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QUANTIFYING THE ELASTICITY OF MECHANICAL VOCAL FOLDS REPLICAS

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Abstract: The mechanical properties of two types of deformable mechanical vocal folds replicas are considered. On one hand, the linear elasticity of multi-layered silicone vocal fold replicas with constant elasticity is considered. On the other hand, the mechanical properties of pressurised latex tube replicas with variable elasticity are assessed. In order to quantify the elasticity of these VF's and their influence on the fluid-structure interaction underlying sustained auto-oscillation, experimental as well as model results are presented. This way this work contributes to customised VF replicas with predicted and quantified elasticity.

Keywords: Deformable mechanical vocal folds replicas, Young's modulus estimation, Small strain range, Fluid-structure interaction

I. INTRODUCTION

For human speech sound production, and particularly for phonation or voiced sound production, the presence of two apposed vocal folds (VF) within the larynx, illustrated in Fig. 1, is crucial. Indeed, the fluid-structure interaction between airflow coming from the lungs and the deformable VF tissues on each side of the glottal constriction can result in sustained VF auto-oscillation which is the major sound source for voiced speech sounds. As a consequence, structural properties of healthy as well as pathological VF's influence the fluid-structure interaction and therefore the voiced sound source and potentially the quality of voiced speech sounds.

Physical studies of the fluid-structure interaction underlying the VF auto-oscillation have a long tradition relying on simplifications of the anatomical VF structure as this approach enhances the reproducibility, quantifiability, controllability and hence interpretability of experimental results.

In this work, the elasticity of two types of deformable vocal folds replicas is considered. A first type of deformable VF approximations focuses on maintaining, up to some degree, the anatomical multi-layered structure so that each layer has an appropriate, but constant elasticity. These replicas are obtained as

an overlap of molding layers composed of different silicone mixtures. This way the influence of the degree of anatomical realism without or with structural abnormalities on the elasticity can be considered. A second type of deformable VF approximations focuses on the elasticity regulating function within a human VF rather than on its anatomy. In this case, each VF is mimicked as a pressurised latex tube for which the pressure can be varied. As such, the elasticity of each VF can be varied and imposed. Normal and pathological conditions can be considered.

In order to quantify the elasticity of these mechanical VF's replicas and its influence on the fluid-structure interaction underlying sustained auto-oscillation, experimental as well as model results are presented. It is sought to quantify their elasticity and in turn to contribute to its predictability. In this work the linear elasticity is focused on, which is expressed with the effective Young's modulus (EYM) of the composite-like vocal folds structure.

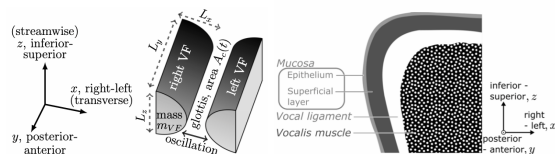


Fig. 1: Illustration of the larynx for VF auto-oscillation and multi-layer structural representation.

II. DEFORMABLE REPLICAS

A. Silicone VF replicas: M5, MRI and EPI

Silicone VF replicas mimic the multi-layer (ML) (micro-)anatomical VF structure to some extent as an overlap of silicone molding layers with constant elasticity following the methodology outlined in [1] and the references therein. Three molded ML silicone VF replicas (M5, MRI and EPI) are shown in Fig. 2 for which layer thickness l_t and overall dimensions L_x and L_z are indicated. The M5 replica is a two-layer (2L) reference model following the body-cover theory of phonation representing thus the vocalis muscle and superficial layer. The MRI replica has a three-layer (3L) structure by adding a thin epithelium-like three-

layer (3L) structure by adding a thin epithelium-like to the 2L-M5 structure. The EPI replica is a four-layer (4L) structure obtained by inserting a soft ligament-like deep layer between the muscle and superficial layer of the 3L-MRI replica. Each VF is mounted on a stiff backing layer and replicas have constant elasticity.

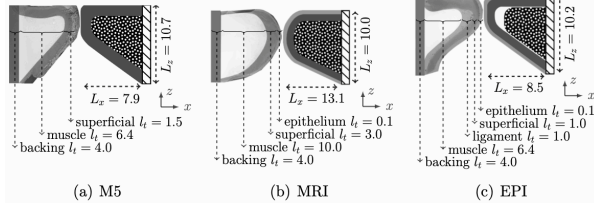


Fig. 2: Coronal section (mm) of a molded silicone multi-layer VF replicas (right VF) and its schematic representation (left VF): a) M5, b) MRI, c) EPI.

B. PLT VF replica

A VF replica with variable elasticity is obtained by representing each VF as a pressurised latex tube (PLT) [2]. Each VF consists of a latex tube enveloping a hollow rigid metal support as depicted in Fig. 3. The latex tube is pressurized (PLT) by filling it with distilled water by means of a water column. The elasticity of the PLT replica depends on the imposed P_{PLT} and thus on the height of the water column. In this work, P_{PLT} is varied between 450 Pa and 6500 Pa (with steps of at most 500 Pa), corresponding to a water column range of about 60 cmH₂O. The PLT VF is positioned in a rigid frame, the same way as during fluid-structure interaction experiments [2], allowing simultaneous observation in the sagittal plane (side view) and the transverse plane (top view).

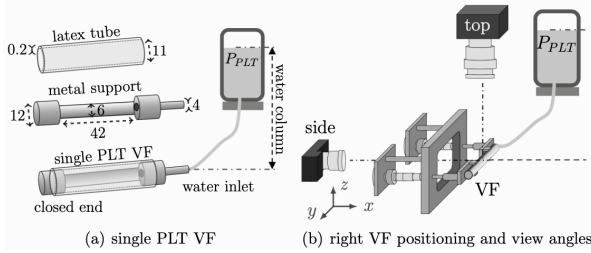


Fig. 3: Overview (mm) pressurized latex tube (PLT): a) single VF, b) spatial VF and camera positioning.

II. EYM ESTIMATION: SILICONE COMPOSITES

A. Six specimens from three silicone VF replicas

Bone-shaped ML silicone specimens [2] with serially stacked layers are designed in order to approximate the ML composition of the three silicone replicas. Each specimen has a test section of length 80 mm in between two clamping ends. The number of layers n , the layer composition, the layer order and layer lengths differ in the same way as between

silicone replicas. Specimens are designed as 2L (Π_{M5} , $n=2$), 3L (III_{MRI} , $n=3$) and 4L (IV_{EPI} , $n=4$) composites for which the layer lengths l_i match either the layer thickness ratio l_i/L_x or the layer volume ratio V/V_{VF} . As shown in Fig. 4, two different specimens are molded based on the composition of each replica.

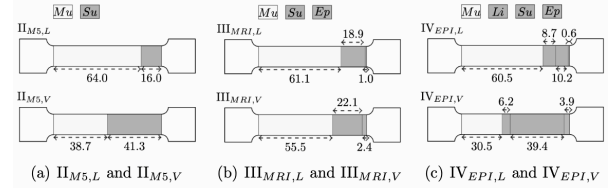


Fig. 4: Serial stacked specimens based on M5, MRI and EPI replicas with layer lengths l_i (mm): muscle-Mu, ligament-Li, superficial-Su, epithelium-Ep.

B. Uni-axial stress tests and EYM estimation

The effective Young's modulus E_{eff} of the molded silicone ML specimen is experimentally estimated from uni-axial stress tests by means of precision loading [1]. Briefly, the force-elongation relationship along the force direction is measured on vertically placed specimens by fixing the upper clamping end and adding a known weight m to the lower clamping end. The weight is gradually incremented. The load force for added mass m is given as its product with the gravitational constant. The specimen's elongation is deduced from geometrical measurements (between 44 and 198 mm) on each layer as a function of weight increment: length and midway area perpendicular to the force direction. The elongation is then the sum of the elongations of each layer, the cross-sectional area of the specimen is obtained as the weighted arithmetic mean of midway areas. Measured force-elongation and area-elongation data are illustrated in Fig. 5a and Fig. 5b for the M5-based specimens. The true stress is then given as the ratio between the force and instantaneous area whereas the true strain is obtained as the natural logarithm of the ratio between the instantaneous length and original specimen length. The EYM corresponds to the slope of a linear fit to the elastic (small strain up to 0.32) region in which the stress is proportional to the strain as plotted in Fig. 5c.

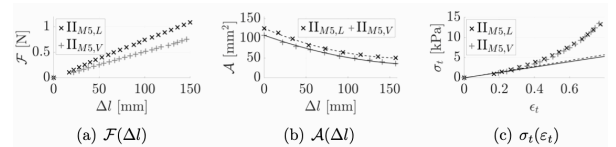


Fig. 5: Uni-axial stress tests for M5-based specimens: a) force-elongation, b) area-elongation, c) stress-strain curves with linear fit (small strain range up to 0.32).

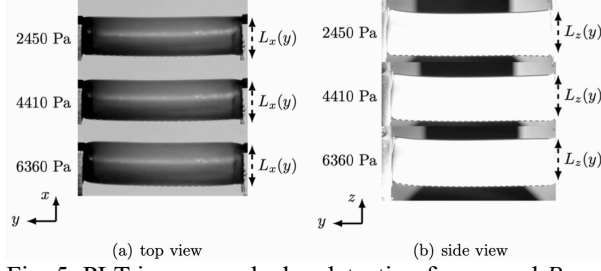


Fig. 5: PLT images and edge detection for several P_{PLT} .

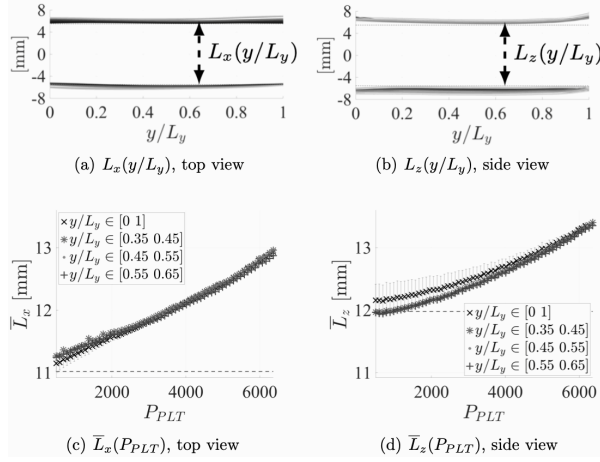


Fig. 6: Characteristic lengths of PLT replica from imaging as a function of P_{PLT} for different y/L_y intervals (symbols): a,b) local and c,d) mean.

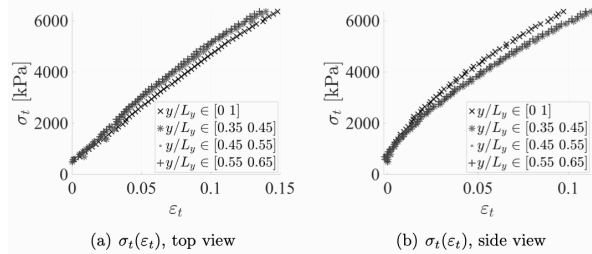


Fig. 7: Image-based stress-strain curves for the PLT replica for different y/L_y intervals (symbols).

B. Modelled EYM for serial stacked specimen

For n serial stacked layers, the stress in the equivalent homogeneous composite and the stress in each layer is constant (Reuss hypothesis) [1]. The effective Young's modulus is then modelled as the harmonic mean of the layers Young's moduli weighted by their lengths. This model was validated in [1] for 2L and 3L silicone specimens for which the layers Young's moduli varies between about 2 kPa up to 65 kPa corresponding to the range of interest for silicone VF replicas. It is noted that model outcome is not affected by the stacking order of the layers within the specimens.

II. EYM ESTIMATION: PLT VF REPLICA

Increasing (or decreasing) the internal water pressure P_{PLT} expands (or shrinks) the PLT replica radially to the posterior-anterior axis. As the PLT can be considered as an inhomogeneous material consisting of both latex and water, the relationship between P_{PLT} and the deformation is governed by a EYM. This EYM is estimated from steady state images taken as a function of P_{PLT} . For each P_{PLT} a top and side view image is taken (see Fig. 3b). Characteristic lengths $L_x(y)$ (top view) and $L_z(y)$ (side view) are obtained as the distances between the replica's edges as illustrated in Fig. 5. Extracted edges and subsequent local characteristic lengths as a function of y/L_y ($L_y=42$ mm) are plotted in Fig. 6a (top view) and Fig 6b (side view). Mean characteristic lengths for different y/L_y ranges (overall, short 4 mm intervals) are plotted in Fig. 6c (top view) and Fig. 6d (side view). Mean values agree to within 0.25 mm with respect to the overall mean and to less than 0.1 mm between the 4 mm intervals. The stress-strain curves shown in Fig. 7 are then calculated in the same way as explained for the silicone specimens. It follows that the EYM corresponds again to the slope of a linear fit to the elastic (small strain) region in which the stress is proportional to the strain.

III. RESULTS

A. YEM of replica-based silicone specimen

Measured (filled symbols) EYM and modelled (empty symbols) EYM for the six silicone VF replica-based specimens are plotted in Fig. 8. For MRI and EPI based specimen, measured EYM are close to their overall mean of 5.7 kPa as the standard deviation of 0.4 kPa as well as the maximum difference of 0.8 kPa is small (less than 15%). It follows that imposing either the thickness ratio (subscript L) or the volume ratio (subscript V) does not significantly affect measured EYM for MRI-based or EPI-based specimens. Measured EYM for M5-based specimens exceed values found for MRI or EPI based specimens with 1.0 kPa (volume ratio) or 2.3 kPa (length ratio), so that the imposed ratio affects EYM for M5-based specimens.

The impact (M5-based, EPI-based) or lack thereof (MRI-based) of the imposed ratio (thickness L or volume V) on modelled EYM is understood as the harmonic mean depends on the layer lengths and the layers Young's moduli. For all replicas, the muscle layer has a larger Young's modulus than the superficial layer so that shortening the muscle layer, corresponding to imposing the volume ratio instead of the thickness ratio, results in smaller EYM predictions. The decrease is significant for M5-based (3.4 kPa) and EPI-based (4.7 kPa) replicas. For MRI-based

specimens the decrease is not significant (0.1 kPa) as the muscle layer is shortened with less than 15% (or less than 5.6 mm) and in addition Young's moduli of the muscle (4.0 kPa) and superficial (2.2 kPa) layer are of the same order of magnitude, which is not the case for the M5-based or EPI-based replicas.

The difference between modelled and measured EYM for all six specimens varies between -2.5 kPa and 2.8 kPa resulting in an overall model accuracy of -0.5 ± 2.1 kPa (mean and standard deviation). Modelled EYM exhibit some of the tendencies described for measured values. Indeed, both measured and modelled EYM for M5-based specimens are greater values associated with MRI-based specimens. Furthermore, the imposed ratio (L or V) affects M5-based specimens more than MRI-based specimens. For the EPI-based replica, measured EYM are in between the range associated with the model. Given the direction of the VF oscillation (Fig. 1), values of specimen for the length ratio is respected are probably more pertinent.

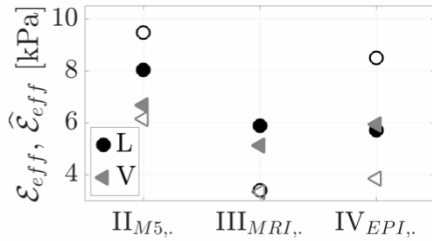


Fig. 8: Measured (filled) and modelled (empty) EYM for specimens respecting either the thickness (L) or volume (V) ratio of silicone VF replicas.

B. YEM of PLT VF replica

The effective Young's moduli estimated from top and side view imaging for the overall and several 4 mm ranges of y/L_y intervals are plotted in Fig. 9. For each viewing angle values obtained for increasing internal pressure P_{PLT} as well as for decreasing internal pressure P_{PLT} are considered. As all P_{PLT} result in a small strain (less than 0.15) deformation, the EYM is obtained from a linear fit to the complete strain range. From Fig. 9 is seen that EYM estimates for different 4 mm y/L_y intervals match for both the EYM obtained for side as well as top viewing. Nevertheless, side EYM exceed values associated with top value with about 6 MPa. Considering the whole y/L_y range stresses this directional difference as it either decreases (to view) or increases (side view) estimated EYM values with about 3 MPa up to 7 MPa. Given the pressure force direction and the movement associated with the oscillation (Fig. 1), values obtained from the top view images are probably most pertinent. EYM associated with the

PLT replica (between 40 MPa up to 57 MPa) are significantly (factor 10^4) greater than values for the silicone based specimens (between 2 kPa up to 10 kPa).

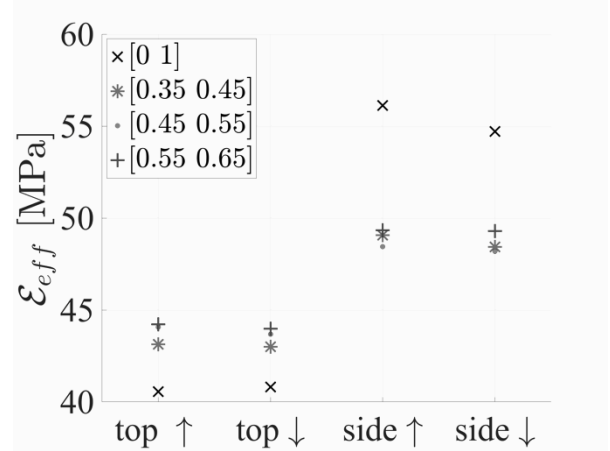


Fig. 9: Measured EYM for the PLT replica from top view and side view images for different y/L_y intervals (symbols) when either increasing (upward arrow) or decreasing (downward arrow) P_{PLT} .

V. CONCLUSION

Effective Young's moduli for silicone specimens representing silicone VF replicas are measured. For silicone specimens measured and modelled values agree, so that the model can be used as a predictor. Effective Young's moduli of the PLT VF replica are measured as well. In future, the pertinence of found values with respect to mechanical properties and oscillation properties need to be considered.

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