Influence of Vortical Flow Structures on the Glottal Jet Location in the Supraglottal Region

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Summary: Within the fully coupled multiphysics phonation process, the fluid flow plays an important role for sound production. This study addresses phenomena in the flow downstream of synthetic self-oscillating vocal folds. An experimental setup consisting of devices for producing and conditioning the flow including the main test channel was applied. The supraglottal channel was designed to prevent an acoustic coupling to the vocal folds. Hence, the oscillations were aerodynamically driven. The cross-section of the supraglottal channel was systematically varied by increasing the distance between the lateral channel walls. The vocal folds consisted of silicone rubber of homogenous material distribution generating self-sustained oscillations. The airflow was visualized in the immediate supraglottal region using a laser-sheet technique and a digital high-speed camera. Furthermore, the flow was studied by measuring the static pressure distributions on both lateral supraglottal channel walls. The results clearly showed different flow characteristics depending on the supraglottal configuration. In all cases with supraglottal channel, the jet was located asymmetrical and bent in medial-lateral direction. Furthermore, the side to which the jet was deflected changed in between the consecutive cycles showing a bifurcational behavior. Previously, this phenomenon was explained by the Coanda effect. However, the present data suggest that the deflection of the jet was mainly caused by large air vortices in the supraglottal channel produced by the flow field of previous oscillations. In contrast, for the case without supraglottal channel, the air jet was found totally symmetrical stabilized by the constant pressure in the ambient region. The emitted sound signal showed additional subharmonic tonal peaks for the asymmetric flow cases, which are characteristics for diplophonia.
Key Words: Human phonation–Synthetic vocal folds–Fluid-structure interaction–Supraglottal flow field–Self-sustained oscillations–Coanda effect.

INTRODUCTION

In investigations of human phonation using both excised and synthetic larynx models, an asymmetric flow field forming within the supraglottal duct was detected a long time ago. In general, the jet that arises from the glottal gap was found to lie not symmetrically in the supraglottal flow region but skewed in a medial-lateral direction. This behavior could be reproduced using all types of models containing excised canine, human, or synthetic larynges, including static,[1–4] externally driven,[5–8] or flow-induced oscillating artificial vocal folds.[9–12] Especially in static models, the jet separates from one vocal fold and attaches to the other entering the supraglottal area skewed from the centerline of the channel. The occurrence of the asymmetry was explained by the Coanda effect, which was described by Coanda[13] in a U.S. patent. This effect can be observed in flow cases containing a jet entering a volume with resting fluid. If a convex surface is connected tangentially to the nozzle and the curvature is below a specified amount, the arising jet attaches to this surface[14] as can be seen in Figure 1. These jets have the ability to follow the surface much further than attached flows, that is, around wing profiles. Because of the constant pressure in the resting fluid, the jet does not have to flow against a positive pressure gradient as is the case in flows around wings. For the Coanda effect, the separation of the attached jet is the result only of the deceleration of the jet due to the wall friction, which plays only a minor role in flow separation from wing surfaces. In the area of experimental research of human phonation, asymmetric flow phenomena have been widely described and explained by the Coanda effect.

The effect was first proposed to occur during phonation by Teager and Teager[15,16] and Kaiser.[17] Since then, a discussion has taken place on whether the multiply observed asymmetry of the flow is the result of the Coanda effect. Using static models, experiments showed that the asymmetry of flow under stationary inflow conditions is caused by the Coanda effect but needs a certain period to develop after the inflow has been switched on.[3,18,19] Applying unsteady inflow conditions similar to time devolutions of the flow rate during human phonation, an asymmetry could not be observed. Hence, it was concluded that the asymmetric flow does not occur during the dynamic process of phonation due to the long time needed for development.

A very detailed analysis of the Coanda effect in glottal models was carried out by Erath and Plesniak[20,21] using a 7.5 times larger static model of the vocal folds. Their geometry was based on the M5 model introduced by Scherer et al[1] forming a divergent glottal duct. The inflow was unsteady and periodical with physiological characteristic over time. The flow field was measured within the glottal duct using a phase-averaged particle-image velocimetry (PIV) technique. They found a jet attached to one vocal fold in each period according to the Coanda effect entering the supraglottal area skewed

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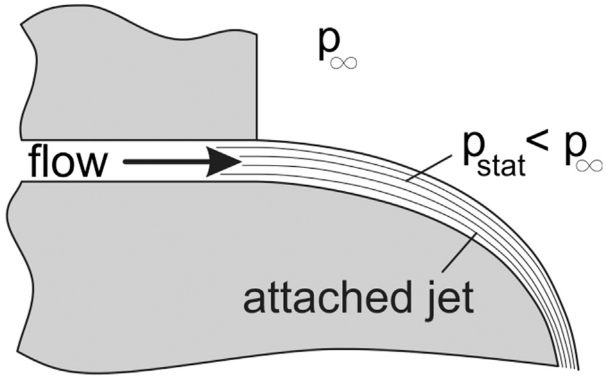

FIGURE 1. Schematic of the attached jet flow due to the Coanda effect with p_∞ displaying the ambient and p_{stat} the static pressure.

against the centerline of the channel. This phenomenon appeared for divergent angles of the glottal duct of 10° and 20° but vanished for 40°, which is also typical for the Coanda effect. Furthermore, for the asymmetric flow cases, a bimodal behavior of the jet could also be seen: the jet was attached to both vocal folds during the experiments, changing sides stochastically from cycle to cycle.

In a recent study, Erat and Plesniak[22] also found the Coanda effect with bimodal behavior using a similar setup but with driven vocal folds. The vocal folds moved linearly in a medial-lateral direction and rotationally around a longitudinal axis in the medial surface. Therefore, the models formed a convergent duct during the opening period and a divergent duct during the closing period of a cycle. Moreover, the results showed a sensitivity of the glottal jet due to vortex structures arising in the immediate supraglottal channel during the closing process. Performing principle component analysis on the PIV data in a later study, Erath and Plesniak[23] found, however, that the rotational motion of the vocal folds is not the dominant mechanism for the development of an asymmetric jet but is suspected to increase energy to higher frequency components in human phonation.

In addition to the above-mentioned works, an asymmetric flow field was also detected in studies applying flexible self-oscillating vocal fold models.[9,10,12] Moreover, a bimodal behavior of the cycle-to-cycle changes of the jet attachment could also be reproduced.[11] However, owing to the limited optical access to the glottal gap, it was not possible to identify the Coanda effect as the cause. Only the asymmetry of the jet in the immediate supraglottal region could be seen. But the studies addressing directly the Coanda effect concentrated mostly on the flow separation within the glottis. The influence of flow field structures in the supraglottal channel was not taken into account. Although Erath and Plesniak[22,23] reported an intracycle jet flip-flopping and explained this by vortices rolled up in the shear layers of the jet. A similar behavior was also reported by Neubauer et al[9] and Becker et al.[11] However, the mentioned studies were performed using a supraglottal channel, which had the same or similar dimensions as the channel upstream of the glottis.

Only Neubauer et al[9] used a channel with much larger dimensions as the glottal channel to concentrate the seeding particles in the immediate supraglottal region. Hence, this case is comparable to a case without a supraglottal channel. However, they considered the asymmetric jet to be a result of an asymmetric mounting of one vocal fold yielding asymmetric oscillation patterns. In a study by Pickup and Thomson,[24] a test setup involving flow-induced oscillating vocal folds without any supraglottal flow boundaries was used. They performed experiments to investigate the influence of different material properties of the synthetic vocal folds forming the glottal duct on the dynamic structural and flow field behavior. In their conclusion, they explained the asymmetric glottal jet location by the asymmetric oscillation pattern of the vocal folds, which is on the other hand, a result of the different values of stiffness of the two vocal folds.

Nevertheless, the flip-flopping of the jet suggests an influence of the supraglottal flow field on the pulsating jet. However, large-scale structures developing during the closed phase within the oscillation cycle and their impact on the location of the pulsating jet have not yet been studied.

The present study addresses the asymmetric behavior of a pulsating jet during the dynamic fluid structure interaction

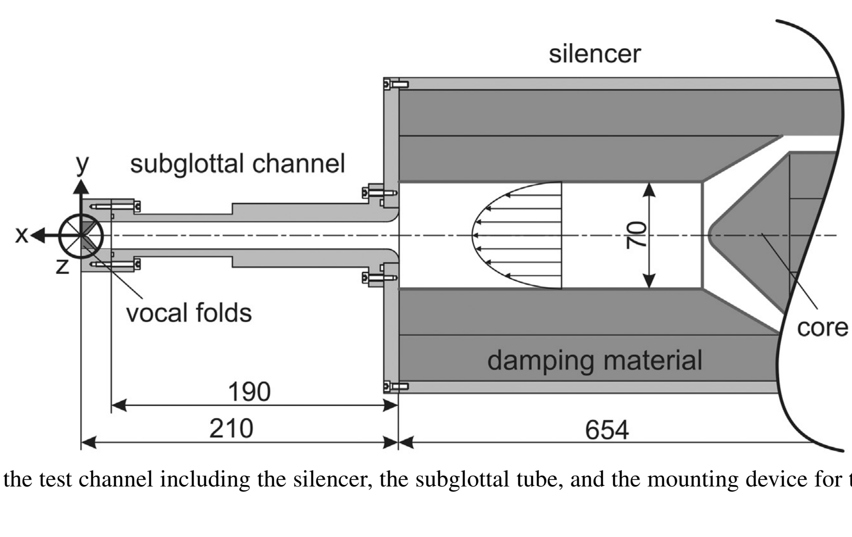

FIGURE 2. Schematic of the test channel including the silencer, the subglottal tube, and the mounting device for the vocal fold models. All dimensions in mm.