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# Threshold of oscillation of a vocal fold replica with unilateral surface growths

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Among vocal fold diseases, the presence of a surface growth is often encountered and can be considered a public health issue. While more energy is required to achieve phonation than in healthy cases, this situation can lead to a wide range of voice perturbations, from a change of voice quality to aphonia. The present study aims at providing finer comprehension of the physical phenomena underlying this type of pathological phonation process. A vocal fold replica is used to perform measurements of mechanical responses of each vocal fold as well as of the subglottal pressure in both healthy and pathological configurations. Besides these physical measurements, a theoretical model is derived, using the one-mass-delayed model involving asymmetry of mass and geometry in order to simulate pressure signals. The theoretical model parameters are determined according to mechanical measurements on the replica. Results from measurements and simulations show that this unique vocal fold replica behaves in a manner comparable to clinical observations. The energy required to produce sound increases in the presence of a growth as well as with the size of the growth. Further investigation tends to show that the contact of the growth on the opposite vocal fold, considered as additional damping, plays a critical role. © 2017 Acoustical Society of America. [<http://dx.doi.org/10.1121/1.4979935>]

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## I. INTRODUCTION

While human voice is an important communication means, it is alterable with 29% of the general population having potentially at least one voice disorder during a lifetime.<sup>1</sup> A number of occupations require an intensive use of voice in terms of duration and loudness, yielding a range of pathologies such as the formation of a surface growth on the vocal folds. This change of shape, mass, and mechanical properties of the vocal fold structure can induce a certain level of voice fatigue and minor to major voice disorders.<sup>2</sup>

The general approach of the present paper is to consider the vocal folds as a mechanical system related to particular physical quantities yielding a range of specific types of vibratory behavior. In order to obtain a finer comprehension of the mechanical phenomena involved in the phonation process including various types of surface growth on vocal folds, different approaches can be adapted. One is to use physical replicas mimicking the mechanical behavior of the human larynx,<sup>3</sup> another is to build theoretical models based on simplified physical laws of coupled fluid-mechanical systems,<sup>4</sup> or even numerical methods such as finite elements.<sup>5</sup> These approaches have been widely developed for healthy vocal folds, but seldom used in the specific case of a surface growth on vocal folds.

A number of studies conducted on vocal fold replicas are based on parameter variations such as vocal fold stiffness,<sup>3,6</sup> subglottal pressure,<sup>7,8</sup> or initial glottal area.<sup>9</sup> This approach enables a clear separation of the influence of each controlled and quantified parameter on the resulting vibration or sound

produced, along with repeatability of measurements, which is not possible with *in vivo* measurements.

In addition to the physical vocal fold replicas, a number of theoretical models of the vibratory behavior of vocal folds have been developed since the first model was published in a pioneering study.<sup>4</sup> These models involve a certain number of mass-spring-damping units, as a simplification of the complex mechanical system. Some of these simplified models of vocal fold vibrational behavior account for the mucosal wave propagation<sup>10</sup> during sound production. A simple means of accounting for this phenomenon is using a one-mass model including a temporal delay to simulate the propagation of the mucosal wave.<sup>11</sup>

While phonation mechanics has been well studied, described, and modeled for healthy vocal folds, little research has been conducted on the specific pathological case of a surface growth. Most of the previous research in this direction is primarily concerned with medical issues such as voice therapy to manage vocal fold polyps, cysts, or nodules from a general point of view.<sup>12</sup> The involved techniques of observation include voice acoustical measurements and analysis<sup>13–15</sup> or videostroboscopy and image signal processing.<sup>16</sup> Analysis of the vibratory behavior of the vocal fold in the presence of a surface growth has been performed using the properties of the spatiotemporal irregularity due to the broken symmetry induced by a polypoid mass.<sup>17</sup> This situation yields more energetic high-order modes of vibration as compared to healthy cases. Analytical modeling of vocal folds behavior with a surface growth includes non-linear dynamics through a physical model<sup>18</sup> based on a specific two-mass model<sup>19</sup> and an additional unilateral mass. Measurements on a vocal fold replica have also been performed including a growth surface

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in the context of a two-layer replica.<sup>20</sup> The study focused on quantifying the effects of controlled parameters (growth size, subglottal pressure) on physical quantities (oscillation onset pressure, fundamental frequency, air flow, and acoustical signal).

Last, another study,<sup>21</sup> which focused on vocal fold disorders due to a surface growth, analyzed the air flow perturbation through the glottis. Particle image velocimetry measurements were performed on an upscaled replica of vocal folds under forced oscillation regime. Results showed that the presence of a growth can significantly modify the air jet behavior. It is noted that the presence of a growth might also change the structural characteristics of the vocal folds, which could contribute to the irregular vocal folds dynamics observed in patients.

The present study is positioned as a complementary work to this previous research. The first goal of the present paper is to show the results of the vocal fold replica in terms of upstream air pressure and fundamental frequency in various configurations with and without growths. The second goal of this paper is to compare the effects of the mass and volume of the growths on the sound and vibrations measured in the vocal fold replica. The third goal of the present study is to determine whether the initial contact between the vocal folds induced by the presence of a growth is significant in the auto-oscillation process. Our hypothesis is that this latter effect is physically predominant and that the mass of the growth plays a minor role on the oscillation onset.

## II. EXPERIMENTAL SETUP

### A. General description

The experimental setup used for this study is composed of a vocal fold replica constructed at scale 1:1 connected to a large pressure reservoir, allowing to change continuously various physical parameters. It is an evolution of the upscaled replica used in a previous study,<sup>3</sup> based on the same principle, using latex tubes filled with water under a controllable pressure. The present replica has been designed to enable the operator to tune more parameters such as the space between the vocal folds. It also embodies a central latex tube between the upstream and downstream metallic tubes that guides the air flow through the glottis to avoid air leakage, which did not exist in the previous replica. The general setup is depicted in Fig. 1. The air supply is provided by a compressor (Atlas Copco, GA5 FF-300-8, Nacka, Sweden) controlled by a pressure regulator (Norgren, 11-818-987, Birmingham, AL), feeding a large pressure reservoir. To prevent unwanted acoustical resonances, the pressure reservoir is filled with acoustic foam. The vocal fold replica is connected to the pressure reservoir using an 8 cm long circular uniform tube having a 2.5 cm internal diameter. Downstream of the vocal fold replica is placed another 2.5 cm diameter circular tube of smaller length (4 cm).

The vocal fold replica is depicted in Fig. 2. It consists of two latex tubes of internal diameter 11 mm and length 80 mm, filled with water under pressure. A thin rubber layer is inserted between the vocal fold replicas in order to control the spacing. A latex tube passes between each vocal fold

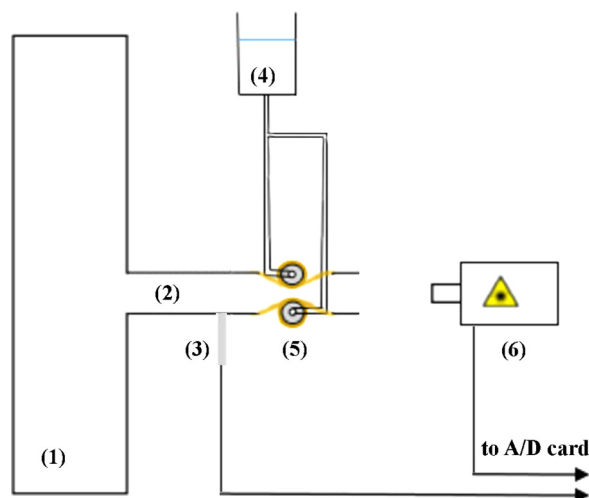


FIG. 1. (Color online) Schematic of the experimental setup composed of (1) the pressure reservoir, (2) the tube supplying air to (5) the vocal fold replica, (3) the air pressure sensor, (4) the water tank, and (6) the laser vibrometer.

replica and connects the upstream region to the downstream one, as shown in Fig. 2. The water pressure,  $P_w$ , inside the vocal fold replica can be controlled by elevating or lowering a water tank. This way, one can modify the stiffness of the replicas but also modify the glottal area at rest because as the pressure of water  $P_w$  changes, the latex tubes are inflating or deflating. The characteristic dimensions of the replica are summarized in Table I.

A pathological configuration is simulated by inserting a growth between the latex membranes, located in the middle

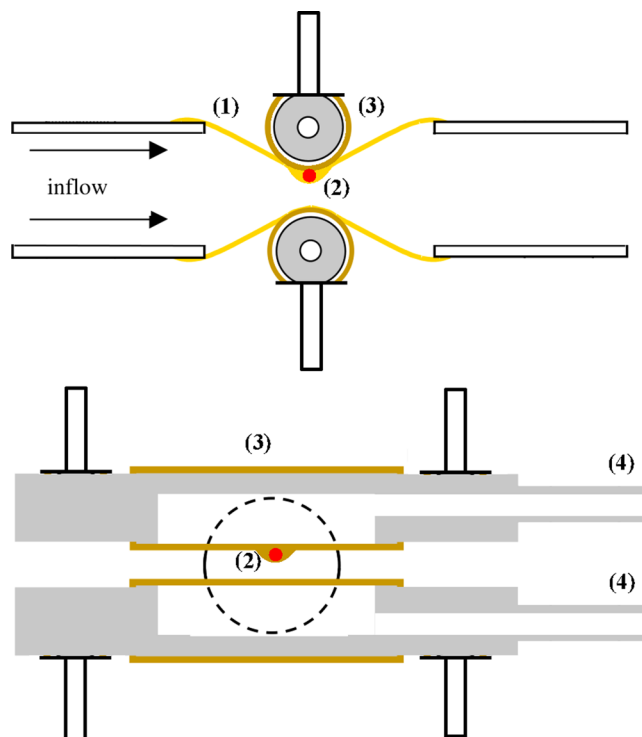


FIG. 2. (Color online) Schematic of the vocal fold replica in side view (top) and front view (bottom). (1) Latex tube connection, (2) growth made of a small solid ball stuck between the latex membranes 1 and 3, (3) latex tubes filled with water, and (4) connections to the water tank.

TABLE I. Comparison of the relevant dimensional and dimensionless parameters from human beings and the replica: glottal width  $L$ , glottal thickness  $D$ , initial (pre-phonatory) glottal area  $A_0$ , oscillation threshold pressure  $P_{th}$ , fundamental frequency  $F_0$ , Reynolds and Strouhal numbers  $Re$  and  $St$ .

	Human larynx	Replica
$L$ (mm)	10–20	10–17
$D$ (mm)	4–10	10
$A_0$ (mm <sup>2</sup> )	0–4	0.5–4
$P_{th}$ (Pa)	200–500	350–1000
$F_0$ (Hz)	60–200	75–220
$Re$	200–600	100–600
$St$	0.01–0.10	0.06–0.10

of the upper fold, on the air flow side. The growths used in the present study are small spheres made of lead whose characteristics are presented in Table II. These spheres represent an increase of the vocal fold replica total mass by, respectively, 5% and 20%. This later value, 20%, is probably an overestimation from a physiological point of view but is interesting, from the point of view of physics, as it represents an extreme loading of the vocal folds.

## B. Dimensions and dimensionless numbers

The dimensions of the vocal fold replica are listed in Table I and compared to the values for the human vocal folds, male speaker in register voice, reported in the literature.<sup>22–28</sup>

In addition the Reynolds ( $Re$ ) and Strouhal ( $St$ ) numbers are calculated. In a flow, the Reynolds number represents the relative importance between the convective terms and the viscous ones. Friction forces are mainly influenced by the height,  $h$ , of the channel. Hence the Reynolds number is defined as  $Re = Uh/\nu$ , where  $U$  is the characteristic velocity of the fluid,  $h$  is the height of the channel, and  $\nu$  is the kinematic viscosity of the fluid. The Strouhal number compares the inertial terms to the convective ones, or in other words, the time needed for the vocal folds to open to the time necessary for the flow to pass the glottis. The relevant length scale is therefore the transversal dimension of the glottis,  $D$ :  $Sr = F_0D/U$ .

## C. Optical measurements

The glottal area at rest is measured by taking a picture of the replica using a digital camera (Mikrotron, EoSens Cube7), equipped with a macrophotographic lens (Tokina, AT-X100mmf/2.8 PRO D), each time the pressure of water is changed. A calibration of the pictures is performed using a calibrated grid (Edmunds Optics, 58-607) placed in the same focal plane as the vocal fold replica. From each picture of

TABLE II. Definition of the spherical growth name, material, mass, and diameter.

Denomination	L1	L2
Material	lead	lead
Mass (g)	0.10	0.34
Diameter (mm)	2.75	3.75

the replica, one can therefore measure the glottal area at rest, its midline aperture, and its width.

## D. Pressure measurements

The pressure upstream of the vocal fold replica is measured using a Kulite XCS093 pressure sensor. Calibration of the pressure sensor is performed against a water manometer with an accuracy of  $\pm 2.5$  Pa.

## E. Mechanical response measurements

Frequency response functions (FRFs) are measured using a laser Doppler vibrometer (Optomet Vector Series) coupled to a scanning system (HGL Dynamics, VL Scanner) allowing for observations at multiple points. Mechanical excitation is provided by a shaker (Modalshop K2007E) fed with random noise between 50 and 400 Hz whose spectrum is modified according to the shaker's response in order to obtain a flat excitation spectrum. The vibration imposed to the structure is measured by means of an accelerometer (PCB 482A21) fixed at the mobile end of the shaker.

## III. RESULTS FROM MEASUREMENTS

To quantify the perturbation induced by the presence of a surface growth on one of the vocal folds, the following measurements are performed on the vocal fold replica.

First, mechanical characterization is required to quantify the natural vibratory behavior of each vocal fold configuration individually, i.e., with and without the growths, namely in pathological and healthy configurations.

Then, in configurations with and without growths, measurements of the oscillation onset in terms of upstream threshold pressure, the corresponding sound fundamental frequency, together with the initial glottal area are performed.

### A. FRFs and fundamental frequency

Mechanical response measurements have been performed using the shaker and the laser vibrometer in order to characterize the system in its dynamic state and derive some mechanical parameters. Two points of the vocal fold replica are considered, one at the center and the other at one-third of the fold length to measure various vibration modes. These measurements yield complex FRFs, i.e., the magnitude and phase signals against frequency, providing information about the frequency and damping of the natural resonances of the system.

Each vocal fold was studied at various levels of inner water pressure  $P_w$ , i.e., various water tank heights. Figure 3 presents an example of FRF measured with and without growths, between 60 and 120 Hz, the water tank being placed at 25 cm of height. A shift of the main resonance peak within the frequency response can be observed around 90 Hz, as the phase angle drops, meaning that the nature of growth (mass, volume) changes the natural vibratory behavior of the fold. The vocal fold in healthy configuration, i.e., without any growth, shows the highest resonance frequency, just above 90 Hz. The presence of a growth tends to lower



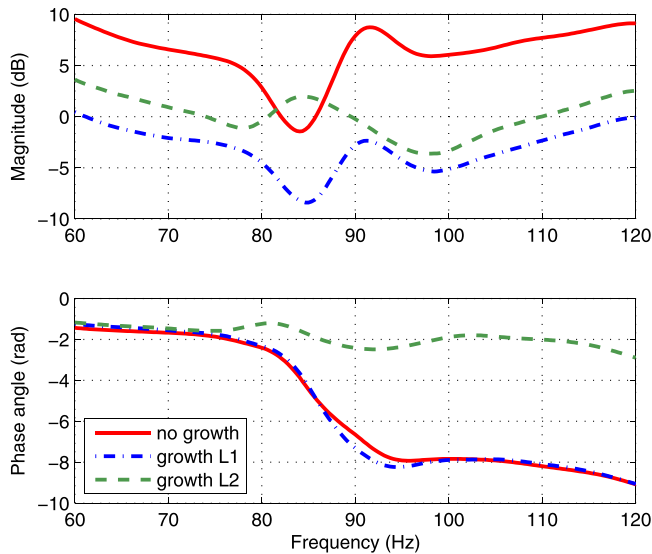


FIG. 3. (Color online) Example of measured FRFs of the vocal fold replica, in healthy and pathological configurations, at the water pressure  $P_w = 25$  cm H<sub>2</sub>O.

the first resonance frequency, with a stronger effect as its mass and volume increase.

This is confirmed and generalized by Fig. 4, which presents the center frequency of two resonance peaks of the mean FRF over the two measurement points of each vocal fold configuration, against the water pressure inside the vocal fold. The resonance frequency without growth is generally among the highest, although the small lead growth L1 presents resonance frequencies close to the case without growth. The heaviest lead growth L2 presents lower resonance frequencies, particularly for the first resonance.

Based on this observation of the system in static conditions, i.e., without airflow, the first result is that the presence of a growth slightly affects the resonance frequencies of the system. For the first resonance, the bigger the growth, the

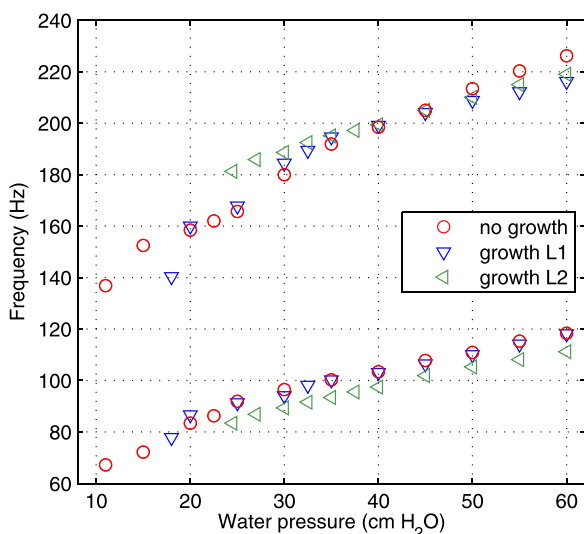


FIG. 4. (Color online) Center frequency of the first two resonances against  $P_w$ , obtained from mechanical measurements (FRFs), with and without growth. The estimated measurement error is 0.3 Hz, i.e., less than the size of the markers.

lower the resonance frequency. For the second resonance, results are less clear. The variation rate of resonance frequency against  $P_w$  is affected: the bigger the growth, the smaller the variation rate of resonance frequency.

It should be noted that the frequency measurements are performed with a precision of 0.3 Hz, making error bars pointless in the figures, given the scales of the latter. The same applies for oscillation threshold pressure measurements whose precision is in the order of 10 Pa. Only glottal area measurements present standard deviations in the order of the mean values.

## B. Oscillation threshold pressure

The oscillation threshold pressure is measured according to the following manner. The upstream air pressure is slowly increased until the vocal folds start to oscillate. The steady-state regime is kept for a few seconds before air pressure is turned off. From the recorded upstream pressure, the oscillation threshold pressure is determined as the pressure value at which the oscillation is first detected.

Results in terms of oscillation threshold pressure together with the associated fundamental frequency generated by the first oscillations are presented in Fig. 5. Two different oscillation regimes have been detected, corresponding to two fundamental oscillation frequencies, with variable oscillation threshold pressure ranges. Within each regime, variations of fundamental frequency between vocal fold configurations with and without a surface growth are less than 10%. Comparison with the natural resonance frequencies presented in Fig. 4 show that the two observed oscillation regimes (i.e., each  $F_0$ ) are well correlated to the mechanical resonance frequencies with averaged differences in the order of 10% in the low frequency (LF) range and in the order of 2% in the high frequency (HF) range. This result indicates that the fundamental frequency of oscillation is mostly induced by the natural resonance frequency of the structure and slightly varies with the growth mass and volume.

The oscillation thresholds against the water pressure,  $P_w$ , inside the vocal folds present a concave shape, showing a local minimum of upstream air pressure necessary to achieve oscillation. This corresponds to the optimal mechanical parameters (vocal fold stiffness, mass, damping, and glottal area) allowing self-sustained oscillation to occur. This general shape is observed for the two oscillation regimes detected and for each vocal fold growth configuration.

The configuration without growth presents the lowest minimal threshold pressure in both LF and HF regimes. The presence of a growth increases the threshold pressure, the larger effect being observed for L2 with the root-mean-square (RMS) deviation to the reference without growth in the order of 66% in the HF range, whereas 13% are obtained for L1. As can be seen in Fig. 5, the threshold pressure obtained for growth L2 in the LF and HF regimes lie in a reduced pressure range. In particular, oscillations with growths in the HF regime could only be obtained for four  $P_w$  values ( $P_w = 45, 50, 55, 60$  cm H<sub>2</sub>O).

Further, one can observe that the threshold pressure of growth L2 in the LF and HF ranges become close to each

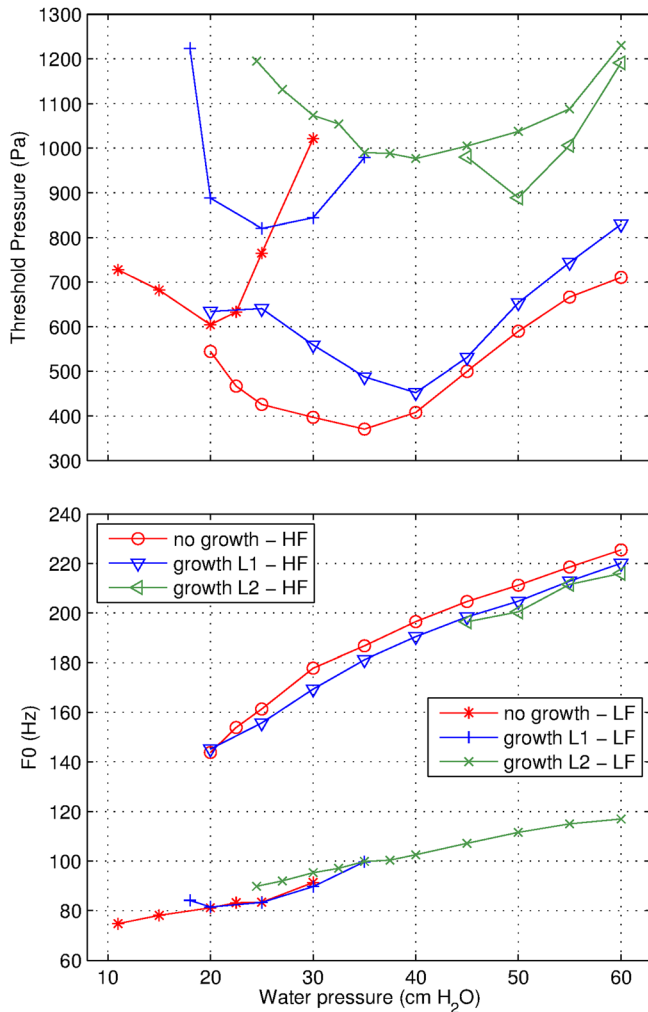


FIG. 5. (Color online) Top: oscillation threshold pressure from measurements for healthy and pathological configurations in both LF and HF oscillation regimes. Bottom: Fundamental frequency of oscillation in the same conditions.

other. In such a case, the replica oscillation could become unstable and jump from an oscillation regime to another.

Contrary to the fundamental frequency, the threshold pressure appears to be considerably affected by the presence of a growth. From the differences observed between *L1* and *L2*, one cannot conclude whether this effect is due to the change of mass, of volume, or of both. In the following, an additional experiment is presented in order to study the effect of the mass solely on the threshold pressure of oscillation, hence discriminate between the effects of mass and volume on sound production.

### C. Differentiation between the effects of mass and volume

While the growths *L1* and *L2* are made of the same material (lead), this section considers a growth of identical volume as *L1*, but made of plasticine. This plasticine growth, denoted *P1*, has a negligible mass ( $<0.01$  g) compared to *L1*. The series with growths *L1* and *P1* were not performed on the same day and therefore have slightly different reference series (without growth), as shown in Fig. 6. A comparison

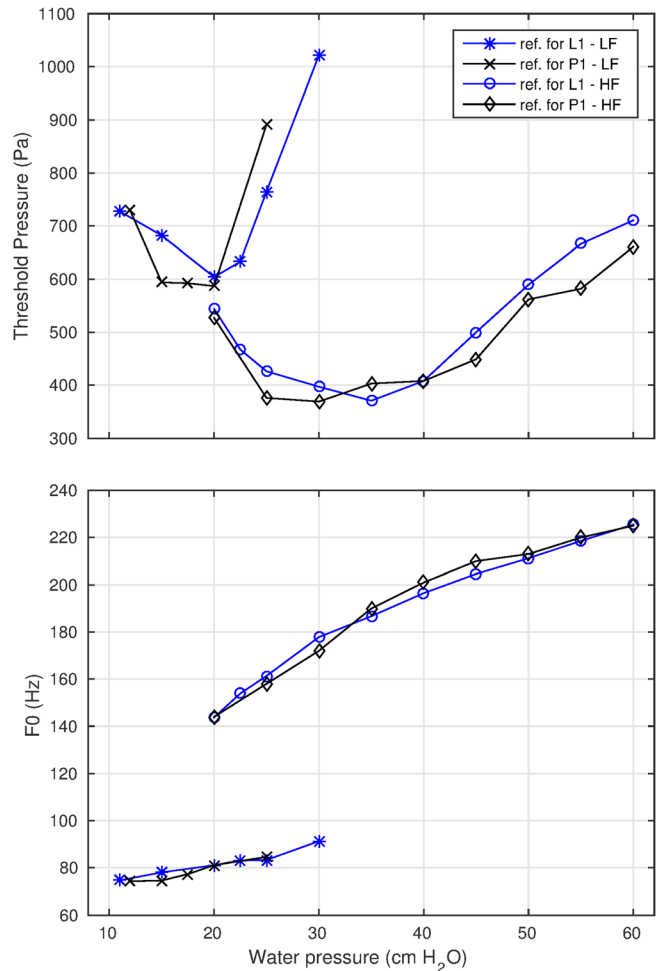


FIG. 6. (Color online) Reference series (without growth) of oscillation threshold pressure (top) and fundamental frequency  $F_0$  (bottom) for the lead (*L1*) and plasticine (*P1*) growths. The reference series for growth *L1* is the series without growth presented in Fig. 5.

between these growths in terms of oscillation threshold pressure is presented in Fig. 7 in a different manner from that in Fig. 5. The relative values ( $P_{rel}$ ) presented in Fig. 7 are the measured values ( $P_{meas}$ ) with growth normalized by the corresponding reference ( $P_{ref}$ ) measured series without growth, as  $P_{rel} = (P_{meas} - P_{ref})/P_{ref}$ .

Although *L1* is closer to the reference without growth for low  $P_w$  values and *P1* is closer to the reference for  $P_w > 45$  cm  $H_2O$ , the curves involving *L1* and *P1* present similar shapes and no significant effect of the mass of the growth could be observed.

At each step of the water tank height, i.e., each  $P_w$  value, a picture of the glottis replica was taken from downstream at rest, before the air flow was turned on. Image analysis allowed for estimating the initial open area through boundary detection. As an example, photographs of the vocal fold replica are presented in Fig. 8 in configurations without growth and with growth *L1* as  $P_w$  is varied. The measured glottal area is presented in Fig. 9. As  $P_w$  increases, vocal folds without growth are pressed one against the other due to their inflation, closing the glottis progressively. In contrast, the configuration *L1* presents a different behavior: the glottal area tends to increase with  $P_w$ . This particular

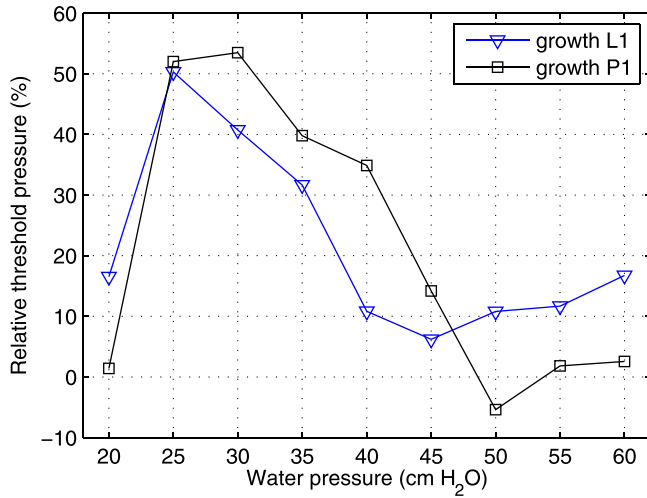


FIG. 7. (Color online) Oscillation threshold pressure with the lead (*L1*) and plasticine (*P1*) growths, relative to their respective reference series without growth (Fig. 6). The series with growth *L1* is the same as in Fig. 5 in the HF regime.

phenomenon can be explained by the fact that the presence of the growth pushes the opposite vocal fold as  $P_w$  increases. As a result, the space between the vocal folds is no longer decreasing but is even increased with  $P_w$ . This observation of different behavior of the initial conditions with and

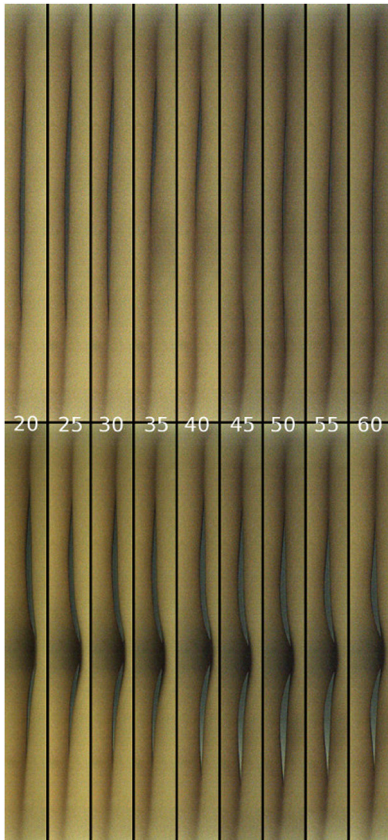


FIG. 8. (Color online) Photographs of the glottis without growth (first row) and with growth *L1* (second row) for water pressure inside the latex tubes  $P_w$  varying from 20 to 60 cm H<sub>2</sub>O. These photographs are flipped (90°): the vocal fold on the left side of each photograph was the upper vocal fold during the experiment.

without a surface growth suggests that the initial contact of the vocal folds is an important parameter in the oscillation process. This hypothesis is investigated by means of a theoretical model of vocal folds dynamics in Sec. IV.

## IV. THEORETICAL ANALYSIS

### A. Description of the theoretical model of oscillation

As a simple theoretical model we use the description proposed by Avanzini<sup>29</sup> which considers the geometry of the vocal folds as controlled by two mass points, one at the entrance and one at the exit of the glottis. The motion of the entrance point  $x_1$  is predicted using a one degree of freedom model, accounting thus for a single mechanical resonance frequency, as

$$m\ddot{x}_1 + r\dot{x}_1 + kx_1 = F, \quad (1)$$

where  $m$ ,  $r$ , and  $k$  are the mass, damping, and stiffness of one vocal fold, respectively. The motion of the point at the exit of the glottis,  $x_2$ , is assumed to be identical to the one at the entrance but delayed by a constant  $\tau$ , such as

$$x_2 = x_1(t - \tau). \quad (2)$$

This delay  $\tau$  can be understood as the time required for the deformation wave to propagate from the entrance to the exit of the vocal fold replica.

The force per unit width exerted on the vocal folds by air pressure is calculated by integrating the pressure distribution  $P(x)$  over the glottal channel

$$F = \int P(x)dx, \quad (3)$$

where the air pressure  $P(x)$  is calculated using the Bernoulli equation accounting for viscosity using a corrective Poiseuille term. More details about the flow model have been previously presented.<sup>30</sup> In summary, the studied parameters in the

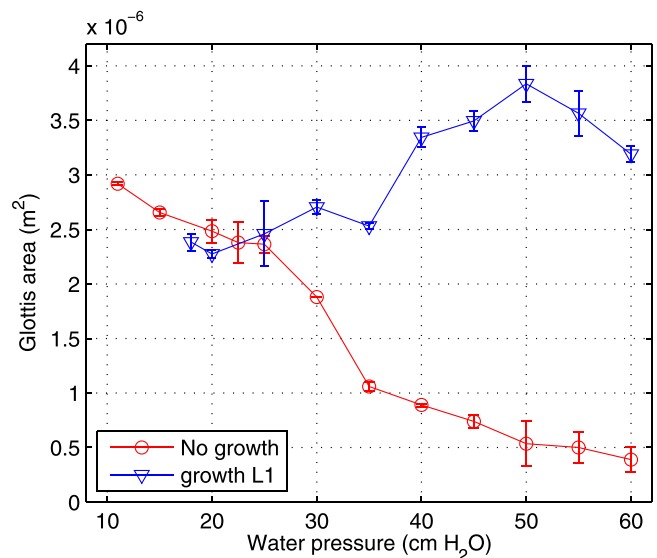


FIG. 9. (Color online) Glottal area against  $P_w$ , measured on the replica in configurations with and without growth.

following are the mass,  $m$ , damping,  $r$ , and stiffness,  $k$ , as well as the propagation time delay  $\tau$  and the initial glottal area. It should be noted that such a simple mechanical model is one-dimensional and therefore is able to describe only one mode of vibration. In the following, the second mechanical mode is studied, corresponding to the range of oscillation frequency from 140 to 225 Hz.

## B. Theoretical model parameters

Using the estimation<sup>10</sup> proposed by Titze for the mucosal wave speed, one obtains a value for  $\tau$  of about 2 ms. However this quantity obviously depends on the elasticity of the replica. To account for this phenomenon, we assume the value of  $\tau$  as a linearly decreasing function from 3.5 ms down to 2 ms in the region  $P_w \in [20; 35]$  cm H<sub>2</sub>O, and as constant  $\tau = 2$  ms for higher  $P_w$ .

The mechanical parameters damping  $r$  and stiffness  $k$  can be calculated from the FRF since they depend on the resonance frequency  $F_r$  and the associated peak bandwidth  $\Delta f$  at peak  $-3$  dB, using the following formulas:

$$r = 2\pi m \Delta f \quad \text{and} \quad k = (2\pi F_r)^2 m. \quad (4)$$

Note that because the resonance frequency,  $F_r$ , depends on the internal water pressure,  $P_w$ , as shown in Fig. 4, the stiffness  $k$  is also a function of  $P_w$ . In practice, since  $F_r$  was found to vary approximately with the square root of  $P_w$ , a quasi-linear relationship was found between  $k$  and  $P_w$ . A previous study<sup>31</sup> has shown theoretically that the damping of the model has a direct influence on the threshold pressure. Therefore to account for the contact of the growth on the opposite vocal fold replica, an additional coefficient  $\beta$  is included in the classical formula of damping such as

$$r = 2\pi\beta m \Delta f, \quad \beta = 1 + \frac{L_{\text{eff}}}{L}, \quad (5)$$

where  $L$  is the length of one vocal fold and  $L_{\text{eff}}$  is the effective contact length of the growth on the opposite vocal fold replica. Equation (5) models thus an increase of damping with the dimension of the growth. Note that when  $L_{\text{eff}} = L$ , the value of  $r$  equals the critical damping yielding a formula similar to the proposition of Ishizaka and Flanagan<sup>4</sup> during the collision of the vocal folds.  $L_{\text{eff}}$  are estimated from the pictures of the experiments such as presented in Fig. 8 and range as  $L_{\text{eff}} \in [0.5; 1]$  mm. Hence, the presence of a growth is intended to induce an increase of damping by friction due to the possible initial contact with the opposite vocal fold, along with the local modification of the vocal fold tissues which depends on the size of the growth.

The value of  $m$  is probably the most difficult to estimate. The total mass of water inside the vocal fold replica,  $m_{\text{tot}}$  can be calculated using simple geometrical considerations

$$m_{\text{tot}} = \rho\pi R^2 L, \quad (6)$$

where  $R = 0.5$  cm is the radius of the replica and  $\rho = 1000$  kg m<sup>-3</sup> the density of water. It is obvious that only a portion of this total mass, the superficial layer, participates

TABLE III. Parameters of the theoretical model, based on measurements from the replica.  $m$  and  $\rho$  are, respectively, the mass and the volumetric mass of water inside the latex tube of radius  $R$  and length  $L$ .  $\alpha$  is the coefficient related to the water actually vibrating in the tube (Ref. 30),  $F_0$  is the peak resonance frequency measured without growth,  $\Delta f$  is the associated bandwidth at peak  $-3$  dB,  $\beta$  is the contact coefficient, and  $\delta m$  is the mass of the growth.

	Without growth	With growth
Mass $m$	$\alpha\rho\pi R^2 L$	$\alpha\rho\pi R^2 L + \delta m$
Stiffness $k$	$(2\pi F_0)^2 m$	$(2\pi F_0)^2 (m + \delta m)$
Damping $r$	$2\pi\beta\Delta f m$	$2\pi\beta\Delta f (m + \delta m)$
Delay $\tau$	Empirically fitted	Empirically fitted

to the vibration of the structure. Given previous simulations<sup>30</sup> an estimation of this proportion is in the order of 20% of the total mass. The value for  $m$  is thus estimated with  $\alpha = 0.2$  as

$$m = \alpha m_{\text{tot}}. \quad (7)$$

The theoretical model parameters with and without growth actually used in this study are presented in Table III.

Last, the initial glottal area, i.e., without air flux, is estimated by analyzing the pictures as explained at the end of Sec. III.

## C. Oscillation threshold pressure

Results in terms of oscillation threshold pressure are presented in Fig. 10 where measured and simulated data are compared in configurations without growth and with growths L1 and L2. Standard deviations between the configurations with and without growths are presented in Table IV. Circles are generally close to each other, showing the degree of precision of the theoretical model with respect to the measured values. For growth L2, the simulations are clearly closer to

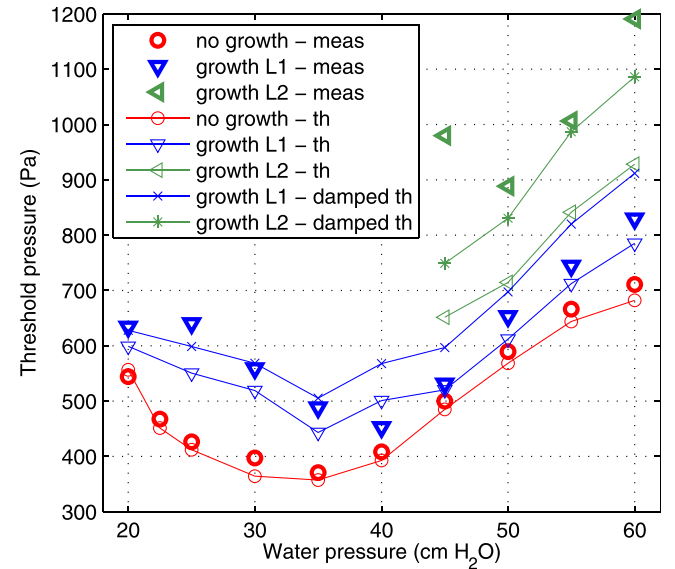


FIG. 10. (Color online) Oscillation threshold pressure in HF regime from the theoretical model of oscillation without (“th”) and with (“damped th”) initial contact, i.e., damping according to Eqs. (4) and (5), respectively, between the vocal folds, compared to measurements from the vocal fold replica.



TABLE IV. RMS deviation between the measured and simulated series of oscillation threshold pressure in different growth configurations, with and without damping (i.e., initial contact between the vocal folds), as presented in Fig. 10. The reference of the values in percent is the measured data.

	RMS dev. (Pa)	RMS dev. (%)
No growth	20	4.4
Growth <i>L1</i>	48	8.9
Growth <i>L1</i> damped	59	9.0
Growth <i>L2</i>	242	32.8
Growth <i>L2</i> damped	130	16.6

measurements when the initial contact is taken into account through the damping coefficient  $\beta$  as defined in Eq. (5). The associated RMS deviation between measurements and simulations doubles if the initial contact is not accounted for. For growth *L1*, this implementation of the initial contact through damping does not significantly affect the oscillation threshold pressure.

It should be underlined that initial contact can have effects on various aspects of the vocal system. The present study considers its effects on vocal fold damping specifically. The discrepancies observed between measurements and theoretical simulations as shown in Fig. 10 can be explained by various factors such as changes in the glottal flow field due to the presence of the growth, or weakened fluid-structure interaction due to left–right asymmetry. Another factor is the modification of vocal fold damping as proposed in Eq. (5), which improves the agreement between the measurements and simulations.

Furthermore, it should be noted that the fundamental frequencies have not been investigated with the theoretical model because their variation has been found to be small (inferior to 10%) within the replica measurements.

## V. GENERAL DISCUSSION

The results of this study are presented in terms of fundamental frequency, oscillation threshold pressure, and glottal area. This section aims at discussing the relationship between these measured values and the physical control parameters, namely the mass and volume of the growth as well as the initial contact between the vocal folds. Results are summarized in Table V

Comparing Fig. 5 with Fig. 9 allows for focusing on the variation of the oscillation threshold pressure against the glottal area. It appears that in the presence of the growth, the threshold pressure and the glottal area are both increased.

TABLE V. Importance of the effect of control parameters (mass of the growth, volume of the growth, initial contact between the vocal folds through damping) on measured estimators (glottal area, fundamental frequency  $F_0$ , oscillation threshold pressure) with respect to sound production.

	Glottal area	$F_0$	Threshold pressure
Mass	weak	weak	weak
Volume	strong	weak	strong
Initial contact	$\emptyset$	weak	strong

## A. Effect of the mass and volume of the growth

The experiment presented in Sec. III shows that neither the mass nor the volume of the growth has much influence on the resonance frequency of the vocal fold, hence the fundamental frequency of the produced sound. Figure 5 shows that the oscillation threshold pressure is significantly affected by the presence and the change of growth. The plasticine growth, which presents the same volume and a negligible mass as compared to the lead growth, is used to investigate the effects of mass and volume of the growth separately. This part of the experiment has shown that the mass has only a moderate effect on the threshold pressure, as illustrated in Fig. 7 where the curves are very similar. Consequently, the volume of the growth is the main control parameter which critically affects the oscillation threshold pressure.

This parameter is strongly related to the stiffness of the vocal fold tissue layers since a deformation affects the rigidity of the material. However it is beyond the scope of the present study to investigate the effects of the vocal fold stiffness which represents a very specific work of material characterization.

## B. Effect of the initial contact between the vocal folds

The numerical experiment presented in Sec. IV is meant to address the question of the effects of the initial contact between the vocal folds through damping. In fact, changing only this condition while keeping all other parameters unchanged cannot be performed using the replica. The initial contact being considered as an additional damping within the oscillation process, the numerical simulations yielded the results presented in Fig. 10. It can be observed that the simulations which include the additional damping are closer to measurements, especially for growth *L2*. This tends to show that the initial contact, which frequently occurs in the presence of a growth, plays an important role regarding the oscillation threshold pressure.

It should be noted that the coefficient involved in modifying the damping parameter is defined as  $\beta = 1 + L_{\text{eff}}/L$  where  $L_{\text{eff}}$  is the glottis width, estimated directly from the photographs of the glottis at rest. The choice has been made to use a geometrical criterion for the damping coefficient, which seemed to be straightforward and simple. Yet another methodology could be employed, e.g., using a quadratic law, yielding potentially finer results. This specific modeling parameter could be developed in further works.

## VI. CONCLUSION

This study of the influence of surface growths on the oscillation behavior of a vocal fold replica has been conducted by means of both experimental measurements and theoretical modeling. The measurements are performed on a unique vocal fold replica with three different spherical surface growths allowing to vary independently some physical parameters related to the growth size and mass.

The measured oscillation threshold pressure values are comparable to those measured on human beings (of order of a few hundreds of Pa). Results also compare well with some

clinical observations:<sup>32</sup> more energy is required in the presence of a growth to achieve self-sustained oscillation of the vocal folds, this effect increases with the size of the growth. Frequency jumps are observed in certain cases where the threshold pressures of two oscillation regimes are close to each other. Last, the presence of a growth is found to reduce the frequency range of oscillation.

An original method of parameter estimation for vocal fold theoretical modeling has been developed, each parameter being individually measured on the vocal fold replica. Results from this experimental and theoretical approach show that the volume of a growth is the main driving parameter and has more influence than the mass on oscillation threshold pressure. Furthermore the initial contact between the vocal folds, considered exclusively as vocal fold damping in the present study, appears to have a critical influence on measurements. This is qualitatively validated by the predictions obtained from the theoretical model.

Following this study, it would be worth investigating a larger range of growth size and mass as well as the influence of the initial glottal area while keeping all other parameters identical. Besides, using non-linear damping in theoretical models, e.g., quadratic models, could yield more accurate results in terms of theoretical modeling. Finally, enhancing the determination of parameters such as the mass and the time delay of the mucosal wave propagation would yield a higher agreement between measurements and numerical simulations.

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