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VOCAL FOLD OSCILLATORS AT LARGE ASYMMETRIES

J. C. Lucero[1], X. Pelorson [2], A. V. Hirtum [2]

[1] Dept. Computer Science, University of Brasília, Brazil
[2] LEGI, UMR CNRS 5519, Grenoble Alpes University, Saint-Martin-d'Hères, France
lucero@unb.br, xavier.pelorson@univ-grenoble-alpes.fr, annemie.vanhirtum@univ-grenoble-alpes.fr

Abstract: **This paper investigates threshold conditions of the vocal fold oscillation in the presence of a natural frequency asymmetry. Theoretical expressions for the subglottal threshold pressure and frequency are derived from a simple dynamical model of the vocal folds, and compared to data measured from a mechanical replica of the larynx under both symmetrical and asymmetrical configurations. The results demonstrate good agreement between theory and experiments, and show that the oscillation threshold is sensitive to the asymmetry with distinct behaviors between regions of low vs. high asymmetry.**

Keywords: **Vocal folds, oscillation threshold, asymmetry, mechanical replica**

I. INTRODUCTION

The vocal folds constitute a pair of coupled oscillators that, in normal configurations, oscillate with in-phase synchrony. Pathological conditions create right-left asymmetries which hamper the oscillation and may induce complex entrainment regimes and other nonlinear phenomena [1].

In a recent theoretical study [2], asymmetries in the stiffness of the vocal folds were analyzed and different behaviors at small vs. large asymmetry were detected. At small asymmetry, the oscillation threshold value of the subglottal pressure increases with the asymmetry. The curve relating threshold pressure and right/left stiffness ratio has a "U"-shape characteristics, with the minimum at the symmetric configuration. Mathematically, the threshold corresponds to a Hopf bifurcation. At large asymmetry, on the other hand, the threshold pattern changes to a double Hopf bifurcation and the oscillation threshold pressure assumes a constant value.

The detected difference may have relevant consequences, not only for the understanding of the dynamics of the vocal fold oscillation, but also for the application of the oscillation threshold pressure as a parameter for clinical diagnosis [3]. Thus, the present study has the purpose of exploring further the effect of asymmetries on the oscillation threshold. At the same time, it will seek validation of the theoretical results by using data collected from a mechanical replica of the vocal folds.

II. METHODS

A. Theoretical model

The vocal folds are represented as a coupled system of two one-degree-of-freedom oscillators of the form

$$\begin{aligned} \ddot{x}_r + \beta\left(1 + x_r^2\right)\dot{x}_r + \omega_r^2 x_r &= \alpha(\dot{x}_r + \dot{x}_l) \\ \ddot{x}_l + \beta\left(1 + x_l^2\right)\dot{x}_l + Q^2\omega_r^2 x_l &= \alpha(\dot{x}_r + \dot{x}_l) \end{aligned} \tag{1}$$

where x is the normalized tissue displacement and subindices r, l designate the right and left folds, respectively, β is the damping, ω_r is the natural angular frequency of the right vocal fold, Q is a coefficient of natural frequency asymmetry, and α is the aerodynamic coupling [2].

Further,

$$\alpha = \frac{S^2 P_s}{k_t a_0 c M}, \tag{2}$$

where S is the area of the medial surface of the vocal folds, P_s is the subglottal pressure, k_t is a transglottal pressure coefficient, a_0 is the glottal area at rest, c is the mucosal wave velocity and M is the vocal fold mass. Coefficient k_t depends on the glottal area and is modeled as

$$k_t = \frac{E}{a_0} + F, \tag{3}$$

where E and F are empirical coefficients [4].

The oscillation threshold pressure P_{th} is obtained by a standard stability analysis of Eqs. (1). In the case of a low asymmetry, the analysis yields

$$P_{\text{th}} = P_0\left(1 + F' a_0\right)\left[1 + \left(\frac{\omega\Delta}{\beta}\right)^2\right], \text{ for } \Delta \le \frac{\beta}{\omega}, \tag{4}$$

where $P_0 = cME\beta/(2S^2)$, $F' = F/E$, ω is the angular frequency of the oscillation, and Δ is a normalized asymmetry coefficient which maps Q $\in [-\infty, +\infty]$ into $\Delta \in [-1, +1]$ and is given by

$$\Delta = \frac{1-Q^2}{1+Q^2}, \tag{5}$$

and

$$\omega = \omega_r \sqrt{\frac{1+Q^2}{2}} \tag{6}$$

is the angular frequency of the oscillation.

In the case of a large asymmetry, the threshold pressure is

$$P_{\text{th}} = 2P_0\left(1+F' a_0\right), \text{ for } \Delta \geq \frac{\beta}{\omega}, \tag{7}$$

and the angular frequency of the oscillation is given by the real solutions to

$$\omega^4 - \left[\left(1+Q^2\right)\omega_r^2 - \beta^2\right]\omega^2 + Q^2\omega_r^4 = 0 \tag{8}$$

Eq. (4) models the threshold pressure when both folds oscillate in synchrony at the same frequency given by Eq. (6). The threshold pressure has a minimum at $\Delta = 0$ (full symmetry) and increases with $|\Delta|$. Eq. (7), on the other hand, represents the threshold when the folds oscillate independent of each other, each one at its own frequency given by Eq. (8). In this case, the threshold pressure is independent of Δ.

B. Data

Oscillation threshold data were collected from a mechanical replica of the vocal folds. The replica and data collection method has been described in detail elsewhere [5,6]. Briefly, the replica consists of two parallel latex sleeves filled with water under pressure and supported by a metallic structure. The latex sleeves represent the vocal folds in a 3:1 scale. Air from a pressure reservoir is blown through a third latex sleeve, representing the glottal passage, situated in-between the two vocal fold sleeves and perpendicular to them.

Values of oscillation threshold pressure and frequency were obtained by increasing the air pressure upstream of the replica from zero until an oscillation of the sleeves was detected. The time instant of oscillation onset was determined by spectral analysis of the upstream pressure signal, and the mean upstream pressure and oscillation frequency at that instant were computed. The glottal area at rest was determined from pictures taken by a digital camera, calibrated with a benchmark grid.

Three experiments were performed, in which measures of the above parameters (pressure, frequency and area) were taken at various values of internal (water) pressures of the fold sleeves, in symmetrical and asymmetrical configurations. In addition, the mechanical constants of one of the vocal fold sleeves (natural frequencies and bandwidths) were measured for various internal pressure values, by means of a shaker in conjunction with a laser vibrometer.

III. RESULTS

A. Frequency response

The frequency response of the vocal fold sleeve is shown in Fig. 1. The first natural frequency (f_1) has a linear relation with the internal pressure (h), and is well fitted by the equation $f_1 = 52.7 + 11.1h$. Its bandwidth (b_1) was simply approximated with the constant value $b_1 = 13.1$ Hz. Thus, we have $\beta = 2\pi b_1 = 82.3\ s^{-1}$.

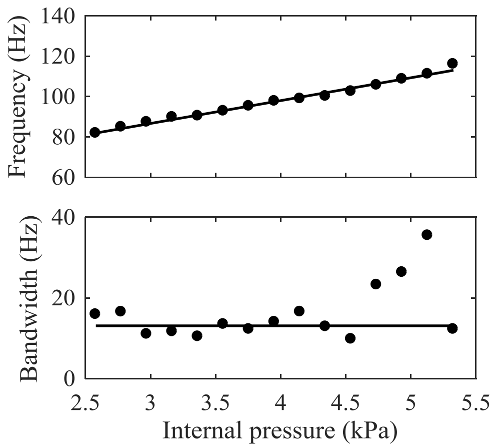

Fig. 1. First natural frequency (top) and bandwidth of a vocal fold sleeve. The solid lines show the fitted approximations.

B. Experiment 1

In this experiment, the internal pressure of both folds was varied simultaneously between 4 kPa and 8.5 kPa, keeping a symmetrical configuration. The results are shown in Fig. 2.

The threshold pressure and frequency are well approximated by Eqs. (4) and (6), respectively, with $\Delta = 0$, $P_0 = 635$ Pa, $F' = -0.0535$ Pa/cm^2, and $\omega = \omega_r = 2\pi f_1$. However, the oscillation frequency seems to follow a nonlinear relation which is not captured by the natural frequency f_1 reported in subsection III.A. A possible cause may be that the nonlinearity becomes evident at large values of internal pressure, whereas the frequency response was measured at a lower pressure range.

The glottal area decreases with the internal pressure, due to the increase in volume of water held inside each vocal fold sleeve. The measured values are well approximated by the quadratic equation $a_0 = -0.77h^2 + 8.26h - 13.7$, and this equation was applied in Eq. (4) when computing the threshold pressure. Note that the increase in threshold pressure with the internal pressure is a direct consequence of the glottal area variation.

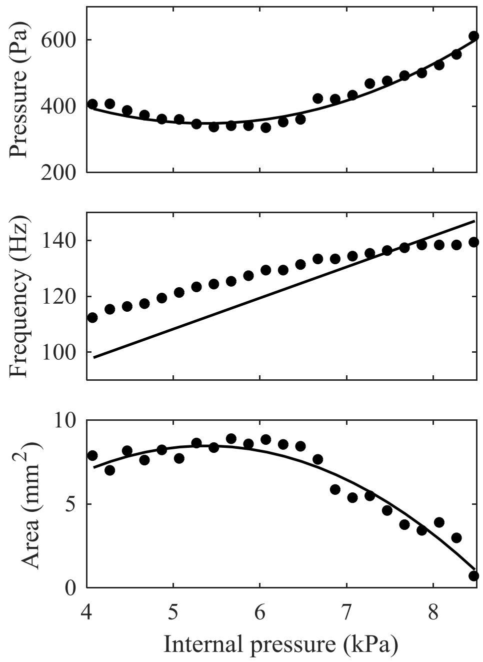

Fig. 2. Results of Experiment 1. Top: oscillation threshold pressure, middle: oscillation frequency, bottom: glottal area at rest. The solid lines show the fitted approximations.

C. Experiment 2

In this experiment, the internal pressure of one fold was fixed at 6.0 kPa whereas the internal pressure of the other was varied between 4.1 kPa and 8.3 kPa. The intention was to obtain both negative and positive values of the asymmetry coefficient Δ, and the results are shown in Fig. 3.

The threshold pressure seems to follow well the pattern given by Eq. (7), with the same values for P_0 and F' as in Experiment 1, even at low asymmetry. Eq. (4), on the other hand, is unable to reproduce the data. A possible interpretation is that the vocal folds are slightly coupled and still act as independent oscillators in this region. The points where both curves intersect mark the limits between the theoretical low and high asymmetry regions.

The oscillation frequency is well modeled by Eq. (6), within the low asymmetry region, with $\omega_r = 2\pi f_2$, where f_2 = 231 Hz is the second natural frequency at 6.0 kPa of internal pressure [6]. In the high asymmetry region, Eq. (8) produces two values, one for each fold. At positive asymmetry, the measured value seems to be the lower of both frequencies, whereas at negative asymmetry, it seems to be the average.

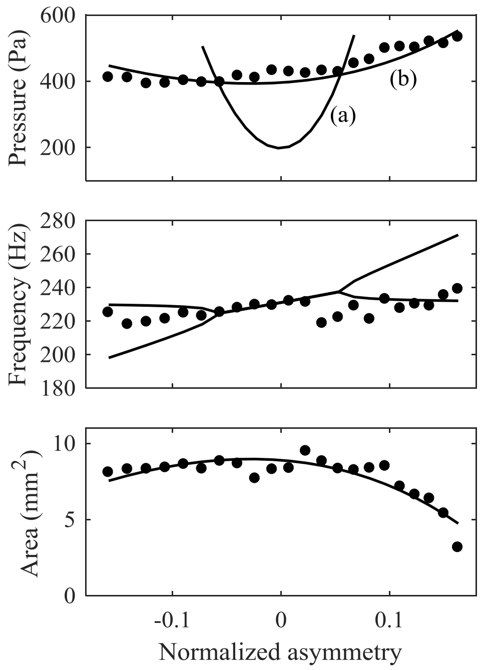

Fig. 3. Results of Experiment 2. Top: oscillation threshold pressure, middle: oscillation frequency, bottom: glottal area at rest. The solid lines show the fitted approximations. In the top panel, curve (a) is produced by Eq. (4) and curve (b) by Eq. (7).

The glottal area may be fitted similarly as in Experiment 1, with the quadratic equation $a_0 = -0.60h^2 + 6.80h - 10.3$.

C. Experiment 3

In this experiment, the internal pressure of one fold was fixed at 2.5 kPa whereas the internal pressure of the other was varied between 2.5 kPa and 5.4 kPa. . The intention was to obtain larger values of the asymmetry coefficient Δ, and the results are shown in Fig. 4.

For the threshold pressure, again Eq. (7) provides a better approximation than Eq. (4), although values for Δ > 0.15 seem to follow a different variation pattern.

The oscillation frequency is modeled by Eqs. (6) and (8), as in Experiment 2, but this time using $\omega_r = 2\pi f$, with f = 95 Hz. This value is a bit higher than the first natural frequency f_1 = 80 Hz measured at 2.5 kPa in the frequency response experiment. With this value, the low asymmetry region is well fitted, and in the high asymmetry region the measured values match the higher of the two theoretical frequencies.

The glottal area may be fitted as in the previous experiments, with the quadratic equation $a_0 = -0.26h^2 + 1.94h - 16.4$.

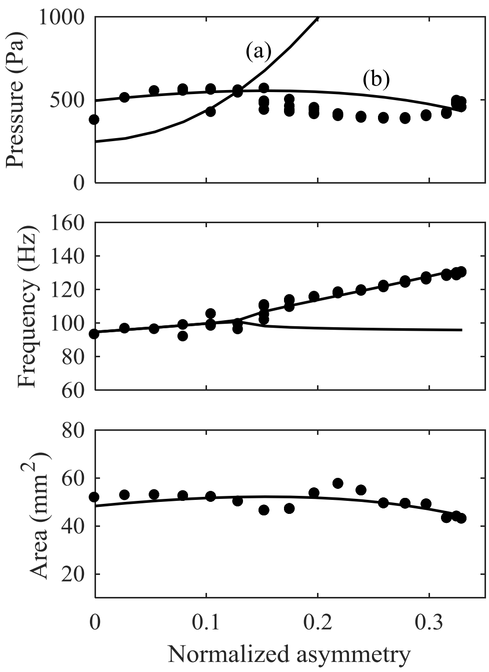

Fig. 4. Results of Experiment 3. Top: oscillation threshold pressure, middle: oscillation frequency, bottom: glottal area at rest. The solid lines show the fitted approximations. In the top panel, curve (a) is produced by Eq. (4) and curve (b) by Eq. (7).

IV. Discussion and Conclusions

The subglottal threshold pressure of the vocal fold oscillation has been interpreted as a measure of ease of phonation and proposed as a diagnostic parameter for vocal health [3]. Therefore, it is important to understand its behavior, particularly in abnormal laryngeal configurations.

Our results show a complex pattern for this parameter. According to the adopted theoretical model, distinct behaviors at low vs. high asymmetry are related to the synchronization vs. desynchronization of the vocal fold oscillators. At large asymmetries and low coupling, the vocal folds act as independent oscillators at their own frequency and constant oscillation threshold pressure. If the asymmetry is reduced or the coupling (pressure) increased, then the synchronized action of the vocal fold facilitates the oscillation and the threshold pressure is reduced up to the minimum at full symmetry.

The model shows agreement with the collected data, except for curves (a) in Figs. 3 and 4. A difficulty when comparing the theory with the experiments is that variations of the internal pressure of the vocal folds affect not only their natural frequency but also their volume, introducing variations in both their separation and oscillating mass which are not contemplated by the theoretical model.

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