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Numerical study of volume sources associated with displacement flow during phonation

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The glottal displacement flow is a flow induced by the motion of the vocal folds walls in the absence of a lung pressure. This source may eventually contribute to the radiated sound, in particular during glottal opening. The displacement flow source strength was numerically computed for a time-varying orifice geometry, and decomposed into monopole and dipole components. The air mass entrained by the dipole moment was found to have a length equivalent to the glottal dimension based on the net force exerted on the fluid by the vocal folds wall. The dipole moment, associated with asymmetric geometries and/or motion, is significant even for the case of motion of an incompressible deformable solid with constant volume, but having a time-varying shape.

1 Introduction

Pressure-driven glottal flow is the source of voice. There have been numerous studies of phonatory aerodynamics [1]-[5], as well as modeling of the vocal fold oscillations [6]-[7], and flow-acoustic interactions [8]-[9]. However, the so-called displacement flow has received little attention because its influence is regarded as small with respect to that of the lung driven flow. Zhao *et al.* [10] discussed a volume flow displaced by vocal folds oscillation in the absence of a mean flow. Because the flat vocal folds profile was assumed throughout the cycle, only the monopole contribution was considered.

The goal of this study was to investigate the role of the oscillating flow displaced by the periodic motion of the vocal folds walls in the absence of a mean lung pressure. Motion of the vocal folds without a mean pulmonary flow source is of course not physiologically possible. However, it is worth considering how much sound would be produced by the vocal folds oscillations as a pure volume source, causing a dipole moment induced by the inferior-superior asymmetric geometry of the vocal folds. Possible contributions to the radiated sound were considered when the viscous and unsteady effects are significant for small glottal opening area. In the present study, numerical simulations were performed to quantify the contribution of the displacement flow to the pressure-driven flow field, and the radiated sound. The monopole and dipole source strengths associated with the motion of the orifice walls were investigated.

2 Numerical model

The mesh geometry for numerical simulation was generated based on the M5 model from a previous study [11]. Simulations were conducted using a commercial software package, Fluent. The flow was assumed to be incompressible and viscous, with air as the working fluid. A converging orifice configuration was used, with an included angle of 30°. Fig. 1 shows the dimensions of the model which has an axisymmetric two-dimensional inferior-superior profile. Because the displacement flow field is local around the orifice, the mesh density was increased around the glottal orifice. There was a total of 35958 cells. One third of the cells were clustered near the orifice for a mesh density of 225 cells/mm^2. Triangular cells were employed for mathematical stability and accuracy. This ensured that cell size skewness, angle skewness, edge ratio, and aspect ratio were kept lower than 0.2 [12]. A rigid body vocal folds motion was imposed with a sinusoidal wall velocity, v_{wall}, in x direction, given by

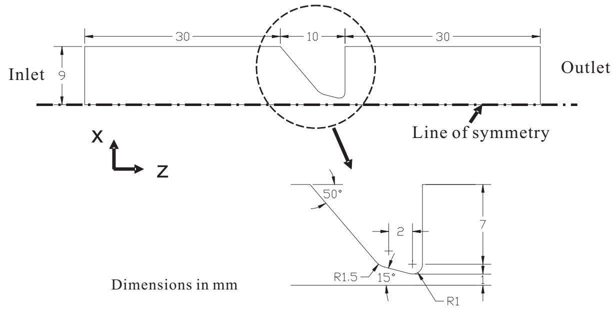

Fig. 1 Geometry of the numerical model for the displacement flow study. Simulation conditions are laminar flow, Δp=0, atmospheric pressure at the inlet and outlet boundaries, and rigid wall motion (f=100Hz).

$$v_{wall} = -\omega \cdot \left(\frac{D_{\max} - D_{\min}}{2} \right) \cdot \sin \omega t \qquad (1)$$

where ω is the angular frequency (ω=2πf) with f = 100 Hz, D_{max} and D_{min} are the maximum and minimum distance from the line of symmetry which are 1 mm and 0.1 mm, respectively. The motion history was implemented using User Defined Functions (UDF) in Fluent. The interior mesh was dynamic with automatically adjusted size as the wall moved. The flow was laminar, and atmospheric pressure was imposed as the boundary condition at the inlet and the outlet. A 2nd-order implicit time marching scheme was used with a fixed time step of 10^{-5} sec for $0 < t < 0.5$. The flow field reached a steady state after approximately 5 cycles. Simulation results are shown for $t > 0.1$, after steady state was reached. It should be noted that $0 < t <$ T/2 indicates the closing phase, and that T/2 $< t <$ T indicates the opening phase. This is opposite to the convention used for the experiment because the simulation started with the orifice fully opened.

3 Simulation results

The time-varying pressure distribution in the glottal channel is shown in the right column of Fig. 2. The pressure was greater than atmospheric during the first half of the closing phase (t = 1/10T). It was lower than atmospheric over the second half of the closing phase (t = 1/10T). The pressure field driven by the motion of the wall is consistent with expectations. Air is accelerated and pumped out of the domain over the first half of the closing phase. Air was then ingested and decelerated by the wall decelerating to stop at t = 1/2T. The pressure field evolution was reversed over the opening phase, i.e., it was below atmospheric for the first half of the opening phase, and above atmospheric pressure for the second half.

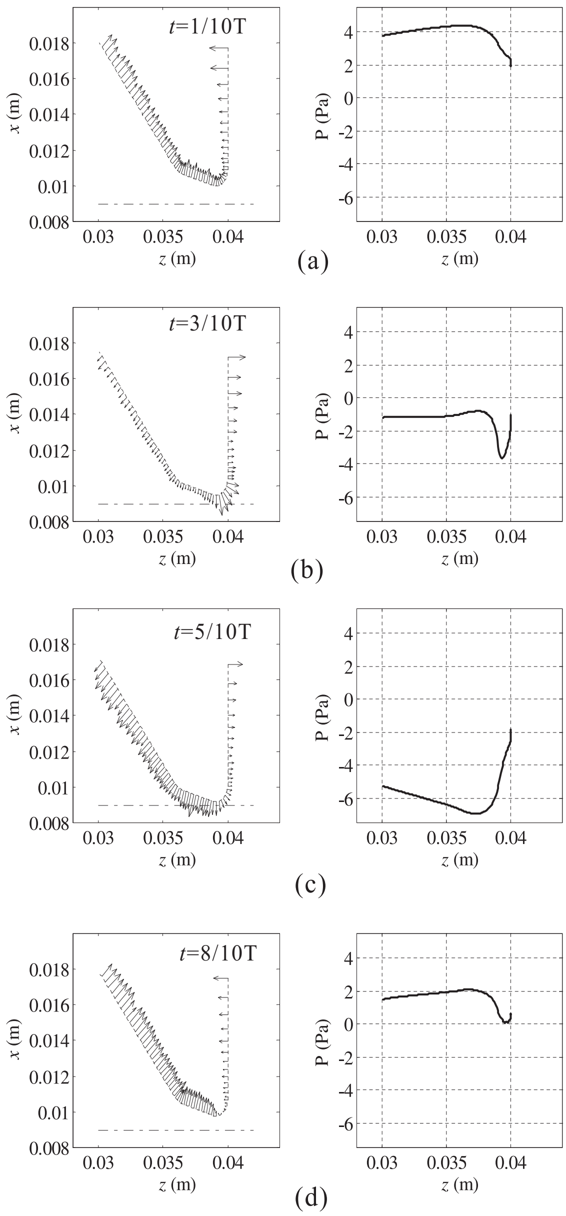

Fig. 2 Force and pressure distributions on the vocal fold induced by periodic folds motion. Figures on left and right column show force vector and pressure distribution acting on the wall, respectively: t = (a) 1/10T; (b) 3/10T; (c) 5/10T and (d) 8/10T.

Based on the pressure profile, the net force acting on the wall, f_w, and the net force acting on the fluid along the inferior-superior axis, F_{net}, are computed as

$$f_w = -p\widehat{A}, \tag{2}$$

and

$$F_{net} = -\sum_A f_{w,z} = \sum_A p\hat{A}_z \ , \tag{3}$$

where $\hat{A}$ is the area vector along the outward unit vector normal to the surface. The force vector is positive in the positive z direction. Fig. 2 (left column) shows the variation of the wall force acting on the vocal fold over the cycle. The subglottal surface of the fold for $z < 0.04$ clearly experiences a higher force field. The fold tip experiences a relatively large change in force magnitude. The resulting

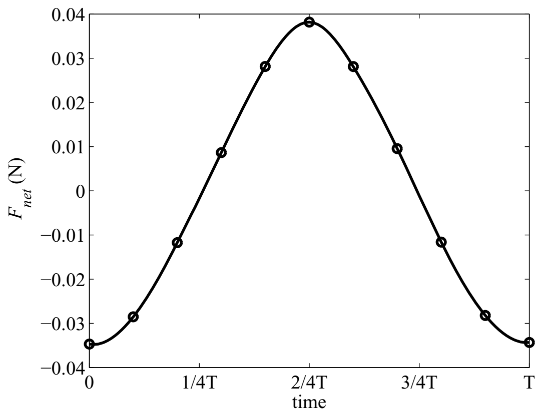

Fig. 3 Net force acting on the air (F_{net}) versus time. Note that $0 < t < T/2$ is the closing phase and T/2 , t < T is the opening phase. The magnitude of the force is largest when the glottal opening is minimum, i.e., when the glottal orifice is almost closed (t =T/2).

net force acting on the surrounding fluid is shown in Fig. 3. The moving fold exerted a positive force on the air over most of the closed phase, $T/4 < t < 3/4T$, and a negative force during the opening phase. The net force was largest when the glottal opening was at its minimum.

The time-varying inlet, outlet and net volume flow rate were obtained from the integration of the streamwise velocity over the channel cross-section as

$$Q(t)\big|_{inlet,outlet} = \int u_z(t)dx\,\big|_{inlet,outlet} \tag{4}$$

and

$$Q_{net}(t) = Q_{outlet}(t) - Q_{inlet}(t)\,. \tag{5}$$

Note that $Q(t) < 0$ means a volume flow along the negative z direction. As shown in Fig. 4, air mass exits the control volume across each boundary, i.e., $Q_{inlet} < 0$ and $Q_{outlet} > 0$, during the closing phase. The flow is reversed during the opening phase. Therefore, Q_{net} was positive during opening and negative during closing. As expected from the sinusoidal motion of the folds, the time-averaged net flow rate, of course, was zero ($\int Q_{net}$(t)= 0).

The flow rates at the inflow and outflow boundaries are not

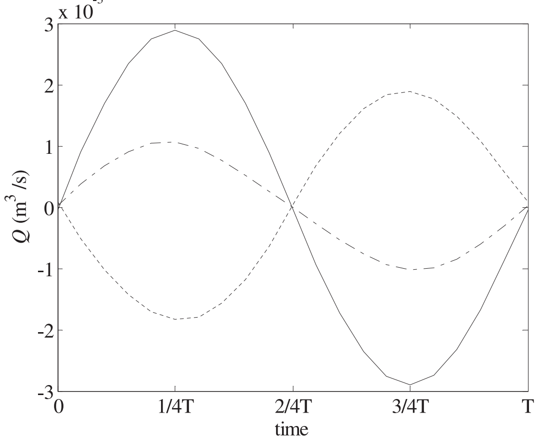

Fig. 4 Volume flow rate through the inlet (Q_{inlet}) and outlet (Q_{outlet}) boundaries and net flow rate (Q_{net}) over one cycle: - - - : Q_{inlet} ; — — — : Q_{outlet}; —— :

equal. The net volume flow can be decomposed into two distinct components: a monopole component, Q_{mono}, and a dipole component, Q_{dipole}. These quantities are defined by

$$Q_{dipole}(t) = \begin{cases} Q_{inlet}(t) - Q_{outlet}(t) & \text{if } Q_{inlet} > Q_{outlet} \\ Q_{outlet}(t) - Q_{inlet}(t) & \text{if } Q_{outlet} > Q_{inlet} \end{cases} \quad (6)$$

and

$$Q_{mono}(t) = Q_{net}(t) - Q_{dipole}(t)\,. \quad (7)$$

Fig. 5 shows the monopole and the dipole flow rate components. The monopole component is a symmetric pulsation which does not exert a net force. On the contrary, the dipole component is due to an asymmetric motion which generates a net force on the air along the streamwise direction. In cases where the geometry is symmetric, the pulsation of the wall would generate only a monopole component, which would be equal to Q_{net}(t).

The relationship between the net force applied by the orifice walls onto the fluid along the streamwise direction, F_{net}(t), and the equivalent dipole source strength, Q_{dipole}(t), can be directly established by introducing an equivalent mass, m_{eq}, equivalent area, A_{eq}, and equivalent length, l_{eq}, as

$$\begin{aligned} F_{net}(t) &= m_{eq} \cdot a(t) \\ &= \rho A_{eq} \cdot l_{eq} \cdot a(t) \\ &= \rho \cdot l_{eq} \cdot d(A_{eq} \cdot u(t)) / dt \\ &= \rho \cdot l_{eq} \cdot \dot{Q}_{dipole}(t) \end{aligned} \quad (8)$$

The equivalent length can be approximated from eq. (8) with F_{net} and $\dot{Q}_{dipole}$ values of 0.04 (N) and 0.88 (m^3/s^2) at t = T/2 as

$$l_{eq} = \left. \frac{F_{net}(t)}{\rho \cdot \dot{Q}_{dipole}(t)} \right|_{t=T/2}, \quad (9)$$
$$\sim 0.0379 \quad \text{(m)}$$

The equivalent length of air mass is approximately twice as large as the anterior-posterior length of the vocal folds at the frequency of interest (100 Hz).

4 Discussion

It may be argued that the vocal folds are incompressible, i.e., they do not change volume as they vibrate. The only way a volume variation would incur would be if the muscle and ligaments moved in and out of an imaginary cylindrical control surface following the main supraglottal and subglottal wind pipes. More detailed flow and vibration measurements using excised animal or human larynges are needed to address the possible monopole contributions.

The magnitude of the acoustic pressure radiated by the displacement flow, p_{disp}, can be roughly estimated as

$$p_{disp} \sim F_{net,rms} / A_{tube} = 0.026 / (0.022)^2 = 53 \text{ Pa} \quad (10)$$

from the root-mean squared amplitude of the net force, where A_{tube} is the downstream vocal tract area, 2.2 x 2.2 cm^2. The amplitude of the radiated sound produced by a physical model of the glottis with a converging shape, p_{gl},

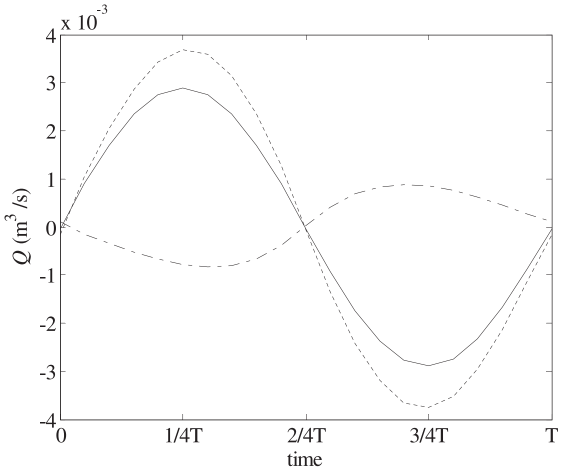

Fig. 5 Decomposition of net volume flow (Q_{net}) into monopole (Q_{mono}) and dipole (Q_{dipole}) volume flow: - - - : Q_{mono} ; — — — : Q_{dipole}; —— : Q_{net} .

in the presence of a mean flow was 150 Pa in a previous study [13]. It is small compared to either the pulmonary pressure for voicing (8 cmH_2O; 780 Pa), or the radiated sound by the pressure-driven glottal flow, p_{gl}, but its contribution to the radiated sound can still be regarded as significant when the glottal opening is small because its magnitude is approximately one third of p_{gl}, and reaches its maximum before the vocal folds are closed.

The profile of the glottal orifice changes during the glottal oscillations. The voice production cycle is often idealized as a two step process: converging during the opening phase and diverging during the closing phase. The exact geometry has certainly an influence on the magnitude of the displacement flow source. While it is hard to evaluate a displacement flow component in the case of a dipole, it may be argued that the dipole strength associated with iso-volume contortions of the vocal folds is intrinsic to the wall motion and independent of the mean flow. The addition of a mean flow through a pressurized inlet flow supply causes a re-distribution of the wall pressure, modifying sound production. The flow resistance of the orifice is then the primary factor that determines the dipole strength.

5 Conclusions

The flow displaced by the motion of the glottal orifice walls in absence of a mean flow was investigated numerically. The numerical model allowed the determination of the monopole and dipole source strengths. The monopole component is a symmetric pulsation which does not exert a net force. The dipole component is due to an asymmetric motion which generates a net force on the air along the streamwise direction. Both components were found to be significant for the orifice geometry considered. Future work is needed to assess the contributions of the “displacement flow” sources in actual voice production.

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