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EXPERIMENTAL STUDY OF THE INFLUENCE OF LOCAL RIGIDIFICATION ON VOCAL FOLDS AUTO-OSCILLATION

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Voicing or vocal folds auto-oscillation results when the expiratory fluid flow coming from the lungs interacts with the deformable vocal folds tissues in the glottis. Consequently, the outcome of this fluid-structure interaction is determined by fluid flow properties, the glottal geometry as well as structural tissue properties. Changes to the vocal fold structure often happens in voice pathologies attributed to structural vocal fold tissue abnormalities. These pathologies affect the general population and in particular voice professionals such as teachers, singers, etc. Whereas an extensive literature attests to the medical, social and economic relevance of these voice pathologies, systematic physical studies are few. Therefore, in this paper, we present an experimental study of the influence of a local rigidification on the auto-oscillation of the vocal folds. Four-layer silicone molded mechanical vocal folds replicas are used. The layers composition and elasticity properties reflect the multi-layer physiological representation of a human vocal fold. Besides this normal reference replica, replicas with an abnormal vocal fold structure are obtained by adding a stiff rectangular inclusion during the molding process so that these vocal folds replicas exhibit a local rigidification. The elastic Young's modulus is at least four times greater than 65 kPa, which is generally the upper range associated with a normal vocal fold. The position and orientation of the inclusion are varied in a way that the replicas elasticity can be determined. For each replica, the auto-oscillation characteristics are experimentally studied by placing the replica in a suitable setup allowing to measure pertinent physical quantities such as up-stream pressure, vocal folds displacement and acoustics. Changes to these auto-oscillation characteristics are outlined and discussed. The implications for pathological voice modeling are then discussed.

Keywords: vocal folds, mechanical replica, biomechanics.

1. Introduction

From the point of view of physics, the production of voiced sounds, also called phonation, is a phenomenon of fluid-structure interaction. The airflow from the lungs exerts aerodynamic forces on the vocal cords which, being made up of an elastic structure, will deform and in turn disturb the flow. Under certain conditions (sufficient pulmonary pressure, adduction and tension of the vocal cords) this interaction can lead to a self-oscillation of the vocal cords which then constitutes the main sound source of voiced sounds and speech.

Vocal capacity can be disturbed by numerous pathologies, some at the level of motor control, others linked to abnormalities in the structure of the vocal cords. The aeroacoustic consequences of anomalies involving growths at the surface of the vocal folds (cysts, nodules...) [1], which are quite common amongst singers and teachers, have been studied experimentally or numerically [2], [3]. In this work we

focus on a less frequently addressed pathology induced by a local rigidification of one vocal fold, such as the one due to a scar [4].

The study and measurement of the vibration of the vocal cords in vivo or on excised larynxes is interesting but difficult to carry out in a quantitative way and, because of the significant inter-individual variability, in a reproducible way. For these reasons, most physical studies use vocal cord replicas. These use approximations of the geometry of the vocal cords and their elasticity. Van den Berg's pioneering work [5], for example, used a rigid artificial vocal cord structure on which pressure distribution measurements were made. This work has been taken up and refined later. The use of deformable materials is more recent, inspired by the work of Gilbert [6], Ruty et al. [7] proposed a model of vocal folds made of latex tubing and pressurized water which, in the presence of airflow, was able to produce comparable self-oscillations, in terms of threshold pressures, frequency and acoustic parameters, to those produced in humans. If these studies were useful for the validation of the theories of the glottal flow and acoustic interactions with the vocal tract [8], they do not take into account the structural complexity of the constituent tissues of the vocal cords.

In this study multi-layered silicone casts aimed at reproducing the internal structure of the vocal cords and the difference in elasticity of its various components (muscle, ligament, mucosa) will be used. The presence of a local stiffening of a vocal fold will be simulated by inserting a stiff inclusion during the molding procedure. The effect of the inclusion and of its position within the vocal folds replica will then be studied quantitatively. Lastly, results concerning the self-sustained oscillations of the replicas will be presented and discussed.

2. Vocal folds replicas

The vocal folds replica is inspired from the MRI replica proposed by Murray and Thomson [9]. It consists of an overlap of four silicone layers as shown in figure 1.

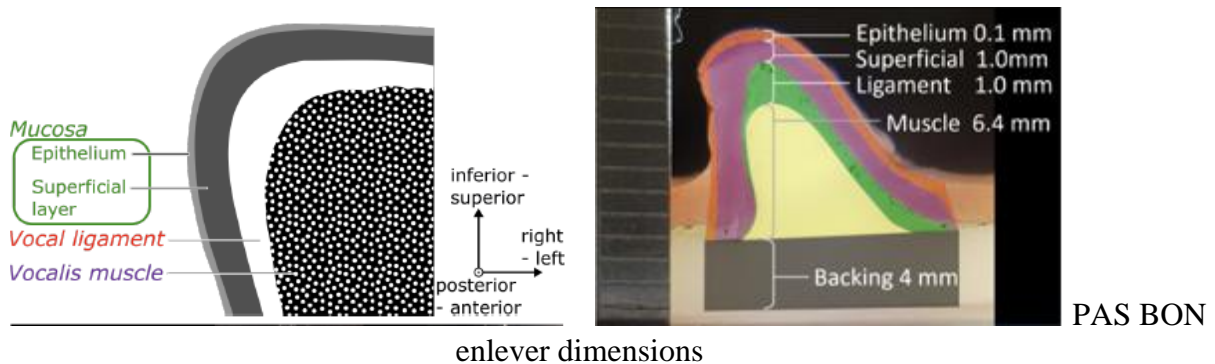


Figure 1 : schematic anatomical view of a vocal fold and of the EPI approximation.

The first layer represents the vocalis muscle, the second one the vocal ligament and the last two ones (superficial layer and epithelium) the fine structure of the mucosa. By using different mixtures of silicones, one can obtain layers with a specific Young Modulus and thickness, l_t , comparable to those observed on humans.

In this study, a simpler geometry for the vocal folds is considered as a rectangular structure. In order to conserve the volume of the different layers of the EPI replica, the following thicknesses will be used: for the muscle $l_t = 3.2$ mm, for the ligament $l_t = 0.7$ mm. Concerning the mucosa, the superficial layer was set to $l_t = 4.3$ mm and the epithelium to $l_t = 0.3$ mm.

To mimic the effect of a local stiffening of one vocal fold, an inclusion made of stiff silicone was added at various locations during the moulding procedure. Although different geometries were considered, the results presented here will only concern a rectangular parallelepiped inclusion of dimensions 10 mm in length x 4 mm in width x 2 mm in height. The inclusion was inserted inside the superficial layer, above the ligament layer, during the moulding procedure. Two different positioning of the insertion are considered as depicted in figure 2. The "serial" inclusion has its width (4 mm) along the direction of the airflow, z while the "parallel" inclusion has its width along the replica's thickness, x .

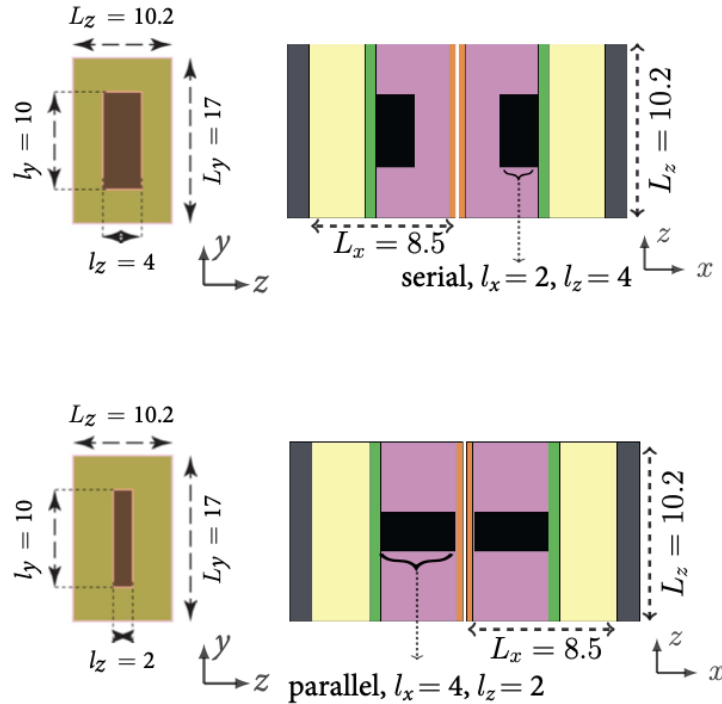


Figure 2 : View of the rectangular EPI replica with serial and parallel inclusions. All dimensions are in mm

3. Stress-strain measurements

3.1 Elasticity measurements

Two different techniques for measuring the Young's Modulus were used. The first one used a mechanical press (3369, Instron Corp.) measuring the force in reaction to a prescribed elongation of the specimen. The second method, using precision loading technique, imposed a force by weighting the specimen and measured the resulting elongation. Both were proven to be consistent and of equivalent accuracy with each other.

From the experimental data one can obtain the Young's Modulus of the specimen either by a linear fitting (low stress region) or by a polynomial/exponential fit when large deformations are involved. A large number of specimens have been measured. First of all, homogeneous specimens, ie made up of a single type of silicone, were considered. Then, heterogeneous compositions constituted by different superimposition and orientations of silicones of different elasticity were measured. Details of the methods and results are presented in [10].

This allowed to validate a theoretical model capable of estimating the overall Young' Modulus of an heterogeneous specimen knowing the Young's modulus and the geometry of each layer it is made of.

3.2 Results

The measured values of each elements (ie layers and inclusion) of the vocal folds replica are listed in table 1.

Table 1 : Measured values of the Young's Modulus of each layers of the rectangular EPI replica.

Layer Name	Young's Modulus
Muscle	23.4 kPa
ligament	4 kPa
Superficial	2.2 kPa
epithelium	64.7 kPa
inclusion	298 kPa

The estimated Young's Modulus, in the direction z, parallel to the airflow, and in the direction x, perpendicular to the airflow, are listed in table 2.

Table 2 : Estimated values of the Young's modulus for replicas without inclusion, with serial and parallel inclusions.

Replica Name	Young's modulus along x	Young's modulus along z
Without inclusion	3.7 kPa	12.5 kPa
Serial inclusion	6.1 kPa	12.9 kPa
Parallel inclusion	15.1 kPa	12.8 kPa

One can observe that the Young's Modulus in the z direction is almost insensitive to the addition of a stiff inclusion. On the opposite the Young's Modulus along the x direction, is strongly affected being almost double for a serial inclusion and quintupled for a parallel inclusion.

4. Dynamic measurements

4.1 Experimental set-up

In order to study the vibratory behaviour of the rEPI replicas against an airflow, the experimental depicted in figure 3 was built.

An air compressor (Atlas Gopca GA FF-300-8 G15 FF-8) is connected to a pressure reservoir (0.22 m³). The reservoir is filled with acoustical foam in order to prevent from acoustical resonances. The airflow entering the reservoir is controlled by a valve (Norgen 11-818-967) and is carried out to the vocal folds replica. The pressure upstream of the replica was measured using a pressure transducer (Endevco 8507C-5) with an accuracy of +/- 5 Pa. The vibration amplitude of the replicas in the stream wise direction, z could also be measured using a laser transceiver (Panasonic HLG112AC5) with an accuracy of +/- 80 μ m.

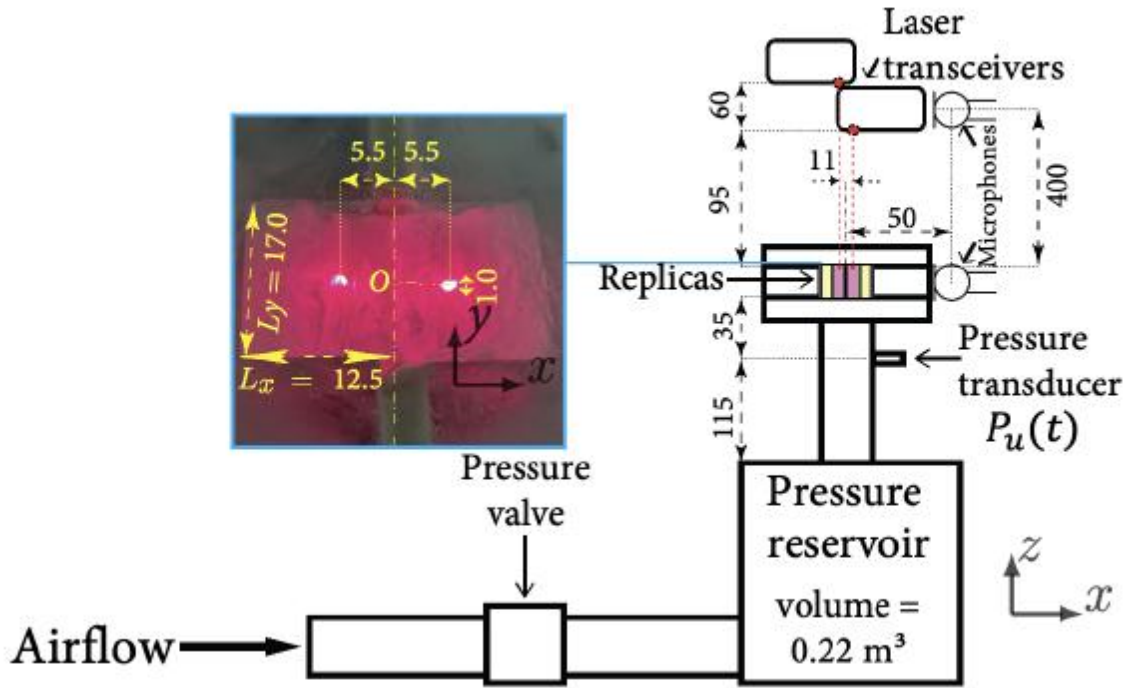


Figure 3 : Experimental set-up for the study of self sustained oscillation of the rectangular EPI replica (shown in the picture). All dimensions are in mm.

4.2 Threshold pressure, vibration frequency and displacement

The threshold onset pressure, P_{on} is defined as the minimum pressure needed to trigger the self-sustain oscillation of the replica. This quantity is measured by slowly increasing the alimentation pressure until an oscillation of the replica can be detected. After the auto-oscillation has been set, the alimentation pressure is shut off, and the lowest pressure at which this oscillation can be sustained is measured as the threshold offset pressure, P_{off} . From the analysis of the recorded pressure signals, the oscillation frequency both at onset and offset, F_{on} and F_{off} respectively, are measured. The measured results are presented in table 3.

Table 3 : Measured onset and off pressures, displacements along the airflow and fundamental frequency of oscillation for three replicas.

Replica name	P_{on} [Pa]	P_{off} [Pa]	Z_{on} [mm]	Z_{off} [mm]	F_{on} [Hz]	F_{off} [Hz]
Without inclusion	1187	1004	5.3	5.2	97	97
Serial inclusion	1599	1160	3.8	3.7	99	105
Parallel inclusion	1040	954	1.0	0.9	103	99

The presence of an inclusion appears to have a limited effect on the frequency of oscillation at onset and offset, 8 % at the most. The same cannot be said about the Pressure onsets which seems also affected by the orientation of the inclusion. An increases of P_{on} by 30 % is observed in the case of a serial inclusion while a decrease by 12 % is measured in the case of a parallel inclusion. The pressure offset,

P_{off} follows the same tendency but to a lesser degree. The displacement of the replica along the flow direction appears to be most affected by the presence of an inclusion.

4.3 Vibration patterns

Figure 4 presents three examples of the spectrogram of vibration patterns for the rectangular EPI replica with serial inclusion.

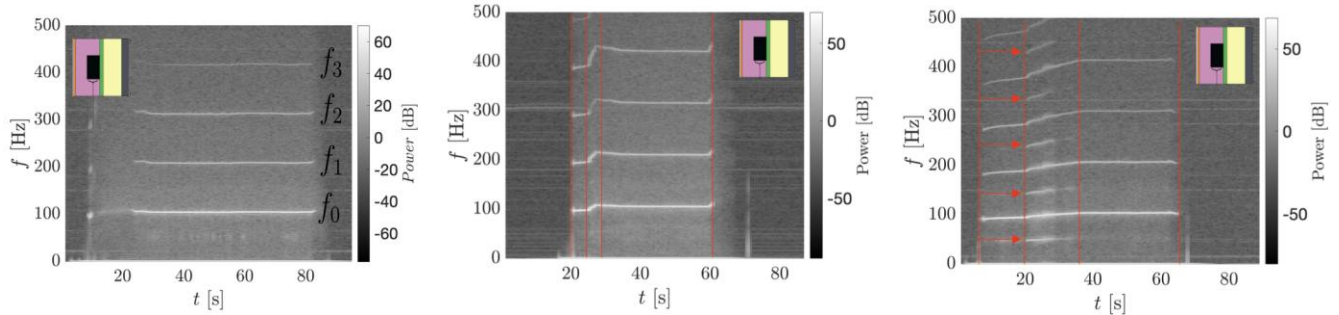


Figure 4 : Spectrogram of three recordings of the pressure upstream of the rectangular replica. The red arrows show the presence of sub-harmonics.

One can observe that the frequency of oscillation can present instabilities, increasing after the onset or even presenting sub-harmonics.

5. Conclusions and implications for modelling of vocal folds pathology

The conclusions that can be drawn from this preliminary study are the following :

The fundamental frequency at onset and offset of oscillation appears to be little affected by the presence of an inclusion. A similar conclusion was drawn in [3] concerning the presence of a growth at the surface of a vocal fold replica. However, the time analysis of the oscillation of the replicas exhibited more complex, unstable behaviour involving an increase of the fundamental frequency or even the presence of sub-harmonics. These phenomenon are interesting since they correlate with clinical observations of pathological voice [1], [4].

The pressure onset (and offset) of the replicas are affected by the presence and the orientation the inclusion. The fact that the orientation of the inclusion has a huge impact on the vibration characteristics tends to indicate that a theoretical model of pathological vocal folds auto-oscillation might need not only to account for the movement perpendicular to the airflow, but also in the airflow direction. The sensibility of the measured displacement along the airflow is another support for this argument.

Further research are carried out in order to refine this analysis. In particular, the rectangular EPI geometry obviously impacts the measured results. Measurements with similar inclusions on vocal folds replicas having a more physiological shape have to be performed.

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