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► **To cite this version:**

Raphaël Girault, Hamid Yousefi-Mashouf, Paul Luizard, Lucie Bailly, Laurent Orgéas, et al.. Testbed design for in-vitro characterisation of biomimetic vocal folds. MAVEBA 2021 - 12th International Workshop Models and Analysis of Vocal Emissions for Biomedical Applications, Universita Degli Studi Firenze, Dec 2021, Florence, Italy. <hal-03510881>

HAL Id: hal-03510881

<https://hal.science/hal-03510881v1>

Submitted on 4 Jan 2022

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TESTBED DESIGN FOR IN-VITRO CHARACTERISATION OF BIOMIMETIC VOCAL FOLDS

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Abstract: An *in-vitro* testbed was designed to study the vibromechanical behaviour of biomimetic and extensible vocal folds. The paper describes the several steps of its conception. It consists of a deformable laryngeal envelope in which stretchable vocal-fold replicas of adjustable material and structural properties can be inserted for testing. The folds are able to oscillate for a wide range of aerodynamic conditions and material elongations.

Keywords: biomimetic vocal fold, in vitro testbed, self-oscillation

I. INTRODUCTION

The understanding of human vocal-fold vibratory properties is based on the development of testbeds that allow to reproduce self-sustained oscillations [1-4]. Such *in vitro* set-ups are used to study the physics of phonation. Most models already developed in past decades correspond to deformable folds, albeit fixed in a given geometry and pre-tension prior oscillations. Their microstructure has been progressively refined, ranging from isotropic and mono-layered oscillators to anisotropic and multi-layered ones [1,4]. To our knowledge however, only two studies present extensible folds, even though vocal-fold stretching is a major aspect of phonation biomechanical control [5,6]. The aim of this work was to design a testbed dedicated to the study of vibromechanical behaviour of biomimetic vocal folds. Emphasis was placed on the possibility of reproducing the actions of crico-thyroid tilt (fold stretching) and inter-arytenoid compression (fold abduction and adduction).

II. METHODS

A. A deformable laryngeal envelope

The chosen approach was to enable folds actuation in stretching and compression. We designed a flexible laryngeal envelope made up of silicone (Ecoflex™ 00-50), into which vocal folds to be tested could be inserted while maintaining a seal. This three-part envelope is

shown in Figure 1. It consists of i) a subglottal tract attached to the air inlet tube, and representing the trachea upper part (subglottal stage); ii) a divergent tract that joins the subglottal and glottal stages; iii) a case in which deformable folds can be positioned (glottal stage). An air pressure sensor is inserted in the subglottal stage.

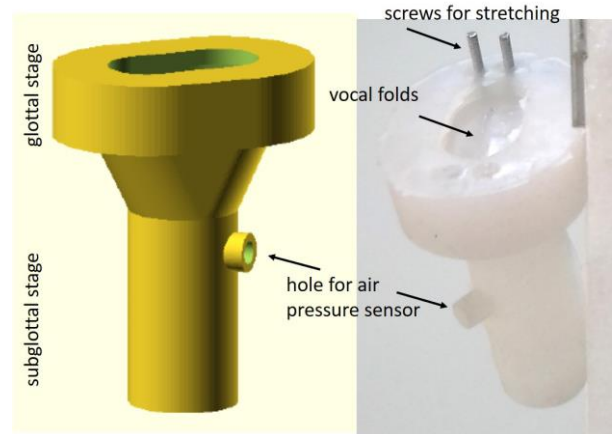


Figure 1 : Design of a deformable laryngeal envelope

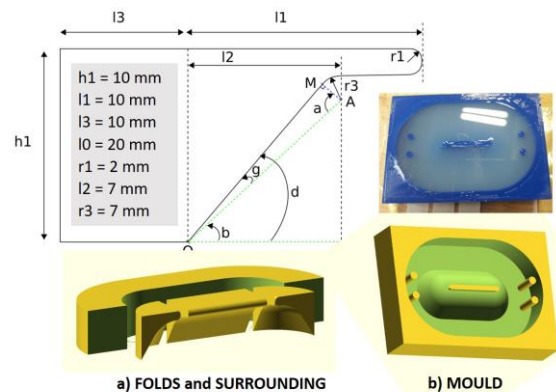


Figure 2 : (a) : 3D initial geometry chosen for one deformable fold and its surrounding (subglottal convergent tract and glottal plane). (b) : illustration of the 3D-printed mould of the folds, and its CAO design.

B. Choice of material and vocal-fold design

Our ultimate goal is to design architected vocal folds. In a first step, homogeneous mono-layered oscillators were conceived, made of isotropic polymers and processed using 3D-printed moulds (see Figure 2). Two complementary approaches were tested, using either : (i) silicone rubbers of reference (Ecoflex™ 00-10, 00-30, 00-50) owning distinct mechanical properties (*e.g.* shore hardness, tensile strength, elongation at break, viscosity); (ii) cross-linked gelatin-based hydrogels chosen for their ability to retain high tissue-like water content. In a second step, a two-layered version was made. The surface layer can be homogeneous or composed of a fiber mat.

C. Mechanical behaviour in tension and compression

The mechanical behaviour of the selected materials were explored in tension and compression, using a uniaxial machine (INSTRON® 5944) equipped with a ± 10 N load cell, and combined to an hygro-regulated chamber. These mechanical tests made it possible to better understand the impact of each material's formulation on its stress-strain behaviour, and to characterize the impact of various loading conditions (*e.g.* loading mode, cyclic paths, deformation rate) on its mechanical properties. This step allowed to compare the mechanical properties of each vocal-fold model to reference database previously acquired on native vocal folds [7], and to better understand their vibromechanical behaviour observed under fluid-structure interaction in step E.

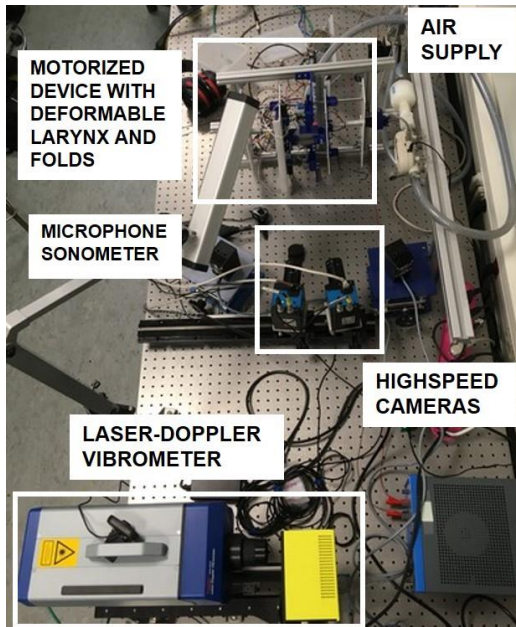


Figure 3 : Photo of the testbed with all equipments
D. Vibromechanical characterisation

In addition to the mechanical characterisation of the selected materials, the vibromechanical behaviour of the 3D vocal folds were measured by laser-Doppler vibrometry. The testbed is shown in Figure 3. The structure was installed on the testbed in its phonatory position and without air supply. The vibromechanical eigenmodes were excited with a sine sweep signal delivered by a vibration shaker.

E. Behaviour in fluid-structure interaction

Pressurised air injected into the model through the subglottal tract enabled the synthetic folds to vibrate. Subglottal air flow was controlled by the degree of valve opening and measured with a flow-meter. For different levels of fold elongation, the aero-acoustic behaviour was characterised by measuring aerodynamic parameters (subglottal phonation pressure, vocal efficiency) and acoustic parameters (intensity, frequency, spectral centroid). Vibratory behaviour was characterised by highspeed cinematography through computing kymograms and glottal area waveforms.

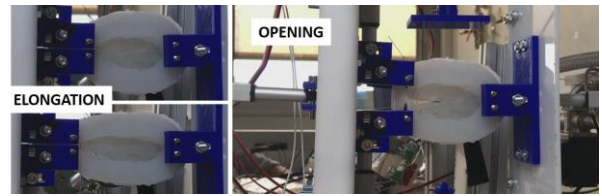


Figure 4 : Illustration of stretching action and abduction/adduction on deformable folds.

III. RESULTS

A. Ability to be stretched and abducted/adducted

Figure 4 illustrates the stretching action on vocal-fold replica. In a first measurement campaign, the stretch ratio $\lambda = L/L_0$ was varied from 1.05 to 1.21, L (resp. L_0) being the length of the fold in the deformed (resp. undeformed) configuration. A greater elongation could be obtained, yet not tested for allowing the whole measurement campaign without damaging the biomimetic folds.

B. Ability to oscillate in fluid-structure interaction

As illustrated in Figures 5 and 6, vocal folds were able to oscillate in response to an increase of subglottal air flow in most cases. The greater the material stiffness, the higher the subglottal pressure measured during stabilized vibration. For a given material, the greater the applied stretching, the higher the subglottal pressure needed to self-oscillate. Homogenous vocal folds in Ecoflex™ 00-10 demonstrated self-oscillations on a

limited mid-to-high range of airflow (from 1.5 to 3.5 L/s), with lesser subglottal pressure variation. On the other side, oscillations of hydrogel-based folds were limited to low-to-mid range of airflow (from 0.5 to 2.5 L/s). The linear relationship between subglottal pressure and airflow was similar for all materials and stretching conditions, except for folds in Ecoflex™ 00-10 for which subglottal pressure did not vary much.

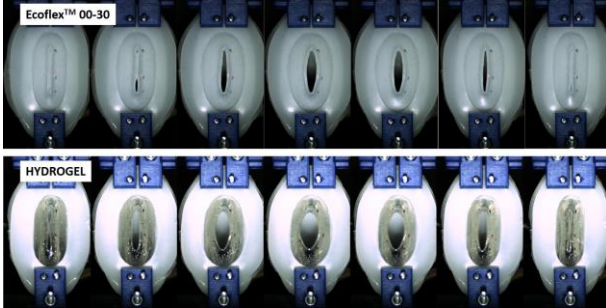


Figure 5 : Visualisation of a glottal vibratory cycle for two types of material. Top : silicone. Bottom : cross-linked gelatin. The laryngeal envelope is identical in both cases.

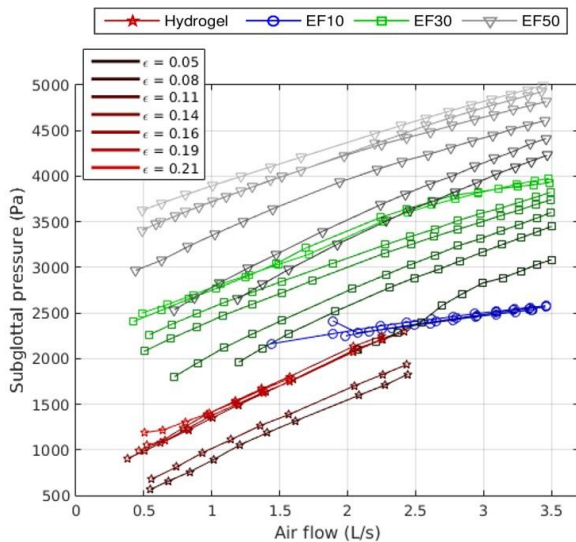


Figure 6 : Subglottal pressure as a function of air flow (control parameter) for three different types of silicone (variable stiffness properties) and for the cross-linked hydrogel. Each dot represents mean value computed on a sequence of stabilized vocal-folds oscillation.

IV. DISCUSSION

With a simple and homogenous model of vocal folds and laryngeal envelope, self-sustained oscillations were obtained on a wide range of subglottal airflow and pressures. Stretching did not impede the oscillatory capabilities for Ecoflex™ 00-30 and Ecoflex™ 00-50 folds. Yet Ecoflex™ 00-10 folds could not oscillate at

low airflow rate, and hydrogel-based one at high airflow rate.

Several improvements can be made. Concerning the folds, a two-layer version has been designed, yet not tested. Other geometries of vocal folds can also be designed, closer to synthetic models used in the literature [7]. Replicas of arytenoid cartilages can be easily 3D printed and inserted in the posterior part.

V. CONCLUSION

The implemented approach allows the development of biomimetic vocal folds step by step, so as to better understand the relationships between material and structural properties of the replica, and their vibratory outcomes under fluid/structure interaction. Vocal folds designed separately (left-right) or as a whole (monobloc setting) were able to sustain self-oscillation at a wide range of subglottal flows and pressures, and at various degrees of stretching.

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