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# VIBRATION MODE DECOMPOSITION FROM HIGH-SPEED IMAGING OF AUTO-OSCILLATING VOCAL FOLD REPLICAS WITHOUT AND WITH VERTICAL TILTING

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**Abstract:** Vertical left-right level difference due to angular asymmetry characterises unilateral vocal fold paralysis. High-speed image sequences of three distinct auto-oscillating silicone vocal folds replicas are analysed simultaneously in both space and time with a dynamic vibration mode decomposition while imposing different degrees of angular asymmetry. From the modes eigenvalue spectra, it is found for all three replicas that the degree of angular asymmetry affects the decay of vibration modes. More in particular, for the assessed vocal fold replicas, increased mode decay is observed when the replica contains a stiff epithelium-like surface layer whereas it decreases otherwise. Spatial mode patterns near the glottal aperture reflect the mode order along the posterior-anterior direction and the imposed angular asymmetry reduces the spatial mode extent near the tilted vocal fold edge. Consequently, the quantified dynamic vibration mode properties, including the ones observed for higher order modes, are of potential interest for clinical studies involving high-speed vocal folds auto-oscillation imaging.

**Keywords:** High-speed vibration imaging, dynamic vibration mode analysis, mechanical vocal fold replica, vertical positioning asymmetry

## I. INTRODUCTION

Unilateral vocal fold paralysis (UVFP) is a common vocal fold (VF) pathology characterised by an air escape due to left-right VF asymmetries of the VF's shape, tension or/and positioning. The glottic insufficiency associated with UVFP is reported to lead to dysphonia as air leakage is often associated with breathy voice or vocal fatigue.

In recent work [1,2], three molded deformable multi-layer silicone VF replicas (two-layer M5, three-layer MRI and four-layer EPI) with different degree of complexity were used to study the effect of vertical tilting of a single VF on their auto-oscillation. Concretely, the right VF was kept in place whereas the posterior edge of the left VF was tilted in the medio-sagittal plane towards the superior direction. The

resulting vertical tilting is parameterised by angular asymmetry angle  $\alpha$ . Imposing angular asymmetry in the range from  $0^\circ$  up to  $25^\circ$  results in a vertical level difference up to a few millimeters as observed in patients suffering from UVFP. Imposed vertical tilting of a single VF causes left-right VF positioning asymmetry whereas left-right VF tension and shape symmetry are maintained. The use of three different VF replicas allowed to consider the impact of tilting for replicas with different shape and multi-layer composition as outlined in [1,2].

Analysis of the upstream pressure [1] showed a decrease of the oscillation frequency and an increase of the oscillation onset threshold pressure with increasing  $\alpha$  was observed. The gradual loss of VF's contact with  $\alpha$ , inducing increased glottal air leakage, was pointed out to catalyse these tendencies.

High-speed (HS) imaging of the vibrating VF's for different  $\alpha$  was considered in [2]. Local image features, exploiting HS videokymographic (VK) line-scans, were quantified during steady state oscillation. Left-right vibration asymmetry parameters showed that the normal VF entrains the movement of the tilted VF. This left-right vibration asymmetry caused the mucosal wave velocity in the tilted VF to be lower than the one in the normal VF.

In this work, it is sought to further investigate sustained steady state VF vibration without ( $\alpha = 0^\circ$ ) and with ( $\alpha > 0^\circ$ ) angular asymmetry by analysing high-speed (HS) image sequences of the vibrating VF's. Instead of focusing on local spatial features or line scans as in previous work [2], it is sought to assess simultaneously temporal as well as spatial information of the global VF's auto-oscillation. A dynamic vibration mode decomposition (DMD) of the observed vibration snapshots is applied as other VF vibration mode decomposition methods such as the empirical eigenfunction analysis do not inform on the temporal mode dynamics. This allows to evaluate how the effect of angular asymmetry affects the spatial and temporal vibration mode features.

## II. EXPERIMENTAL & ANALYSIS METHODS

The experimental setup and flow supply used to generate the FS interaction underlying the VF auto-oscillation is similar to the one described in [1,2]. The pressure difference driving the VF's auto-oscillation corresponds to the measured upstream pressure. All experiments are performed with a mean upstream pressure set just ( $< 50$  Pa) above the oscillation onset. Angular asymmetry degrees are set to  $0^\circ$ ,  $4^\circ$ ,  $10^\circ$  and  $20^\circ$  for all replicas. For the M5 VF replica also  $16^\circ$  is considered. The upstream pressure varies between 400 Pa and 1500 Pa depending on the asymmetry degree as well as on the VF replica and the oscillation frequency ranges from 93 Hz up to 144 Hz. As detailed in [2] a single HS camera (frame rate 4 kHz) is placed in the medio-frontal plane in order to acquire instantaneous images of the vibrating VF's. In this plane, three viewing angles  $\theta_{HS}$  are considered non-simultaneously resulting in top, diagonal and level views. Acquired instantaneous images are two-dimensional grayscale intensity matrices whose dimension is set by the camera resolution of  $240 \text{ px} \times 320 \text{ px}$ .

For each assessed condition, 1 second or 4000 subsequent snapshots of steady-state auto-oscillation are analysed. A DMD analysis is applied to each image sequence rearranged in the system matrix  $\mathbf{X}$  [3]. DMD results in a temporal and spatial decomposition of the global VF auto-oscillation assuming a locally linear system dynamics  $\mathbf{s}(t)$  with time  $t$ . The system dynamics is then obtained from the eigenvectors and eigenvalues of the system matrix which is matrix notation becomes

$$\mathbf{s}(t) = \mathbf{\Phi} \exp(\mathbf{\Omega}t) \mathbf{b},$$

with  $\mathbf{\Omega}$  a diagonal matrix whose entries are the eigenvalues,  $\mathbf{\Phi}$  is a matrix whose columns are the eigenvectors and  $\mathbf{b}$  is a column vector of the coefficients of the first image in the eigenvector basis. The sought spatial analysis of the global auto-oscillation is provided by the DMD modes given by the eigenvectors. The sought temporal analysis is provided by the corresponding eigenvalues. For each spatial mode, its mode frequency is obtained from the imaginary part of the eigenvalue  $\Im(\omega)$  whereas its growth rate is determined from the real part of the eigenvalue  $\Re(\omega)$ , which is smaller or equal to zero for stable modes. The DMD eigenvalue spectrum is thus obtained by plotting for each mode its frequency as a function of its growth rate. The amplitude of each mode is given by the associated coefficient in  $\mathbf{b}$ .

### III. VIBRATION ANALYSIS RESULTS

#### A. Temporal DMD mode analysis: eigenvalue spectra

DMD eigenvalue spectra of stable vibration modes for top views of all three replicas and different asymmetry angles are plotted in Fig. 1.

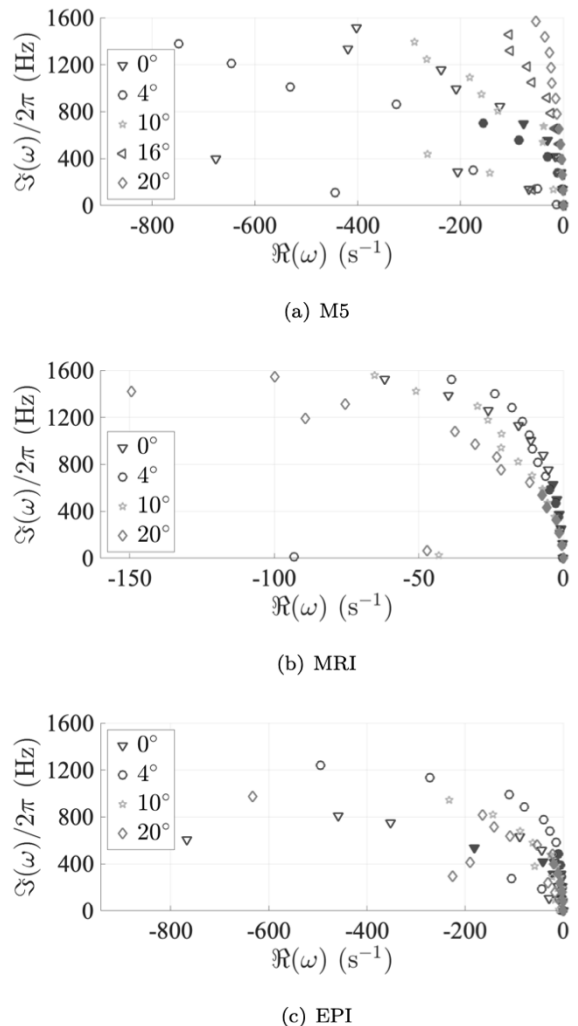


Fig. 1: DMD eigenvalue for top views and different asymmetry angles (symbols) for: a) M5, b) MRI and c) EPI. Filled symbols indicate dominating modes with oscillation frequency up to 750 Hz.

All spectral branches originate with a non-oscillation mean flow mode ( $j=1$ ) associated with the zero eigenvalue at the origin. This non-oscillation mode expresses the influence of the mean flow along the inferior-superior direction on the VF's vibration pattern. Stable branches with least decay are identified as main spectral branches. Dominating oscillation modes ( $j = 2 \dots 6$ ) on the main spectral branches with frequencies up to 750 Hz are indicated with filled symbols. Both the non-oscillation mode and most dominating oscillation modes decay slowly as their real parts approximate zero. The real part of the eigenvalue

decreases as the mode frequency increases, typically above 750 Hz for the main spectral branches, so that these modes decay rapidly and hence contribute less to observed temporal vibration patterns. It is noted that primary oscillation (PO mode, mode  $j = 2$ ) frequencies obtained from the DMD eigenvalue spectra matches with previous reported values in [1,2]. Despite these similar tendencies for all VF replicas, Fig. 1 shows that the type/structure of VF replica affects the influence of angular asymmetry angle on the eigenvalue spectra. This is most obvious for the M5 replica compared to the MRI and EPI replicas.

Increasing the angular asymmetry from  $0^\circ$  to  $4^\circ$  either decreases (MRI/EPI) or increases (M5) the decay of high frequency modes. Therefore, in terms of the number of non-decaying stable oscillation modes, introducing a slight angular asymmetry either enriches (MRI/EPI) or strips (M5) the vibration pattern. Further increasing the angular asymmetry angle above  $4^\circ$  reveals the opposite tendency as mode decay either decreases (M5) or increases (MRI/EPI). So that in terms of the number of non-decaying stable oscillation modes, the vibration pattern either enriches (M5) or recedes (MRI/EPI). Given the geometry and multi-layer composition of the used VF replicas, it is suggested that observed eigenvalue spectral differences are due to the presence (MRI/EPI) or absence (M5) of a surface layer representing the epithelium.

As perfect angular symmetry ( $0^\circ$ ) is unlikely to occur in real life, the found robustness of the MRI/EPI VF replica to small angular asymmetries ( $4^\circ$  in Fig. 1) supports the hypothesis that adding an epithelium-like layer alters silicone VF replicas from a vibratory point of view. In addition, it provides evidence of the importance of this layer for normal VF vibration. Larger angular asymmetries ( $> 4^\circ$  in Fig. 1) mimic pathological VF vibration as all replicas become prone to glottal air leakage due to vertical level difference. Increased mode decay, only observed for the MRI/EPI replica and not for the M5 replica, is consistent with impaired oscillation and reduced vibration quality associated with glottal insucieny reported for human speakers. Thus, it is hypothesized that from a vibration point of view the presence of an epithelium-like layer results in more reasonable vibration patterns. From Fig. 1 is seen that the effect of angular asymmetry on mode decay is most obvious for higher frequency modes (typically  $> 750$  Hz). Therefore, it might be of interest to investigate higher frequency vibration modes as potential clinical markers for voice pathology studies such as UVFP.

The described changes in mode decay rate with angular asymmetry can be partly explained by changes in structural damping. Structural damping is likely to increase (or decrease) as the duration of vocal fold contact along the inferior-superior direction inside each glottal cycle increases (or decreases). This duration was quantified for the assessed VF replicas in [2]. It follows that structural damping either increases (MRI/EPI) or decreases (M5) for angular asymmetry larger than  $4^\circ$  as vocal fold contact was found to increase (MRI/EPI) or decrease (M5).

### B. Spatial DMD mode analysis

Modes  $j$ , indicated by filled symbols, are arranged ( $j = 1 \dots 6$ ) according to increasing frequency.

Examples of non-oscillation or mean flow modes, corresponding to the zero eigenvalue at the origin of the eigenvalue spectra (mode  $j = 1$ ), depend on the imposed asymmetry angle as the resulting glottal air leakage affects the mean glottal flow. Non-oscillation mode amplitudes  $b_1$  are plotted in Fig. 2. Amplitudes are normalised by the amplitude of the PO mode ( $j = 2$ ) associated with the lowest stable oscillation frequency denoted as  $b_{2,0^\circ}$ . All values exceed unity so that the mean flow mode dominates the eigenvalue spectra for all assessed configurations. View angles other than top view (diagonal or level) allow to observe phenomena along the medio-sagittal plane, and hence along the main flow direction in the inferior-superior direction, more directly resulting in larger mean flow amplitudes.

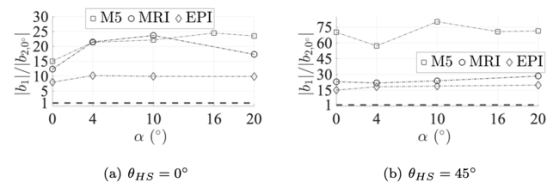


Fig. 2: Normalised non-oscillation mode ( $j=1$ ) amplitude magnitude: a) top view ( $\theta_{HS}=0^\circ$ ), b) diagonal ( $\theta_{HS}=45^\circ$ ) view.

Mean flow mode amplitudes ( $j=1$ , Fig. 2), in particular for diagonal and level views, are most pronounced for the M5 replica, which quantifies the the large displacement in the flow direction experimentally observed for the M5 replica.

Normalised amplitudes of five oscillation modes ( $j = 2 \dots 6$ ) for the MRI and EPI replicas from top and diagonal view angles are plotted in Fig. 3. The PO mode, whose frequency corresponds to the fundamental frequency characterising voiced speech utterances, has the largest amplitude for each angular

asymmetry angle. The plots confirm the decrease of the PO mode frequency with increasing angular asymmetry angle reported in [1,2]. Higher order post-PO modes obtained for  $j = 3 \dots 6$ , exhibit oscillation frequencies near the harmonics of the PO mode frequency  $f_2$  for all angular asymmetry angles as  $f_j/f_2 \sim j-1$  holds. As for the mean flow mode, non-top view angles result in larger mode amplitudes as mode patterns develop along both the horizontal transverse and medio-sagittal plane. Overall mode amplitudes decrease with mode order  $j$  regardless of view angle or angular asymmetry angle.

Spatial oscillation mode patterns of the MRI replica (top and diagonal views) are illustrated in Fig. 4. Increasing mode order ( $j$ ) changes the spatial mode with respect to its extent and with respect to the node pattern. In the vicinity of the glottal aperture (within the frames in Fig. 4) typical higher order mode patterns are observed as the number of nodes increases with  $j$ . For small angular asymmetry angles ( $4^\circ$ ) mode patterns develop similarly along the posterior-anterior direction and occupy both VF surfaces as tilting does not alters the elasticity of each VF. For large angular asymmetry angles ( $20^\circ$ ) spatial modes reflects the loss of full VF contact along the posterior-anterior direction. It is observed that a surface region extending from the posterior edge of the tilted VF is no longer part of the spatial mode pattern and that the area of the excluded surface region increases with  $j$ . Near the glottal aperture the spatial mode pattern for large asymmetry angles depends on the used view angle. For top view, the loss of VF contact limits the node pattern. For diagonal view, the node pattern becomes more apparent as the tilted VF is observed more directly.

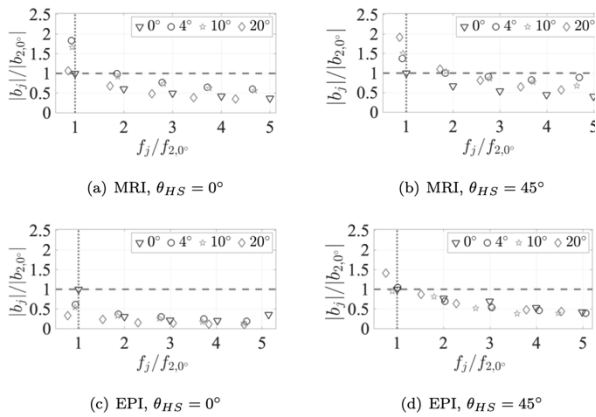


Fig. 3: Normalised oscillation mode amplitude ( $j=2\dots 6$ ) for top ( $\theta_{HS}=0^\circ$ ) and diagonal ( $\theta_{HS}=45^\circ$ ) views for MRI and EPI replicas.

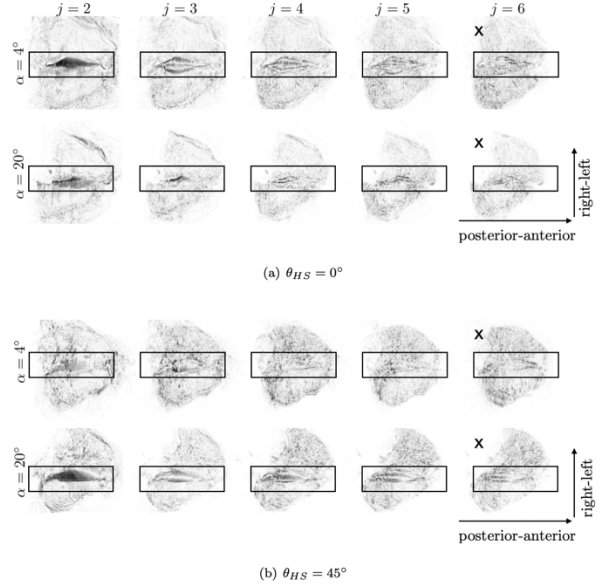


Fig. 4: Spatial oscillation mode patterns scaled between 0 (white, invariant) and 1 (black, most variant) for the MRI replica and asymmetry angles  $4^\circ$  and  $20^\circ$  for top ( $\theta_{HS}=0^\circ$ ) and diagonal ( $\theta_{HS}=45^\circ$ ) views. The glottal aperture is framed. Posterior side of the left VF is tilted as indicated ( $\times$ ) for  $j=6$ .

## V. CONCLUSION

Dynamic vibration mode decomposition in space and time of HS images of auto-oscillating silicone vocal folds replicas without and with vertical tilting is assessed. Results encourage to further investigate the potential interest of DMD mode properties, and in particular higher order vibration modes, as potential clinical HS image markers, e.g. for UVFP.

## ACKNOWLEDGEMENTS

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