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On the acoustical relevance of supraglottal flow structures to low-frequency voice production

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Abstract: The supraglottal flow exhibits many complex phenomena such as recirculation, jet instabilities, jet attachment to one vocal fold wall, jet flapping, and transition to turbulence. The acoustical relevance of these flow structures to low-frequency voice production was evaluated by disturbing the supraglottal flow field using a cylinder and observing the consequence on the resulting sound pressure field. Despite a significantly altered supraglottal flow field due to the presence of the cylinder, only small changes in sound pressure amplitude and spectral shape were observed. The implications of the results on our understanding of phonation physics and modeling of phonation are discussed.

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1. Introduction

There have been many recent studies on characterization of the supraglottal flow field (for a detailed list of such studies see the literature review in, e.g., Neubauer *et al.*, 2007; Luo *et al.*, 2009; Triep and Brucker, 2010). These studies show that the downstream glottal flow is highly three-dimensional and exhibits many complex phenomena such as recirculation, jet attachment to one vocal fold wall, jet instabilities (vortex shedding and roll-up), jet reattachment to vocal tract walls, jet flapping, and transition to turbulence. While accounting for such phenomena significantly increases the computational load of phonation models, the acoustical relevance of such flow features, i.e., how they affect the fluid–structure interaction and eventually the acoustics of the produced sound and its perception, is still unclear. Considering that the ultimate goal of phonation models is to accurately predict the characteristics of the radiated sound, the supraglottal flow structures, if can be shown to be acoustically irrelevant, do not have to be included in such phonation models.

From the sound production point of view, on the one hand, these complex flow structures in the downstream glottal flow field are sound sources of quadrupole type (dipole type when obstacles present in the pathway of airflow) and radiate sound mostly at high frequencies (generally above 2 kHz) due to the small length scales associated with the flow structures (Zhang *et al.*, 2002; Howe and McGowan, 2007). Therefore, these flow features have to be accurately modeled if the high-frequency component of voice is to be reproduced.

On the other hand, it has been postulated that the unsteady supraglottal flow structures may affect the intraglottal flow and pressure distribution, which is the driving force of vocal fold vibration, and therefore affect the low-frequency sound production. Once separated from the vocal fold walls, the glottal jet starts to develop jet instabilities and is therefore susceptible to downstream disturbances, especially when the glottis takes on a divergent shape. In this way, the unsteady supraglottal flow structures may strongly interact with the boundary layer at the glottal exit and affect flow separation point within the glottal channel (Hirschberg *et al.*, 1996). Previous works

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suggested that asymmetric vortical structures downstream may cause jet deflection or oscillation near the glottal exit (Thomas and Chu, 1989; Shinwari *et al.*, 2003; Neubauer *et al.*, 2007; Luo *et al.*, 2009). For confined jet flows, a strong recirculation zone exists surrounding the jet region. The unsteady flow in the recirculation zone may also strongly influence the jet orientation, particularly during glottal opening and closing (Alleborn *et al.*, 1997; Neubauer *et al.*, 2007). However, it is unclear how and to what extent such upstream influence, if it exists indeed, can affect the intraglottal pressure distribution and the resulting voice.

This study attempted to quantify the acoustical relevance of supraglottal flow structures in the low-frequency or the harmonic component of phonation in a self-oscillating model of the vocal folds. The focus on the low-frequency harmonic component was justified by the fact that, in normal phonation, the low-frequency harmonic component dominates the inharmonic component (the so-called noise component due to flow turbulence) and therefore is perceptually more important (Klatt and Klatt, 1990).

Our approach was to disturb the supraglottal flow field and observe how the low-frequency component of the sound (amplitude, fundamental frequency, and spectral shape) produced by the disturbed supraglottal flow field would be different from that produced by the undisturbed supraglottal flow field. The hypothesis is that if the supraglottal flow structures are essential to the production of the low-frequency harmonic component of voice, significant changes in the low-frequency sound should be observed if these supraglottal flow structures are significantly altered. Otherwise, if these supraglottal flow structures are acoustically irrelevant, alterations of the supraglottal flow field would not produce noticeable difference in the low-frequency sound field.

2. Methods

The same experimental setup as in Zhang *et al.* (2006a) was used. It consisted of an expansion chamber, a 12.4-cm-long uniform circular tracheal tube (inner diameter of 2.54 cm), a two-layer self-oscillating vocal fold model, and a 2.8-cm-long uniform rectangular vocal tract tube. Airflow was supplied through a pressurized flow supply. The short vocal tract was used to provide confinement to the jet flow exiting the vocal fold model. The short tube length also helped to reduce possible supraglottal acoustic feedback (Zhang *et al.*, 2006a), which allowed us to focus on aerodynamic feedbacks from the supraglottal flow field. The two-layer vocal fold model had a Young's modulus of approximately 9.3 and 3.0 kPa for the body (inner) and cover (outer) layers of the vocal fold model, respectively. Phonation onset occurred at around 3.09 kPa at a phonation frequency of 147 Hz, which was accompanied by a sudden increase in the sound pressure amplitude. Beyond onset, the sound pressure amplitude increased significantly with increasing upstream pressure. For example, for a mean upstream pressure of 3.27 kPa (at which the results below were obtained), a $\pm10\%$ change in upstream sound pressure amplitude roughly corresponds to a ±0.05 kPa change in the mean upstream pressure.

Previous studies showed that the physical model exhibited qualitatively similar vibratory pattern (Zhang *et al.*, 2006b, 2009) and supraglottal flow field pattern (Neubauer *et al.*, 2007; Drechsel and Thomson, 2008) to that observed in excised-larynx (Khosla *et al.*, 2007) and *in-vivo* canine models (Dollinger *et al.*, 2005). In general, the vocal fold models exhibited vibratory patterns (e.g., onset frequency and pressure, pressure–flow relationship, vibration amplitude, and flow modulation, etc.) similar to that typical of humans. The glottal jet exhibited cyclic variations in both the jet width and jet length during one oscillating cycle, with the jet disappearing at the end of the closing phase and reappearing at the opening phase of the next cycle. Readers are referred to these previous studies for further details of the vibratory and flow field pattern of this physical model.

To disturb the supraglottal flow, a hexagonal cylinder of 1.27 mm diameter was aligned in the anterior–posterior direction downstream of the vocal fold model [Fig. 1(a)] and traversed in the flow direction at different left–right locations. The cylinder was long enough to cover the entire anterior–posterior span of the vocal fold model

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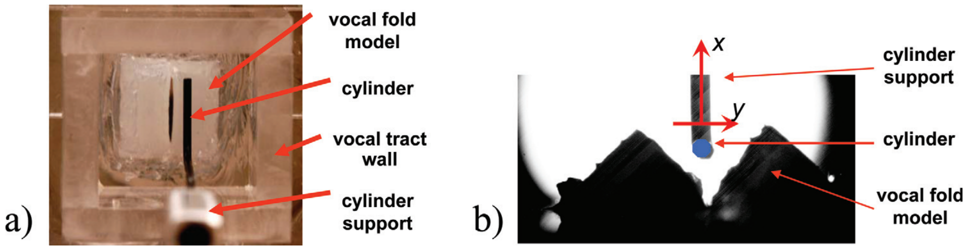

Fig. 1. (Color online) (a) Superior view of the vocal fold model and the cylinder used to disturb the supraglottal flow. (b) Side (frontal) view of the vocal fold model during vibration and the definition of coordinate system.

but slightly smaller than the cross-sectional dimension of the vocal tract tube. Figure 1(b) defines the coordinate system which was used later in Sec. 3. The axial location (x) of the cylinder was measured with reference to the point of maximum downstream excursion of the vocal fold model [Fig. 1(b)]. During experiments, this reference location ($x=0$) was first identified using high-speed recordings of the vocal fold model and then used for determination of cylinder locations in later experiments. The left–right direction (y-axis) was defined with regard to the nominal glottal centerline.

The effectiveness of the cylinder in disturbing the supraglottal flow was verified by visualizing the supraglottal flow field using a high-speed laser and a high-speed camera. Comparison between the flow field with and without cylinder shows that the supraglottal flow field was significantly disturbed by the presence of the cylinder except for extreme off-center cylinder locations in the left–right direction. The jet was either deflected to one side or split into two separate jets at the location of the cylinder, and the distribution and evolution of vortical structures were also significantly altered (Fig. 2).

For each cylinder location, the mean subglottal pressure, the mean flow rate, and the acoustic pressure inside the tracheal tube (2 cm upstream from the entrance of the glottis) and outside were measured for a 1-s period.

Note that high-frequency tonal sounds were generated due to jet impingement onto the cylinder when the cylinder was placed directly inside the jet flow. To focus on the low-frequency voiced sound production and facilitate comparison to cases when the cylinder was away from the jet axis and no jet tones were produced, the outside sound pressure was low-pass filtered with a cut-off frequency of 2.5 kHz. No filtering was applied to the upstream sound pressure.

3. Results

Figure 3(a) shows the normalized amplitude of the outside sound pressure as the cylinder was traversed in the flow direction, for five left–right locations. The five left–right locations include two locations on the left (locations 1 and 2), one approximately at the glottal center (location 3), and two locations on the right (locations 4 and 5). The data were normalized by their corresponding values when the cylinder was traversed to the farthest point downstream from the vocal fold model. Therefore, by definition, a value significantly different from one indicates a significant influence of the presence of the cylinder on the sound pressure amplitude. During the course of each experiment, the mean upstream pressure was manually kept at 3.27 kPa.

For all five left–right locations of the cylinder, the influence on the sound pressure amplitude decreased as the cylinder moved away from the vocal fold model and was less than 10% for cylinder locations $x > 3$ mm [Fig. 3(a)], which compares with a maximum glottal opening width of about 3 mm in the left–right direction. For location 3 at the glottal center and location 5 on the right, this region of negligible influence (sound pressure amplitude change less than 10%) extended even further upstream to $x > 0.75$ mm.

Figure 3(b) shows the corresponding fundamental frequency as a function of the cylinder location in the flow direction, for the five cylinder locations in the left–

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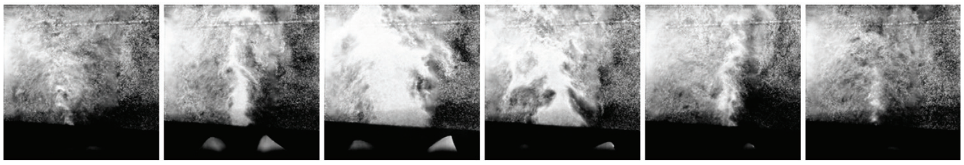
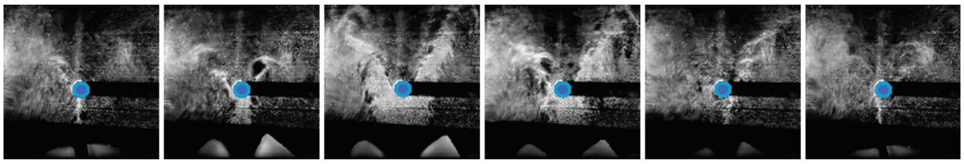
a. without cylinder



b. cylinder at the glottal center



c. cylinder off-center

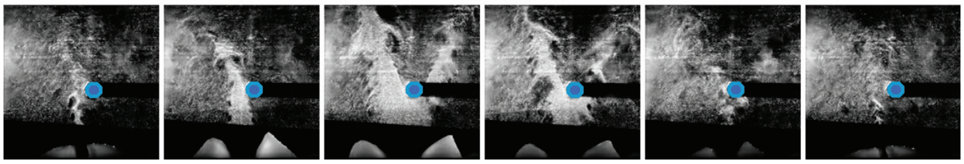


Fig. 2. (Color online) Typical images of the supraglottal flow field in the left–right and axial plane during one oscillation cycle: (a) Without cylinder; (b) cylinder was about at the glottal center ($x = 4.5$ mm, $y = 0$ mm); and (c) cylinder was on the right of the glottal center ($x = 4.5$ mm, $y = 1.5$ mm). The cylinder was highlighted by a hexagon. The black horizontal strip to the left of the hexagon is the shadow of the cylinder as the laser light sheet came from the left side.

right direction. Similar to that of the sound pressure amplitude, changes in the fundamental frequency decreased as the cylinder was traversed away from the vocal fold model. For all cylinder locations $x > 3$ mm, changes in fundamental frequency were within ±2 Hz.

Although not shown in this paper, both the subglottal and outside sound spectra remained qualitatively the same as the cylinder was traversed (except for the tonal sound above 3 kHz in the outside sound spectra, due to jet impingement onto the cylinder).

4. Discussion

The results of this study show that the presence of the cylinder had little influence on the sound pressure amplitude (less than 10% change) and fundamental frequency (less

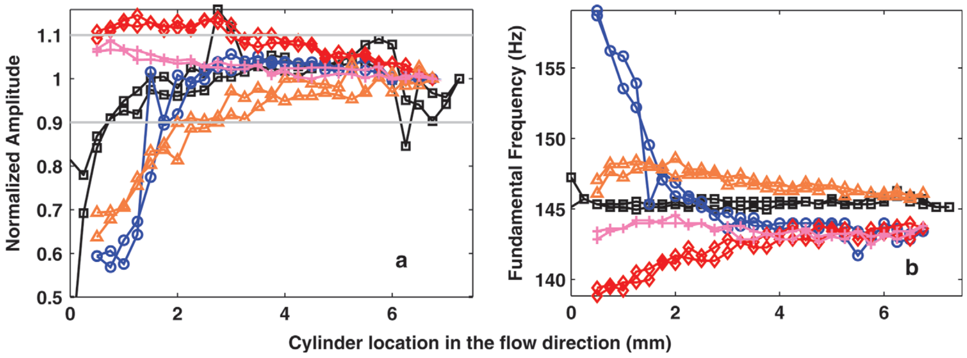


Fig. 3. (Color online) The normalized outside acoustic pressure amplitude (top) and fundamental frequency (bottom) as the cylinder was traversed in the flow direction for five cylinder locations in the left–right direction, ○: cylinder at $y = -2$ mm (location 1); ◇: cylinder at $y = -1.4$ mm (location 2); □: cylinder at $y = 0$ mm (glottal center, location 3); △: cylinder at $y = 1.2$ mm (location 4); and +: cylinder at $y = 2.2$ mm (location 5). The two straight lines in Fig. 3(a) indicate the borderlines of ±10% change in sound pressure amplitude.

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than 2 Hz change) when the cylinder was located further than 3 mm downstream of the glottal exit ($x > 3$ mm or one maximum glottal width). For cylinder locations in the jet center or outside of the jet, this region of negligible influence extended further upstream to 0.75 mm downstream of the glottal exit ($x > 0.75$ mm or 0.25 times the maximum glottal width).

A rough estimation of the upstream influence of a circular non-rotating cylinder of diameter 1.47 mm (the width of the hexagonal cylinder of this study in the left–right direction) in a uniform potential flow suggests that a change in upstream velocity greater than 10% is induced at locations within 1.59 mm upstream of the cylinder. Therefore, the results of this study indicate that disturbances in the part of the supraglottal flow field that was approximately 1.4 mm downstream of the glottal exit had little influence on the low-frequency sound production. In this study, the jet flow during most part of the oscillating cycle persisted for at least 6 mm downstream of the glottal exit before it broke down into turbulence. Therefore, this region of negligible influence included a significant part of the jet region as well as the turbulence region further downstream.

The fact that significant alterations in supraglottal flow structures did not lead to significant change in sound production indicates that jet instabilities, the detailed vortical structures, and transition to turbulence in the supraglottal flow field may only have little influence on the low-frequency vocal fold vibration and sound production.

Previous studies have suggested possible upstream aerodynamic feedback mechanisms by which asymmetric downstream vortical structures can induce deflection or oscillation in upstream shear layer or flow separation patterns (Thomas and Chu, 1989; Neubauer *et al.*, 2007). However, the observed small influence of the disturbed supraglottal flow field in this study seems to indicate that such aerodynamic feedback mechanisms either did not induce significant aerodynamic changes in the upstream flow field or, if they did, such aerodynamic changes were not able to induce significant acoustic changes.

Such small influence is consistent with our experience with excised larynx experiments, in which no noticeable changes in phonation were observed when the flow was disturbed in the supraglottal region. Also, recent studies have shown that predictions from phonation models using low-dimensional flow models (both one-dimensional and two-dimensional) compared well with experiments, despite the many complex flow phenomena being neglected in these models (Pelorson *et al.*, 1994; Zhang *et al.*, 2002; Ruty *et al.*, 2007; Kaburagi and Tanabe, 2009), indicating possibly a minor role of the supraglottal flow structures in phonation.

We would like to emphasize the importance of more systematic study to further clarify the acoustic relevance of supraglottal flow structures in more realistic phonatory conditions. The vibratory behavior of the physical models used in this study was slightly different from that observed in human. It is unclear how the observations of this study would be affected under vibratory patterns typical of humans or different pathological conditions. Also, when close to bifurcation boundaries, it is possible that the vocal fold vibration and sound production may be more susceptible to disturbances in supraglottal flow structures. Further studies are needed to quantify the influence of the supraglottal flow on phonation in more realistic phonatory conditions. If the observation of this study can be generalized to more realistic phonatory conditions, it will then suggest that the supraglottal flow structures do not need to be accurately resolved in phonation models for predictions of reasonable accuracy (e.g., 10% difference in amplitude and a few hertz in phonation frequency).

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