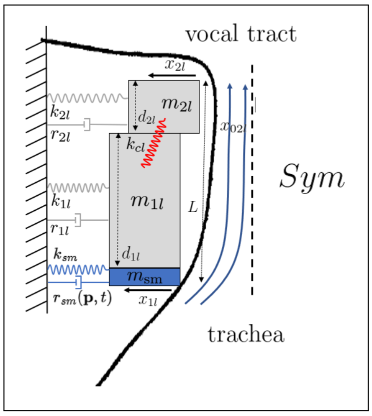

Figure 1. Two mass model of the VFs. The red color indicates an abnormal value of the flexural stiffness k_{cl} between the two masses that can lead to chaotic motion of the VFs. The blue mass represents the pacemaker whose damping $r_{sm}(\boldsymbol{p}, t)$ can be adjusted to make the motion regular again.

*__Corresponding author__: oriol.guasch@salle.url.edu.

we want to explore the effects that the pacemaker might have on the numerical generation of vowel /a/. For this purpose, we compute the 3D vocal tract (VT) impulse response of /a/ by solving the mixed-form wave equation using a stabilized finite element method (FEM), and convolve it with the volume flow velocity computed from the two-mass model (see e.g., [7–9] for vowels and [10–12] for diphthongs).

It is shown that the control strategy has a profound impact on the quality of the generated vowel. This can be easily appreciated by comparing the spectra of the acoustic pressure for the chaotic and controlled cases and, more clearly, in the audio files that will be presented at the conference.

2. THEORY

2.1 Vocal fold model

We consider the two-mass model of the vocal folds shown in Fig. 1, whose dynamics are governed by the first order non-linear ordinary differential equation (ODE) system,

$$\begin{pmatrix} \dot{\boldsymbol{v}} \\ \dot{\boldsymbol{x}} \end{pmatrix} = \begin{pmatrix} -\mathbf{M}^{-1}\mathbf{C}(t,\boldsymbol{p}) & -\mathbf{M}^{-1}(\mathbf{K}(\boldsymbol{x})+\boldsymbol{\Theta}(\boldsymbol{x})) \\ \mathbf{I} & \mathbf{0} \end{pmatrix} \begin{pmatrix} \boldsymbol{v} \\ \boldsymbol{x} \end{pmatrix} + \begin{pmatrix} \mathbf{M}^{-1}\boldsymbol{f_v}(\boldsymbol{x}) \\ \mathbf{0} \end{pmatrix}, \tag{1}$$

where the vectors $\boldsymbol{x} = (x_{1l}, x_{2l})^\top$ and $\boldsymbol{v} = (v_{1l}, v_{2l})^\top$ respectively contain the displacements and velocities of the VF upper, m_{2l}, and lower, m_{1l}, masses. The pacemaker mass is attached to m_{1l} and it will have the same displacement and velocity. $\mathbf{I}$ and $\mathbf{0}$ in the second row of the block matrix of Eqn. (1) respectively stand for the identity and zero matrices, while in the first row we get the mass matrix $\mathbf{M}$, the damping matrix $\mathbf{C}$, the stiffness matrix $\mathbf{K}$ and the collision matrix $\boldsymbol{\Theta}$. Explicit expressions for them can be found in [4]. The force vector is given by $\boldsymbol{f_v} = (P_1 L d_{1l}, 0)^\top$, where L is the glottis length, d_{1l} the thickness of m_{1l} and P_1 the glottal pressure,

$$P_1 = P_s \left[1 - \Theta(a_{\min}) \left(\frac{a_{\min}}{a_1} \right)^2 \right] \Theta(a_1). \tag{2}$$

Here, P_s is the subglottal pressure, $a_{\min}$ is the minimum of the upper, a_1, and lower, a_2, glottal areas, and $\Theta(z)$ is the collision function (see [1–3] for details). $\mathbf{K}$, $\boldsymbol{\Theta}$ and $\boldsymbol{f_v}$ are the nonlinear terms of the ODE system of Eqn. (1).

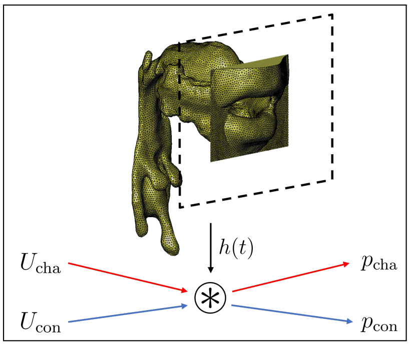

Figure 2. Procedure to compute the sound of vowel /a/ for chaotic and controlled phonation. The VT geometry has been obtained from MRI data.

Our variable of interest for vowel numerical generation is the volume flow velocity,

$$U = \left(\frac{2P_s}{\rho} \right)^{1/2} a_{\min} \Theta(a_{\min}), \tag{3}$$

which can be computed for each time from the solution of Eqn. (1) (ρ in Eqn. (3) is the density). U will be input at the glottis of the 3D VT of a vowel and the wave equation for the acoustic pressure will be solved to generate the corresponding sound. The procedure will be detailed in section 2.3.

2.2 Chaos control strategy

As already mentioned, for large values of k_{cl} the oscillations of the VF can become chaotic. To control them we resort to the altering energy method [5, 6], but instead of applying an external force to the system we exert an internal control by modifying the damping of the pacemaker made of an ideal smart material whose properties can be tuned on demand. The damping matrix of the system $\mathbf{C}$ is split into $\mathbf{C} = \mathbf{C}_{\text{CV}} + \mathbf{C}_P$, where $\mathbf{C}_{\text{CV}}$ is the natural damping of the VFs and $\mathbf{C}_P$ is that exerted by the pacemaker.

The derivative of the mechanical energy with respect to time for the VF system is

$$\dot{E} = \boldsymbol{v}^\top [-\mathbf{C}_{\text{VF}}\boldsymbol{v} - \boldsymbol{\Theta}(\boldsymbol{x})\boldsymbol{x} + \boldsymbol{f_v}(\boldsymbol{x}) + \mathbf{C}_{\text{P}}(t,\boldsymbol{p})\boldsymbol{v}] \tag{4}$$

and the idea is to regulate the power injected or removed by the pacemaker, $\boldsymbol{v}^\top \mathbf{C}_{\text{P}}(t,\boldsymbol{p})\boldsymbol{v}$, to recover a regular motion of the VFs. In this work, this is done by setting the

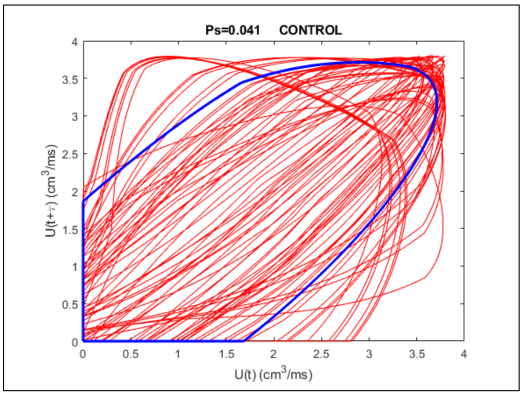

Figure 3. Phase space plot in time delay coordinates for the glottal volume velocity without control, $U_{\rm cha}$ (red), and with control, $U_{\rm con}$ (blue), for a subglottal pressure of $P_s = 0.041$.

damping of the pacemaker $r_{sm}(\boldsymbol{p},t)$ in $\mathbf{C}_{\rm P}$ as

$$r_{sm}(\boldsymbol{p},t) = r_{sm}^0 \,\mathrm{sgn}(v_{1l}) \qquad (5)$$

where sgn denotes the sign operator and $r_{sm}^0 \ll r_{1l}$, r_{1l} being the damping of the lower mass.

2.3 Generation of vowel sounds for abnormal and controlled phonation

To see how chaotic phonation affects the generation of a vowel sound and how the control strategy can improve its quality, we proceed as follows. First we compute the impulse response, $h(t)$, of the 3D VT corresponding to vowel /a/. The geometry of the VT is obtained from magnetic resonance imaging (MRI) and attached to a flat baffle as an approximation to the human head [13]. $h(t)$ is calculated by solving the mixed form of the acoustic wave equation inside the VT with the FEM by imposing a Gaussian volume velocity pulse at the glottis [7–9]. The vowel sound is then obtained from the convolution,

$$p_a(t) = U_a(t) * h(t) = \int h(t-\tau)U_a(\tau)\mathrm{d}\tau, \qquad (6)$$

where $a = \{\mathrm{cha},\ \mathrm{con}\}$, for the chaotic and controlled cases respectively, and U_a is obtained from Eqn. (3). The procedure is depicted in Fig. 2.

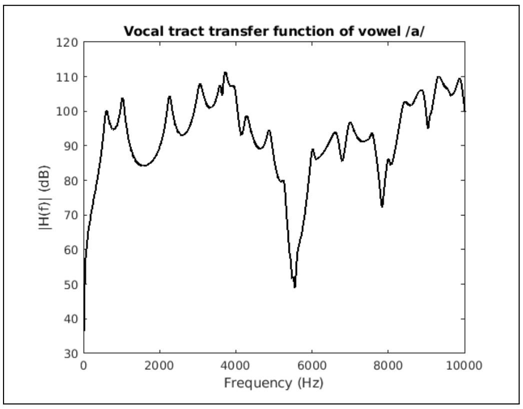

Figure 4. Vocal tract transfer function for vowel /a/ computed with FEM.

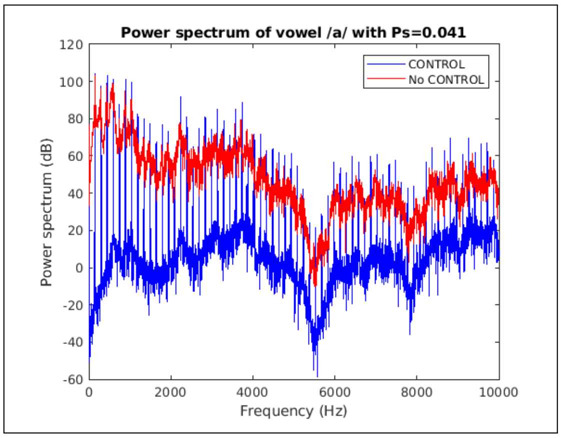

Figure 5. Power spectrum of vowel sound /a/ with and without chaos control.

3. NUMERICAL SIMULATIONS

According to the methodology described in the previous sections, the first step is to compute the volume flow velocity in Eqn. (3) in the cases of chaotic and controlled phonation. In Fig. 5, we show the phase space plots for $U_{\rm cha}$ (red line) and $U_{\rm con}$ (blue line) in time delay coordinates and for a flexural stiffness of $k_{cl} = 0.09$ and a subglottal pressure $P_s = 0.041$. As can be seen, if no control is applied we obtain a strange attractor in phase space, while we recover a regular periodic motion when we activate the control pacemaker.

The second step is to obtain the impulse response $h(t)$ of the VT. In Fig. 4, we present the vocal tract transfer function (VTTF) for vowel /a/, computed from the Fourier transform of $h(t)$, i.e. $H(f) = \mathcal{F}[h(t)]$, using FEM (see Fig. 2).

Finally, once we have $U_{\rm cha}$, $U_{\rm con}$ and $h(t)$, the third step is to calculate the acoustic pressure for vowel /a/ without control, $p_{\rm cha}$, and with control, $p_{\rm con}$, according to Eqn. (6). The spectra of $p_{\rm cha}$, and $p_{\rm con}$ are plotted in Fig. 5. While the latter is essentially controlled by the fundamental frequency $f_0 = 149$ Hz and its harmonics, and shaped by the VT impulse response, the former is a noisy signal with no clear pattern. This is very evident if one listens to they corresponding audio files. Whereas $p_{\rm cha}$ can hardly be recognized, when the control is applied the situation changes completely and $p_{\rm con}$ can be clearly identified as the vowel /a/.

4. CONCLUSIONS

In this work we have explored the potential of a phonation pacemaker to improve the generation of vowel sounds. An ideal pacemaker has been incorporated into a two-mass model of the vocal cords and we have seen how it can transform their chaotic motion into regular one. This has a critical impact on the FEM generation of the vowel /a/. In chaotic phonation, the vowel is barely recognized, whereas it is fully identifiable when VF chaos control is activated.

5. ACKNOWLEDGMENTS

The first three authors thank the support of the project FEMVoQ (PID2020-120441GB-I00-AEI-10.13039/501100011033) from the Spanish Ministerio de Ciencia e Innovación and that of the Catalan Government (Departament de Recerca i Universitats) for the grant 2021 SGR 01396 given to the HER group. The fourth author would like to acknowledge the financial support from the CNRS through the 80 Prime program.

6. REFERENCES

[1] J. J. Jiang, Y. Zhang, and J. Stern, "Modeling of chaotic vibrations in symmetric vocal folds," *J. Acoust. Soc. Am.*, vol. 110, no. 4, pp. 2120–2128, 2001.

[2] K. Ishizaka and J. Flanagan, "Synthesis of voiced sounds from a two-mass model of the vocal cords," *Bell Syst. Tech. Journal*, vol. 51, pp. 1233–1268, 1972.

[3] I. Steinecke and H. Herzel, "Bifurcations in an asymmetric vocal-fold model," *J. Acoust. Soc. Am.*, vol. 97, no. 3, pp. 1874–1884, 1995.

[4] O. Guasch, A. Van Hirtum, A. I. Fernández, and M. Arnela, "Controlling chaotic oscillations in a symmetric two-mass model of the vocal folds," *Chaos Solit. Fractals*, vol. 159, p. 112188, 2022.

[5] V. Tereshko, R. Chacón, and V. Preciado, "Controlling chaotic oscillators by altering their energy," *Phys. Lett. A*, vol. 320, no. 5-6, pp. 408–416, 2004.

[6] V. Tereshko, "Control and identification of chaotic systems by altering their energy," *Chaos Solit. Fractals*, vol. 40, no. 5, pp. 2430–2446, 2009.

[7] H. Takemoto, P. Mokhtari, and T. Kitamura, "Acoustic analysis of the vocal tract during vowel production by finite-difference time-domain method," *J. Acoust. Soc. Am.*, vol. 128, no. 6, pp. 3724–3738, 2010.

[8] M. Arnela, S. Dabbaghchian, R. Blandin, O. Guasch, O. Engwall, A. Van Hirtum, and X. Pelorson, "Influence of vocal tract geometry simplifications on the numerical simulation of vowel sounds," *J. Acoust. Soc. Am.*, vol. 140, no. 3, pp. 1707–1718, 2016.

[9] M. Freixes, M. Arnela, J. C. Socoró, F. Alías, and O. Guasch, "Glottal source contribution to higher order modes in the finite element synthesis of vowels," *Appl. Sci.*, vol. 9, no. 21, p. 4535, 2019.

[10] O. Guasch, M. Arnela, R. Codina, and H. Espinoza, "A stabilized finite element method for the mixed wave equation in an ALE framework with application to diphthong production," *Acta Acust. united Ac.*, vol. 102, no. 1, pp. 94–106, 2016.

[11] M. Arnela, S. Dabbaghchian, O. Guasch, and O. Engwall, "MRI-based vocal tract representations for the three-dimensional finite element synthesis of diphthongs," *IEEE/ACM Trans. Audio Speech Lang. Process.*, vol. 27, no. 12, pp. 2173–2182, 2019.

[12] S. Dabbaghchian, M. Arnela, O. Engwall, and O. Guasch, "Simulation of vowel-vowel utterances using a 3D biomechanical-acoustic model," *Int. J. Numer. Meth. Biomed. Eng.*, vol. 37, no. 1, p. e3407, 2021.

[13] M. Arnela, R. Blandin, S. Dabbaghchian, O. Guasch, F. Alías, X. Pelorson, A. Van Hirtum, and O. Engwall, "Influence of lips on the production of vowels based on finite element simulations and experiments," *J. Acoust. Soc. Am.*, vol. 139, no. 5, pp. 2852–2859, 2016.