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EXPERIMENTAL STUDY OF THE INFLUENCE OF A RECTANGULAR VOCAL FOLDS INCLUSION ON THEIR AUTO-OSCILLATION

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ABSTRACT

Vocal folds auto-oscillation is the result of a fluid-structure-acoustic interaction within the larynx. Vocal folds structure changes are often associated with voice pathologies affecting voice professionals as well as the general public. Therefore, in this work, the influence of the vocal folds structure on the auto-oscillation is investigated. An experimental study of the influence of local vocal folds rigidification on the resulting auto-oscillation is presented. Silicone molded four-layer mechanical vocal folds replicas are used. The layers composition and elasticity properties reflect the multi-layer anatomical representation of a human vocal fold. A local rigidification within these vocal fold replicas is obtained by adding a stiff rectangular inclusion during the molding process. The position and orientation of the inclusion are varied in a way that the elasticity of the replica is affected. For each replica, the auto-oscillation characteristics are experimentally studied from measured physical quantities as upstream pressure and vocal folds displacement. The inclusion is shown to result in complex dynamic behaviour of the oscillation frequency and to affect the upstream threshold pressures associated with oscillation onset and offset.

Keywords: phonation, mechanical vocal folds replica, fluid-structure interaction,

1. INTRODUCTION

Phonation or voiced speech sound production is due to vocal folds (VFs) auto-oscillation following the fluid-structure interaction between the airflow coming from the lungs and the deformable vocal folds tissues. Vocal folds structural pathologies, such as cysts or nodules near the surface, are known to affect the auto-oscillation and thus the sound source for voice production. In this work we focus on pathologies inducing a local rigidification of one vocal fold such as due to a VF scar [1]. Given the complexity of a human VF, physical studies of the VF auto-oscillation commonly rely on deformable mechanical VF replicas which simplify the anatomical VF structure and functionality in order to ensure the reproducibility, quantifiability, controllability and thus interpretability of findings. One type of deformable VF replicas consists of silicone molded VF replicas. These silicone VF replicas mimic the multi-layer (ML) (micro-)anatomical VF structure as an overlap of silicone molding layers with appropriate yet constant elasticity. 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. METHODS

2.1 Deformable vocal folds replica

The vocal folds replica is inspired from the EPI replica following the silicone molding process introduced by Murray and Thomson [2]. It consists of an overlap of four silicone

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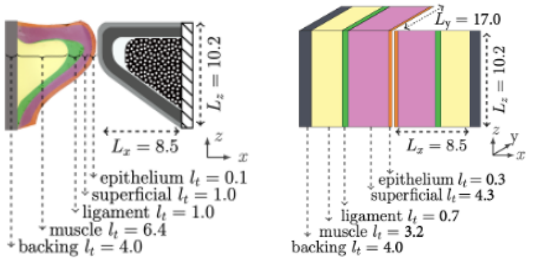
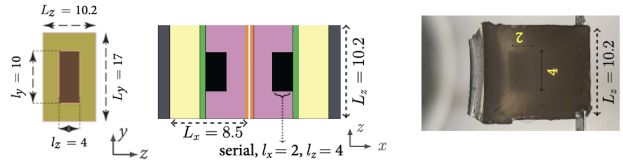


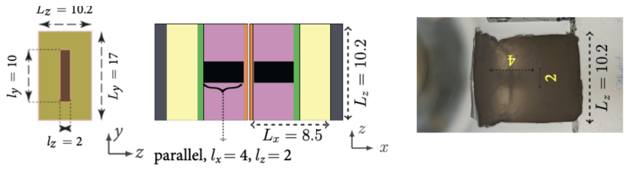
(a) original EPI

(b) rectangular no inclusion, $R^{\emptyset}$

Figure 1. Silicone VF replicas without inclusion (dimensions in mm): a) molded EPI VF replica (right VF) and its schematic four layer anatomic representation, b) derived rectangular four layer replica ($R^{\emptyset}$).



(a) rectangular with serial inclusion, $R^{\perp}$



(b) rectangular with parallel inclusion, $R^{\parallel}$

Figure 2. Rectangular four layer replicas with inclusion: a) serial $R^{\perp}$, b) parallel $R^{\parallel}$

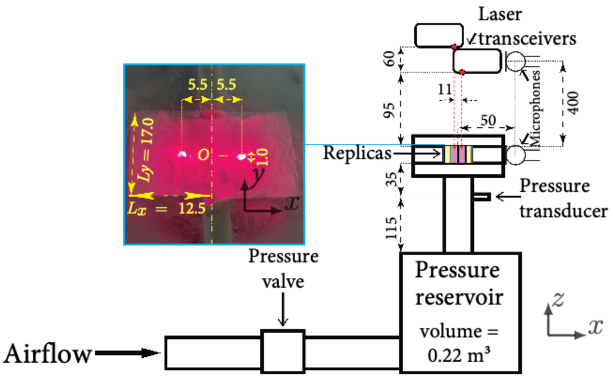
layers as shown in Fig. 1(a). The first layer represents the vocalis muscle, the second one the vocal ligament and the last two ones (superficial layer and epithelium) the fine structure of the mucosa. By using different mixtures of silicones, one can obtain layers with a specific Young's Modulus and thickness, l_t, comparable to those observed on human VFs.

In order to assess the influence of a local rigidification, on the fluid-structure interaction of VFs replicas, a replica with simplified geometry inspired by the EPI model is built. This new replica, labelled $R^{\emptyset}$, has a rectangular cross-section in the medio-frontal plane. Therefore, each layer has constant thickness $L_z = 10.2$ mm along the inferior-superior direction corresponding to the main airflow direction. The layers are stacked on top of each other in the left-right (x) direction as shown in Fig. 1(b). The overall dimensions $L_y = 17.0$ mm along the posterior-anterior direction and $L_x = 8.5$ mm (excluding the backing layer of a thickness $l_t = 4.0$ mm) along the left-right direction rest unchanged from the original EPI replica. The thickness of each layer in the left-right direction, l_t, is designed so that the normalised volume of each layer, V_i/V_{VF} with V_i the volume of each layer $i = 1, \ldots, 4$ and V_{VF} the total VF replica volume, corresponds to the appropriate value of the original EPI replica.

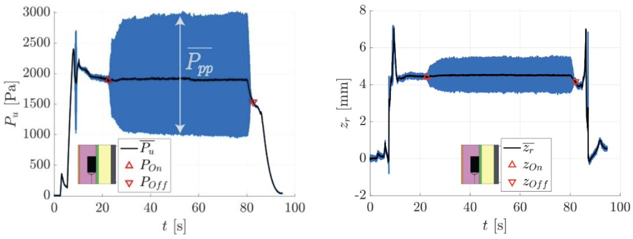
To mimic the effect of a local stiffening of one vocal fold, an inclusion made of stiff silicone was embedded during the moulding procedure. The inclusion has a fixed length of 10 mm, fixed width of 4 mm, and a fixed thickness of 2 mm. It is centered (using markers) in the superficial layer near the ligament interface in such a way that it is either serial (replica denoted $R^{\perp}$) or parallel (replica denoted $R^{\parallel}$) with respect to the x-direction as shown in Fig. 2.

2.2 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, i.e. 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 [3, 4]. This allowed to validate a theoretical model capable of estimating the effective Young's modulus of an heterogeneous specimen knowing the Young's modulus, the geometry and the stacking orientation of each layer in the composite.



(a) setup



(b) upstream pressure $P_u(t)$, displacement z_r

Figure 3. a) setup for fluid-structure interaction experiments, b) examples of measured upstream pressure $P_u(t)$ (Pa, pressure transducer) and displacement z_r (mm, laser transceiver) for the rectangular replica without inclusion $\mathrm{R}^{\emptyset}$ and the onset ($\triangle$) and offset ($\triangledown$) of steady auto-oscillation.

2.3 Fluid-structure interaction setup

In order to study the vibratory behaviour of the rectangular replicas against an airflow, the experimental setup depicted in Fig. 3(a) was built. An air compressor (Atlas Gopca GA FF-300-8 G15 FF-8) is connected to a pressure reservoir (0.22 m^3). 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 to the vocal folds replica. The pressure upstream of the replica P_u was measured using a pressure transducer (Endevco 8507C-5) with an accuracy of ±5 Pa. The displacement of the replicas in the streamwise direction z_r could also be measured using a laser transceiver (Panasonic HL-G112-A-C5, wavelength 655 mm) with an accuracy of ± 80 μm. Typical examples of measured time signals $P_u(t)$ and $z_r(t)$ for the rectangular replica without inclusion $\mathrm{R}^{\emptyset}$ are shown in Fig. 3(b). The onset (subscript on) and offset (subscript off) of steady VFs auto-oscillation is indicated.

Table 1. Overview Young's modulus of each layer.

layer	modulus [kPa]
muscle	23.4
ligament	4
superficial	2.2
epithelium	64.7
inclusion	298

Table 2. Overview effective Young's modulus of rectangular replicas along x and z.

replica	modulus [kPa]	
	x	z
without inclusion, $\mathrm{R}^{\emptyset}$	3.7	12.5
serial inclusion, $\mathrm{R}^{\perp}$	6.1	12.9
parallel inclusion, $\mathrm{R}^{\parallel}$	15.1	12.8

3. RESULTS

3.1 Elasticity characterisation

Measured Young's moduli of each layer and the stiff inclusion used to built vocal folds replicas (Fig. 1 and Fig. 2) are summarised in Table 1. The resulting effective elastic Young's modulus of the composite vocal folds replicas is given in Table 2 along the direction z, parallel to the airflow, and in the direction x, perpendicular to the airflow. The effective Young's Modulus in the z direction is almost insensitive to the addition of a stiff inclusion. The effective Young's Modulus in the x direction on the other hand increases when an inclusion is present as its value doubled for a serial inclusion and quadrupled for a parallel inclusion. As the x direction corresponds to the main force direction of the airflow on the deformable structure, the fluid-structure interaction and resulting auto-oscillation instability is likely to be affected.

3.2 Fluid-structure interaction characterisation

The onset and offset characteristics of the steady vibration gathered on the measured pressure (P_{on}, P_{off}) and

Table 3. Auto-oscillation onset and offset characteristics for rectangular replicas.

	$\mathrm{R}^{\emptyset}$	$\mathrm{R}^{\perp}$	$\mathrm{R}^{\parallel}$
P_{on} [Pa]	1187	1599	1040
P_{off} [Pa]	1004	1160	954
z_{on} [mm]	5.3	3.8	1.0
z_{off} [mm]	5.2	3.7	0.9
f_{on} [Hz]	97	99	103
f_{off} [Hz]	97	105	99

displacement (z_{on}, z_{off}) signals illustrated in Fig. 3(b) are given in Table 3. The vibration frequencies at onset f_{on} and offset f_{off} are indicated as well. The presence of an inclusion on the oscillation frequencies at onset and offset is limited as it is less than 8%. The same can not be said about the pressure onsets which seems also affected by the orientation of the inclusion. An increase 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 as it reduces from about 5 mm to about 1 mm. Vertical displacement is hypothesized to affect threshold pressures at onset and offset.

Typical time-frequency spectrograms of upstream pressure signals $P_u(t)$ obtained from several repetitions on the replica with serial inclusion are plotted in Fig. 4. The spectrograms can be either stable (top plot and values in Table 3), reflect dynamic behaviour after the onset (middle plot) or even complex behaviour such as subharmonics associated with non-linearities (arrows in bottom plot). These spectrograms reflect small initial left-right asymmetries in the streamwise positioning between the left and right vocal fold. These small asymmetries in turn can lead to large left-right streamwise positioning differences, such as found in the case of unilateral vocal fold paralysis (UVFP) [1], resulting in complex vibration patterns. This is further illustrated in Fig. 5. In the case of asymmetrical opening a first brief auto-oscillation event occurs associated with an initial pressure increase which is absent in the case of symmetrical opening. It is hypothesized that this is a general behaviour.

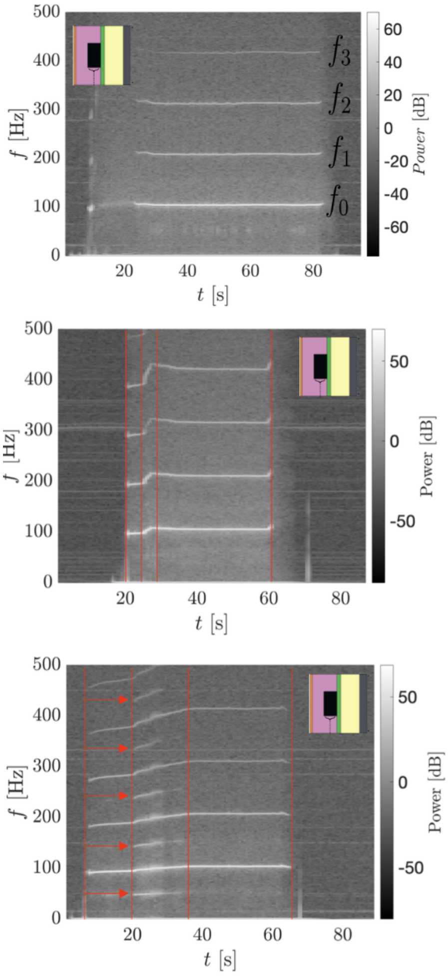


Figure 4. Upstream pressure spectrograms measured for rectangular replica with serial inclusion.

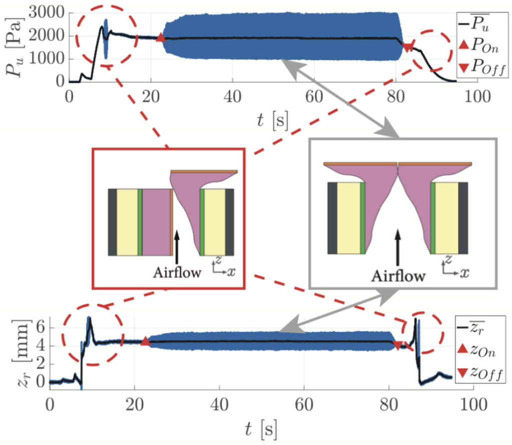


Figure 5. Influence of asymmetrical (left) or symmetrical (right) vocal fold positioning on measured upstream pressure signals.

4. DISCUSSION AND CONCLUSION

Rectangular composite silicone vocal fold replicas can reproduce auto-oscillation of vocal folds.

It is observed that a local rigidification at the center within the superficial layer only marginally affects the oscillation frequency. This confirms the finding reported in [5] concerning the presence of a growth at the surface of a vocal fold replica. On the other hand, complex dynamic behaviour of the oscillation between onset and offset is observed and might induce an increase of the fundamental frequency or even provoke subharmonics. Reproducing these phenomena using a mechanical replica is of particular interest as it opens the potential to study voice pathologies for which such phenomena are often reported [1,6,7].

Furthermore, a local rigidification affects in particular the pressure onset and thus the minimum pressure needed to support auto-oscillation. The pressure onset is observed to either increase for a serial inclusion or decrease for a parallel inclusion. This indicates that a theoretical model of the auto-oscillation of these rectangular replicas need to account for the movement perpendicular to the airflow as commonly done as well as to the movement within the airflow direction.

Further research is needed to further strengthen these experimental findings. In addition, measurements with similar inclusions on vocal fold replicas with a non-rectangular shape are needed to extrapolate these results.

5. ACKNOWLEDGMENTS

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