Published in final edited form as:

J Acoust Soc Am. 2007 December ; 122(6): 3659–3670. doi:10.1121/1.2409485.

Unsteady behavior of flow in a scaled-up vocal folds model

Michael Krane^a,

Center for Advanced Information Processing, Rutgers University, Piscataway, New Jersey 08854

Michael Barry^b,

Department of Mechanical Engineering, Rutgers University, Piscataway, New Jersey 08854

Timothy Wei^c

Department of Mechanical Engineering, Rutgers University, Piscataway, New Jersey 08854

Abstract

Measurements of the fluid flow through a scaled-up model of the human glottis are presented to determine whether glottal flow may be approximated as unsteady. Time- and space-resolved velocity vector fields from digital particle image velocimetry (DPIV) measurements of the flow through the gap between two moving, rigid walls are presented in four cases, over a range of Strouhal numbers: 0.010, 0.018, 0.035, 0.040, corresponding to life-scale f_0 of 30, 58, 109, and 126 Hz, respectively, at a Reynolds number of 8000. It is observed that (1) glottal flow onset is delayed after glottal opening and (2) glottal flow shutoff occurs prior to closure. A comparison between flow through a fully open, nonmoving glottis and that through the moving vocal folds shows a marked difference in spatial structure of the glottal jet. The following features of the flow are seen to exhibit strong dependence on cycle frequency: (a) glottal exit plane velocity, (b) volume flow, (c) vortex shedding rates, and (d) vortex amplitude. Vortex shedding appears to be a factor both in controlling flow resistance and in cycle-to-cycle volume flow variations. All these observations strongly suggest that glottal flow is inherently unsteady.

I. INTRODUCTION

This paper presents an experimental assessment of the assumption that glottal flow is quasisteady. The study presents temporally and spatially resolved *in vitro* measurements of the velocity field through a model of the time-varying glottis. The focus is on (1) a description of the test rig and how the flow measurements were made, (2) observations concerning the structure and cycle frequency dependence of the glottal jet, and (3) how this behavior indicates unsteady, as opposed to quasi-steady, glottal flow.

The question of whether glottal flow is inherently unsteady has arisen largely from modeling considerations (see, e.g., Ishizaka and Flanagan, 1972; Story and Titze, 1995; Liljencrantz, 1996). The issue may be stated essentially thus: Does the flow in the glottis respond more or

^aCurrent address: Fluids Research Dept., Applied Research Laboratory, Penn State University, State College, PA 16804.

^bCurrent address: Sunset Park Preparatory School, Brooklyn, NY 11232.

^cCurrent address: Department of Mechanical, Aerospace, and Nuclear Engineering, Rensselaer Polytechnic University, Troy, NY 12180.

PACS number(s): 43.70.Bk, 43.28.Ra, 43.28.Py [AL]

less instantaneously to a change in the transglottal pressure gradient? In other words, is the inertia of air in the glottis negligible compared to that of the airflow in the trachea and the pharynx? Observations of flow through glottis like ducts (Hofmans *et al.*, 2003) show that the steady-state jet structure downstream of the vocal folds is established during a period longer than a typical vocal fold vibration cycle. This observation strongly suggests that glottal flow never reaches a quasisteady state during phonation, and that the inertia of the glottal jet flow is a controlling factor. Hofmans *et al.* (2003) did caution, however, that, because their model glottis walls did not move, the conclusions may not fully apply to phonation. On the other hand, other experimental studies in ducts with moving walls [Mongeau *et al.* (1997), Zhang *et al.* (2002), and Vilain *et al.* (2004)—the follow-on to Hofmans *et al.* (2003)] have so far seemed to support the notion that glottal flow inertia is indeed quasisteady. However, as Krane and Wei (2006) pointed out, for normal phonation, glottal flow may be approximated as quasisteady if (1) the separation point does not move and (2) if the inertia of the glottal jet is neglected. They also suggested that the aforementioned studies seem to demonstrate quasisteady, flow because the data reduction was performed implicitly assuming the pressure is uniform downstream of the separation point, which is equivalent to neglecting the inertia of the glottal jet. Krueger and Gharib (2003, 2005) and Krueger (2005) have shown that the pressure downstream of the formation point is indeed not uniform for an unsteady jet, so that its inertia is clearly not negligible. Clearly glottal jet speed changes continuously though the entire cycle. Is its inertia small enough to be neglected? Answering this question is best accomplished by a study of the glottal jet in a model with moving walls, in which the jet flow is characterized with sufficient spatial and temporal resolution.

In vitro experiments are described here, in order to build upon previous work. This approach to studying glottal flow has a long history, having the distinct advantages [compared to *in vivo* experiments like those of Cranen and Boves (1985) or of Teager (1980)] of repeatability, controllability, and accessibility. The pressure measurements made by van den Berg *et al.* (1957) in static models of the glottis established the foundations of the notion that the Bernoulli effect plays a role in vocal fold vibration. Coker *et al.* (1996) and Mongeau *et al.* (1997), using similar life-scale models, measured both transglottal pressure and hot-wire measurements of the glottal jet issuing from a cast silicone model of the vocal folds that were driven into motion patterns mimicking those observed in phonation. The latter study demonstrated that for low-frequency vibrations studied (not higher than 80 Hz), flow was quasisteady for roughly 60% of the open portion of the cycle. The unsteadiness in the first and last phases of the cycle were attributed to the effects of starting and stopping vortices near the glottis. Barney *et al.* (1999) also conducted hot-wire and pressure measurements of the flow in a tube downstream of a time-varying shutter, but their interest was less in glottal flow *per se* than in the aeroacoustic effect of interaction between the tube exit and the residue of the glottal jet.

Where air velocity was measured in the studies mentioned, hot-wire anemometers were used. While this technique has many advantages, such as ample time resolution, it also has several drawbacks in the study of a spatially and temporally evolving glottal flow. First, it is an inherently invasive procedure, thus modifying the flow it measures, especially in confined spaces. Second, the measurement is limited to the small region occupied by the wire. For

these reasons, it is not possible for a hot-wire to measure snapshots of the entire flow; its spatial structure must be inferred by performing multiple measurements in many locations and ensemble averaging the results. If the jet's structure is unsteady and does not develop repeatably in phase with the wall motion, ensemble averaging must be done carefully to ensure realizations of like behavior are averaged together. In addition, the use of ensemble averaging precludes study of cycle-to-cycle variations in volume flow.

More recently, several different approaches have been taken to characterize glottal flow and assess the degree to which it is quasisteady. Zhang *et al.* (2002) measured the acoustic volume flow far away from the model glottis while transglottal pressure was also measured. The results of this study were interpreted to indicate that the flow through the model glottis is in fact quasisteady, but neither this nor any of the previous studies presented velocity field measurements with sufficient temporal and spatial resolution to address whether glottal jet inertia can be neglected. Deverge *et al.* (2003) and Vilain *et al.* (2004) studied the dynamics of glottal flow using measurements of pressure in a scaled-up model of rigid vocal folds while one of the folds was in motion. These measurements were compared to predictions of the pressure using approximate aerodynamic models. These comparisons showed that, when the glottal gap is small, viscous forces and the unsteady motion of the vocal fold walls predominate. In other words, just after opening and just before closure, the steady Bernoulli equation is not sufficient to predict glottal volume flow. These results are consistent with those of Mongeau *et al.* (1997), which advocated the validity of quasisteady flow in the middle of the cycle, but not during flow initiation and shutoff. Krane and Wei (2006) showed that these intervals of inherently unsteady flow comprised a larger fraction of the cycle as cycle frequency increased. Taken together, these results imply that frequency dependence of the jet flow in the middle interval of the cycle would indicate that glottal jet inertia is non-negligible.

For the current study, a series of experiments was designed in order to address the above mentioned issues using precise measurements of the velocity field of a flow through a time-varying duct, which mimics the motion of the vocal folds. Digital particle image velocimetry (DPIV) measurements were made of the flow, providing a series of snapshots of the velocity field in the plane of symmetry. The model was scaled up and used water as the working fluid in order to reduce the aerodynamic and vocal fold wall motion time scales so that these motions can be resolved using standard video framing rates. These measurements were taken over several realizations of a single oscillation cycle. Four oscillation frequencies were studied in the expectation that as the oscillation frequency increases, the relative importance of unsteady effects also increases. Three types of information are presented. First, inspection of the velocity fields provides information about the evolution of the flow's spatial structure. Second, the waveform of peak velocity at the glottal exit plane allows an assessment of the relevant dynamics during each phase of the cycle, identification of the relevant aerodynamic time scales, and how these vary with cycle frequency. Finally, the relevance of this information to voice production can be obtained from the volume flow at the glottal exit plane. Specifically, the correlation of the volume flow waveform shape to wall motion and particle velocity, and how these vary with frequency, allows further identification of the aerodynamic mechanisms that are likely to most affect the production of voiced speech sounds.

II. EXPERIMENTAL DESIGN

The experimental setup described here was designed to obtain temporally and spatially resolved measurements of the glottal flow velocity field. Digital particle image velocimetry (DPIV), a noninvasive optical technique, was used to obtain these measurements on the glottal midplane while the model vocal fold walls are in motion. In order to obtain temporal resolution at standard video framing rates (<15 image pairs per second) used by DPIV, it was necessary to use a scaled-up model. The test model was sized using dynamic similarity by matching the Reynolds and Strouhal numbers that occur in real speech. In addition, the model was designed for maximum optical access, as described below.

Two steps were taken to slow the model flow down from that which occurs at life scale. First, the model was scaled up approximately ten times life size, which also improves spatial resolution. Thus, the ratio of model length scale d_M to life length scale d_L is 10. Second, water was used as the working fluid, so the ratio of model kinematic viscosity ν_M to that of air (ν_L) is roughly 1/15. By matching the Reynolds number Ud/ν , where U is the velocity scale and d the minimum glottal width, the model flow speed is 150 times smaller than the life scale flow. By further matching the Strouhal number $L/(UT)$, where T is the time scale of the wall motion and L the glottis axial length, the model time scale is 1500 times that of life scale. For example, in the scaled up, water model flow equivalent to a 100-Hz life-scale vocal fold vibration (period 0.01 s), the model vocal fold vibration period is 15 s. At a 15 Hz sampling rate, it is then possible to obtain 150 snapshots of the fluid motion during an oscillation cycle.

A. Test model

The test rig consists of an optically accessible model vocal tract, through which two rigid model vocal folds insert and are made to move perpendicular to the tract axis by stepper motors. A sketch of the test rig is shown in Fig. 1. The entire vocal tract model is immersed in the Open Water Channel Facility at Rutgers University (see Shah *et al.*, 1999; Hsu *et al.*, 2000). The side and bottom walls of the rectangular cross-section water channel test section (6.1 m long $\times$ 55 cm wide $\times$ 1.22 m deep) are 1.27-cm-thick glass panes, allowing optical access. The water channel pumps are set to a constant speed, and the water flows around the test rig—not only around the sides, but also the top and bottom.

By placing the model vocal tract in the steady flow so that the water flows around it, an essentially constant pressure gradient boundary condition is obtained. In other words, the pressures at the model vocal tract inlet and outlet are not only uniform, but a positive pressure difference is also maintained throughout the cycle. The pressure difference arises because the vocal tract model is essentially a bluff body. When the glottis is closed, the flow is deflected around the inlet and a wake is formed. The upstream deflection results in a high pressure at the inlet, while the wake flow ensures a low pressure at the outlet. As a result, a pressure difference between the fluid on either side of the model vocal folds is produced when the glottis is closed, just as in the real system. When the model glottis is opened, not more than 4% of the incident flow passes through the glottis. The glottal flow is then but a small perturbation to the bulk flow around the model, ensuring that the pressure distribution is not significantly altered. What alterations to the pressure distribution do occur are

consistent with those that occur in the vocal system—when the glottis opens and flow through the model vocal tract is initiated, the model subglottal pressure accordingly decreases. However, because the bulk flow pattern around the model is maintained, the model subglottal pressure is always greater than the supraglottal pressure, maintaining the pressure gradient.

Figure 2(a) shows a photo of the test rig in the water channel, looking upstream. The model vocal folds can be seen, as well as the motor drives located just above the test rig. The test rig was fabricated from clear cast acrylic and is composed of the 28×28 cm square cross section duct 3.66 m in length, and the rigid model vocal folds. The vocal folds are placed 45.7 cm downstream of the test section inlet, so that the distance between the glottal exit plane and the model outlet is approximately 3.08 m.

The model folds were fabricated to a 6.35-cm-radius half-circle shape and measure 14×12.7×28 cm³ (transverse, axial, and height dimensions, respectively). A photo of a model vocal fold is shown in Fig. 2(b). The target maximum glottal gap used in the experiments was 2.88 cm. Small gaps (~1.3 mm) were allowed between the top and bottom duct walls and the top and bottom of the vocal fold models to allow free travel and prevent wear due to friction between the walls and the moving model vocal folds. Similarly, small gaps of similar dimension were allowed between the side walls and the vocal fold model.

The experimental design also attempts to preclude artifacts from strongly affecting the flow in the glottal region. First, the water channel is set to run at an incident flow speed of roughly 14 cm/s, slow enough that only standing waves, of less than 1 mm in height, appear on the free surface. Second, it should be emphasized that the model vocal tract was completely immersed, so the water flowed around the top of the model, as well as the bottom and sides. Second, the model vocal tract is suitably long (see below) to ensure that any wake fluctuations at the model outlet have minimal effect on the flow in the model glottis region. Third, flow through the gaps between the vocal fold model and the side, top, and bottom walls was minimized. The importance of the latter two effects was determined using dye visualization and DPIV measurements downstream of the model vocal folds when closed, a condition when both the leakage flow and any upstream effect of the model wake should be maximum. Leakage flow was found to be minimal using visual inspection of dye in these regions using dye. In addition, DPIV measurements of the flow downstream of the vocal folds, when the folds were in the closed position, showed that any velocity fluctuations were no greater than the uncertainty of the DPIV measurement (0.16 cm/s) made with the same settings as used in the measurement of the flow during the period when the glottis is open. In other words, velocity fluctuations downstream of the closed model vocal folds due to leakage flow or the upstream effect of the model wake are less than 0.5% of the maximum velocity (28 cm/s) observed when the vocal folds are open.

The model vocal folds are moved using Servo Systems® stepper motors and linear stages such that a single motor step supplies a 0.003 175 mm linear displacement of the vocal folds. A 1.6-mm-thick by 7.62-cm-long stainless steel strip attaches the linear stage to the vocal fold at the stainless steel angle visible in the photo of the model vocal fold. For motion stability, the vocal folds are mounted on two linear bearings, each of which slides over a

2.54-cm-diam stainless steel rod attached to the outer wall of the test section. Because of a slight clearance between the bearings and the mounting rods, the model vocal folds rocked slightly when moved by the motors. As discussed below, this rocking caused some frequency dependence of model vocal fold motion.

B. Data acquisition and reduction

DPIV measurements of the flow velocity field were performed during single realizations of one cycle of motion of the model vocal folds. At each acquisition time step, a velocity field estimate was obtained from a pair of images acquired at a known time delay, typically 1–1.6 ms. The flow was seeded by silver-coated hollow glass spheres (Conduct o-Fil, manufactured by Potter Industries, mean diameter $\sim 10\text{ }\mu\text{m}$). In each 1018×1008 pixel image the seed particles were illuminated by a single 150-ns illumination pulse from a NewWave Research Solo 120PIV dual Nd:Yag laser. Velocity field estimates were performed by applying a cross-correlation technique (see below) to two successive images. Image pairs were acquired at 15 Hz using a Redlake Mega-plus ES-1.0 digital video camera (8-bit resolution) operating in triggered double exposure mode.

Image acquisition, illumination, and model vocal fold motion control were coordinated using a Berkeley Nucleon-ics BH-555 waveform generator, as shown in Fig. 3. In the figure, T is the period of the image pair acquisition cycle (1/15 s) and t is the time delay between acquisition of each image in the image pair. This time delay varied from case to case (1–1.6 ms) but was chosen so that particle displacements were no greater than 8 pixels. In each acquisition cycle, two trigger pulses are sent to the laser, and a single pulse is sent to the camera. The camera needs only a single pulse when operating in triggered double exposure mode, in which the camera shutter opens twice in an acquisition cycle. The laser triggering is timed so that one each of the 150-ns laser pulses illuminates the field during the two shutter openings. Motion control of the model vocal folds was synchronized to the DPIV acquisition using the BH-555 waveform generator, which sent a trigger pulse to the motion controller during the first image pair acquisition cycle. To ensure that the whole flow evolution in a single glottal cycle was captured, the motion controller was set to wait for 200 ms after image acquisition began before initiating the motion.

Estimation of the velocity field was obtained from image pairs using a two-pass cross-correlation technique (Hsu, 2000; Hsu *et al.*, 2000). The first pass used a 128×128 pixel interrogation window to obtain the average displacement for the window, to the nearest pixel. The second pass used a smaller interrogation window of 64×64 pixels to fine tune the estimate to subpixel precision. Images were cropped prior to processing so that they were centered vertically about the axis of symmetry. The processing program output provides, for each time step, a representation of the velocity vector and vorticity fields in the plane of the light sheet. After cropping the image, the measurement region is discretized into a 58×59 grid on which the velocity and vorticity are computed from the cross correlation of the illuminated particle patterns between the two images in each image pair.

III. RESULTS

A. Cases studied

Because this study is concerned with the frequency dependence of the flow, measurements were taken for four values of open time T_o . Dynamic similarity was obtained by matching Reynolds number of 8000, based upon a life-scale jet speed of 40 m/s, a glottal gap of approximately 3 mm, a kinematic viscosity of $1.5 \times 10^{-5} \text{ m}^2/\text{s}$ for air, a Strouhal number $L/(U_2 T_o)$ based upon the same flow speed, a glottis length of 1.3 cm, and the vocal fold oscillation period. Note that $f=1/(2 T_o)$, assuming that the vibration period $T=2 T_o$. In other words, for purposes of constructing a life-scale equivalent frequency, the open quotient (fraction of cycle that glottis is open) is taken to be 0.5. The four frequencies studied, in life scale, are $f_{ls}=30, 58, 109$, and 126 Hz , corresponding to $St=0.01, 0.018, 0.035$, and 0.040 , respectively. This range of frequencies allowed acquisition of from 124 to 512 image pairs per open phase to be taken, depending on the oscillation frequency studied. For each cycle frequency studied, ten realizations of a single cycle of wall motion were acquired.

The target wall motion was a uniform speed of opening, then closing, the maximum opening occurring at halfway through the open phase of the cycle. The acceleration of the motors was set to the minimum allowed by the hardware, 1.27 cm/s^2 (4000 steps/s^2). Figure 4 shows the wall motion for the four St studied: the closest distance between the centerline and each model vocal fold, normalized by the target maximum distance, versus the percent time the glottis is open. The lowest frequency case most closely approximates a straight-line motion, with some rounding at opening, as the walls reverse direction, and just before closing. This rounding becomes more pronounced as the cycle frequency increases. In addition, it can be observed that the opening is not entirely symmetrical, and that the asymmetry is greatest for the slowest motion. The dependence of the wall motion on cycle frequency is due to the slight clearance between the bearings and the mounting rod, as described above. When the vocal fold motion is initiated, or when it changes direction, a slight rocking occurs, and this rocking is manifested differently for different wall motion speeds.

As a reference case, the steady-state flow through a fully open glottis was measured. The steady state flow was allowed to develop for several minutes after the glottis was opened. A jet flow was observed to cling to one or the other wall, occasionally switching sides, due to the Coanda effect. The maximum speed in the narrowest part of the glottis was measured to be 28 cm/s .

B. Evolution of spatial structure of flow

Figure 5 shows a typical set of images from the $St=0.035$ case, corresponding to a life-scale fundamental frequency of 109 Hz . Each of the four images shown is composed of the measured velocity field superimposed on the corresponding raw image so that the spatial relationship between the jet structure and model vocal folds may be observed at each time step. In each image the flow is from left to right. For clarity, not all vectors are shown. (Note that in some images, vectors appear as though the flow moves through the model walls. This is an artifact of the manner in which the velocity vectors are estimated: the vectors are

placed at the center of the fine interrogation windows—see Sec. II B. When a correlation window contains mostly wall and only a small amount of flow, the correlation technique correlates on the particle motion in the flow, but places the vector at the center of the window, even if that location is inside the model. In this paper, we largely discuss the motion on the exit plane, where this artifact does not occur.)

Each vector field shown was chosen as an exemplar of an event common to all realizations acquired. The first image (a) corresponds to the opening phase ($t/T_o=0.15$), in which, soon after the glottis opens, a small puff of fluid is released in the form of a weak vortex pair, visible in the velocity disturbance just to the right of the minimum glottal opening. During this phase, a weak suction of fluid into the glottis is evident, along with a retardation of the convection speed of the starting vortex. A jet forms and follows behind the starting vortex, initially increasing in speed and size. The maximum jet width occurs halfway through the oscillation cycle [Fig. 5(b)]. From this point, until roughly three quarters of the way through the time the glottis is open [Fig. 5(c)] the jet speed increases rapidly, then begins to decrease until the flow shuts off *prior to closure* roughly 90% of the way through the open phase. After the jet flow shuts off in this manner, the remains of the jet convect downstream, mixing in an increasingly three-dimensional motion with the surrounding stagnant fluid, as shown in Fig. 5(d).

Several features of flow structure are immediately observable. First, glottal flow separates at roughly the same location, just downstream of the minimum constriction point. Second, starting at the point of minimum glottal width and moving toward the glottis exit plane (right to left in the images), a *vena contracta* is observed. Third, downstream of the minimum jet width, the jet shear layers begin to roll up into vortex pairs. For any sequence, the rate of vortex formation is initially slow, and the amplitude of the vortex pairs decreases as the flow reaches its plateau. As the walls begin to move together ($t/T_o>0.5$) the vortex formation rate increases and the vortices that form become more intense. In addition, the number of vortices formed in a sequence increases with T_o . This behavior reflects the expectation that the rate of vortex formation is expected to scale more strongly on the local flow conditions: speed, acceleration, and shear layer thickness. Fourth, the shape of the velocity profile in the jet changes from a relatively flat shape in the early stages of the cycle, then becoming more “fully developed” in the later stages. This suggests that the viscous resistance of the glottis is different during opening than it is during closure, and that friction plays a stronger role during closure than during opening. The final observation from Fig. 5 is that, strictly speaking, the flow is not turbulent, at least in the field of view shown here, though flow visualization indicates that the jet becomes turbulent further downstream.

Figures 6(a)–6(d) show snapshots of the velocity field at $t/T_o=0.75$ for each of the four St studied. In these images, all vectors are shown in order to see more clearly the vortex pair structure. The spatial structure of the jet flow is roughly similar for all cases. Of particular interest is the comparison of Figure 6(a) with the rest—the jet flow is asymmetrical only in this case, but not nearly as asymmetrical as the steady flow case. It should be pointed out that out of ten realizations, only this one showed this behavior. In any case, comparison of steady and unsteady flow topology suggests that indeed the time for the jet flow to reach a

state where it fully “clings” to one or the other glottal wall is longer than a realistic glottal cycle period, as suggested by Hofmans *et al.* (2003).

C. Behavior of velocity maximum on glottal exit plane

Figure 7 shows waveforms of the maximum axial velocity at the exit plane for $St=0.035$, normalized by the velocity measured in the same location with the glottis fully open and the flow in a steady-state condition. The maximum velocity is considered because it generally denotes the dynamic behavior of the jet. If the centerline velocity was used in an asymmetric jet, it would reveal much less about the jet’s evolution. Of concern here are (1) the correlation of the velocity waveform shape with the behavior observed in the vector fields presented above, (2) the variability of the waveform shape, and (3) frequency variations in waveform shape.

Waveforms for a single realization, a low-pass filtered version of that realization, and the ensemble average of the ten realizations measured are shown in Fig. 7. Filtering was performed by convolving a nine-point triangle window with the original signal. The major difference between the three waveforms lies in the level of the high-frequency fluctuations. In the unfiltered single realization, each of the peaks is associated with the passage of a vortex pair through the exit plane. In the low-pass filtered waveform, these peaks are smoothed. Note that, in the ensemble averaged waveform, vortex-associated fluctuations have largely disappeared, with the exception of that associated with the starting vortex and the vortex pairs that appear during the interval when the velocity is maximum ($0.6 < t/T_0 < 0.8$). While only ten realizations are clearly not enough to converge an ensemble average, this result is suggestive that cycle-to-cycle fluctuations in vortex formation intervals are smallest for the starting vortex and during the interval when vortex formation is strongest.

The first feature of exit velocity behavior that should be noted is that the moment of flow onset does not coincide with the moment at which the glottis opens ($t/T_0=0$). The delay in all cases is on the order of several percent of T_0 . Once the flow onset occurs, the flow rapidly accelerates over a brief interval until it reaches a peak, corresponding to the passage of the starting vortex through the exit plane. After this passage, the velocity rapidly decreases, then rises again as the next vortex passes through the exit plane. The absolute velocity during each subsequent vortex passage is higher than the previous until a plateau level is reached at roughly $t/T_0=0.45$. The fluctuations due to vortex pair passage are reduced during this plateau phase, which is more or less maintained until around $t/T_0=0.6$, after the maximum glottal width is reached ($t/T_0=0.5$). At this point in time the flow accelerates due to a combination of the narrowing glottis and the fact that the flow throughout the model vocal tract has finished its startup transient and has inertia. As the glottis narrows, the velocity increases until roughly $t/T_0=0.9$, at which point the flow undergoes a rapid deceleration. As can be observed, the vortex pairs formed in this phase of motion are formed more rapidly and are more intense than previously, as shown in Fig. 5 and Fig. 6. Note that the exit plane velocity does not go to zero simultaneously with glottal closure because the residue of the jet is still moving away from the vocal folds, even after the glottis is closed, as seen in Fig. 5(d).

The above trends appear consistent with those observed in the hot-wire measurements of flow through (1) a canine larynx *in vivo* (Berke *et al.*, 1989), (2) an excised canine larynx (Alipour *et al.*, 1995), and (3) an *in vitro* model of the glottis (Mongeau *et al.*, 1997). Several discrepancies with these previous results are evident, however. First, a double peak is sometimes observed in the previous work, likely due to flapping of the jet, which may be a consequence of probe interference of the flow. Second, the temporal shape of the waveform is time reversed from that of Alipour *et al.* (1995). Third, the magnitude of the peak velocity, relative to that observed during the remainder of the cycle, is larger in the present experiment than previously observed. It is possible that compressibility plays a more important role during closure in the real glottis than previously understood. In other words, during closure, the incoming air, by virtue of its inertia, causes an accumulation of mass in the subglottal region. In this case, the subglottal pressure is split between driving the transglottal flow and compressing the subglottal air. In the experiment described here, this effect would be reduced because of the relative incompressibility of the working fluid (water), resulting in a higher jet velocity peak. However, it should be pointed out that these previous measurements were taken much farther downstream than the measurements described here, so that the jet, having mixed with the surrounding stagnant fluid, simply has a lower peak velocity. These assertions clearly require further investigation.

Figure 8 shows waveforms of single realizations of maximum jet speed, again on the exit plane, as a function of normalized time, for the four wall cycle frequencies studied. While the overall shapes of the waveforms are similar, the occurrences of the events described above are frequency dependent. The most obvious is the rate of vortex formation: the number of vortices shed per unit cycle decreases with frequency, suggesting that the vortex formation rate does not correlate as strongly to cycle frequency as to the local conditions at the jet formation point: jet speed, local acceleration, and shear layer thickness. Vortex strength also appears to increase with cycle frequency. In addition, several events described above occur earlier in the cycle for lower frequencies: flow onset, reaching the plateau level, acceleration after the glottis begins to close, and the time the maximum is reached. As a result, the normalized waveforms do not collapse, except during their final deceleration phase. However, the maximum value reached in each waveform shows little if any frequency dependence.

These trends do not seem to follow what would be expected if the flow were quasisteady, which, according to Mongeau *et al.* (1997) and Krane and Wei (2006), will only occur in the middle of the cycle, not in the startup or shutoff transient. In that case, the normalized waveforms would be expected to collapse in the middle intervals, but not during the initial and final intervals. Instead, only the shutoff interval shows a collapse, although the modulation of the waveform due to vortex shedding has a strong dependence on cycle frequency. Furthermore, the fact that the vortex behavior does not collapse upon scaling the velocity waveform in the manner presented here also demonstrates that the jet is inherently unsteady.

The mechanism responsible for frequency dependence in the middle interval is partially explained by the inertance of the flow in the vocal tract upstream and downstream of the glottis. This might explain why the jet speed plateau level decreases with frequency: as

frequency of vibration increases, less time is available for subglottal fluid to accelerate, under the action of an identical pressure gradient, while the glottis is opening. However, if that were the whole explanation, then the jet speed would not likely reach a plateau, but would increase until it reached the maximum. In addition, the maximum velocity should also vary with frequency. The measured behavior does not show this trend. Another mechanism is likely involved, perhaps relating to the unsteady development of the glottal jet. This is especially evident in the relation between the passage of the starting vortex through the exit plane and the occurrence of the plateau. This coincidence suggests that formation of the starting vortex modulates volume flow, and hence determines glottal resistance during the startup transient.

Finally, it should be noted that the fluctuations due to vortex formation show the most pronounced cycle-to-cycle variations in both amplitude and phase during the final deceleration near the end of the cycle. Air motion in this phase of the cycle contributes most to power and quality of the voice, suggesting that aperiodic vortex shedding may, in fact, modulate glottal volume flow during this perceptually relevant interval.

D. Volume flow waveform behavior

Volume flow per unit span, obtained by integrating the velocity distribution on the glottal exit plane, is shown in Fig. 9 for the four values of Strouhal number studied. As in the jet speed waveforms, the time coordinate is normalized by the total time the glottis is open, while the volume flow is normalized by the volume flow measured for the fully open, steady state case. As with the jet speed waveforms, the short-time waviness is attributed to vortices passing through the glottal exit plane.

The volume flow waveforms in Fig. 9 all have a similar shape. First, a weak negative volume flow is observed due to the suction of fluid while the vocal folds are opening and the through-flow has not yet been established. The onset of the through-flow is delayed from the opening of the glottis. Once established, the volume flow rises to a maximum that occurs after the glottis begins to close, and then a decline to zero before glottal closure, followed by a weak negative overshoot. Frequency dependence can be observed in the slope of the curve and the time the volume flow maximum level is reached. The slope is higher for low St , corresponding to the maximum occurring earlier in the cycle with lower St . These trends result in the familiar skewing of the volume flow waveform. The maximum value of volume flow shows a strong inverse frequency dependence, rising from 0.78 for $St=0.040$ to 0.87 for $St=0.010$. It should be pointed out that the variation of volume flow peak level across frequency is of the same order of magnitude as the maximum glottal opening variation, shown in Fig. 4. The two effects may thus be related. However, results from a study in which St was varied by changing the channel flow speed, but holding the wall motion speed constant (Barry, 2005), show frequency dependence trends similar to those reported here. This study will be the subject of a future paper.

The occurrence of nonzero flow after glottal closure needs some explanation. The flow in this interval is becoming three-dimensional, given that the cause of two-dimensionality (the through-flow) has disappeared once the model glottis has closed. In such a case, the remnants of the jet undergo turbulent diffusion, an inherently three-dimensional process. It

should be emphasized that the waveforms in Fig. 9 are not volume flow, but volume flow per unit span, computed from the data on a single plane of the flow. As a result, when the flow contains out-of-plane motion, volume *flow per unit span* can go negative. It is clearly not the result of a complete back-flow through the entire glottis, which would occur because the transglottal pressure difference switches sign. In the experimental setup used here, the flow around the vocal tract model would have to contrive a way to generate thrust, unlikely since bluff bodies in a uniform stream are unable to do so.

Perhaps the most surprising behavior shown in Fig. 9 is that the flow shuts off prior to glottal closure, and that this premature shutoff occurs at the same part of the cycle for each cycle frequency studied. The lack of frequency dependence of the volume flow is also surprising. It might be expected that the shutoff flow has a similar frequency dependence to the flow onset, as argued by Krane and Wei (2006). This behavior is, however, consistent with the collapse of the exit plane velocity waveforms (Fig. 8) during the final deceleration of the flow during glottal closure.

A final point concerning the volume flow waveforms echoes the final point made above about the particle velocity behavior: the fluctuations due to vortex formation show the most pronounced cycle-to-cycle variations in both amplitude and phase during the final deceleration near the end of the cycle. Again, this demonstrates that aperiodic vortex shedding does, in fact, modulate glottal volume flow during this perceptually relevant interval.

Whether the results presented here hold in all respects for phonatory flows is certainly an open question, given the differences in vocal fold wall behavior between the real and the model vocal folds. These differences were also present in the models used by Mongeau *et al.* (1997), Barney *et al.* (1999), Zhang *et al.* (2002), Deverge *et al.* (2003), and Vilain *et al.* (2004). Clearly similar measurements performed in a mode in which the walls move in a manner more consistent with the real vocal folds are warranted.

IV. DISCUSSION

The measurements presented above provide evidence that glottal flow is inherently unsteady. The glottal jet generally flows down the center of the passage, except for the lowest frequency studied, in contrast to the steady state, where the jet spent most of its time attached to one wall or the other. The flow does not start until well after the glottis is open. The flow shuts off before the glottis closes. The waveforms of particle velocity and volume flow show that the flow is strongly modulated by vortex shedding, and that this modulation varies with frequency. The low-frequency trends of these waveforms also show strong frequency dependence.

A. Frequency dependence of glottal flow

The unsteadiness of the startup flow was observed by Mongeau *et al.* (1997) and attributed to the action of the starting vortex. The starting vortex observed in measurements presented here was relatively weak, compared to those that followed. The starting vortex acts in combination with (1) the inertia not only of the flow in the model glottis, but that upstream

of the vocal folds, and (2) the displacement of fluid by motion of the model vocal fold walls. The first of these would result in the occurrence of flow onset being proportional to the cycle frequency. In other words, the flow onset occurs at an earlier part of the cycle as the cycle frequency decreases. The latter effect is expected to be important when the glottis is narrow (Deverge *et al.*, 2003; Vilain *et al.*, 2004; Krane and Wei, 2006). The percentage of the cycle during which both effects are important is proportional to the Strouhal number (Krane and Wei, 2006), which is consistent with the measurements presented here.

The startup transient, as well as the middle interval between onset and the maximum flow, also appears to be strongly modulated by vortex shedding. In a sense, this is related to the inertance of the flow downstream of the glottis—the glottal jet. The amount of flow that can be pushed through the glottis for a given transglottal pressure gradient depends on the manner in which the fluid downstream of the glottis is accelerated. The glottal jet flow downstream of the glottis is divided into the high-momentum jet and the relatively quiescent ambient fluid. Because of transverse diffusion, the jet entrains ambient fluid by dragging it along. The rate at which this occurs depends on the flow topology. A purely laminar flow will diffuse slowly due to viscosity, i.e., molecular collisions, alone. If the jet shear layers roll up into vortices, or are turbulent, then the diffusion process is accelerated, and more ambient fluid is dragged along with the jet. Clearly, it takes time to accelerate not only the fluid in the jet, but the ambient fluid as well. Just as clearly, this process, depending as it does on the history of jet structure, is more complex than the acceleration of the fluid upstream of the glottis, which is well understood. This process is currently under investigation.

The part of the cycle after the startup transient and the maximum velocity is generally thought to be quasisteady (Mongeau *et al.*, 1997; Vilain *et al.*, 2004; Krane and Wei, 2006). The results here suggest that it may not be due to its strong frequency dependence. However, quasisteadiness implies that the instantaneous transglottal pressure gradient (not measured here) and the instantaneous velocity are related through the steady Bernoulli equation. Determining whether the frequency dependence of the flow observed in the current experiments is due to the time to accelerate the flow upstream and downstream (even with modifications to account for the unsteady behavior of the jet) will be the subject of future work.

B. Shutoff flow

Perhaps the most striking thing about the behavior of the flow between the maximum velocity and shutoff is that, in the ensemble mean, it appears to have at most a weak dependence on cycle frequency. This behavior is unexpected—the shutoff transient might have been expected to have the same frequency dependence as the startup transient, if it were dominated by the motion of the vocal fold walls, for example (Deverge *et al.*, 2003). In this case the flow would exhibit the same sort of frequency dependence as the startup transient (Krane and Wei, 2006). The fact that the flow does not display frequency dependence suggests that the flow in this interval is governed by processes that are in phase with the motion of the walls.

Deverge *et al.* (2003) showed how viscous blockage of glottal flow may restrict the amount of fluid a given subglottal pressure can pump through the glottis. If the boundary layers on the vocal fold walls are quasisteady (for discussion, see Krane and Wei, 2006), then the degree to which the boundary layers restrict glottal flow will be in phase with the wall motion. In this case, this mechanism may in fact govern the shutoff flow.

However, the hypothesis that viscous blockage governs the flow during shutoff may not completely explain why the flow seems to shut off prior to glottal closure. Premature flow shutoff may also be aided by the increased pressure in the glottis where the folds collide upon closure, as shown in the results of Deverge *et al.* (2003). However, this effect should display the same type of frequency dependence as the startup transient (Krane and Wei, 2006). Because the shutoff behavior appears frequency independent here, friction may, in fact, predominate.

Another possible mechanism for premature jet shutoff relates to the mismatch of momentum between the jet and the flow external to it. In a steady jet flow, a recirculation of the “stagnant” region surrounding the jet occurs. Recirculation is driven by turbulent and/or molecular diffusion of jet momentum, which causes the jet to drag essentially stagnant fluid along with it. This entrainment is strongest near the separation point. Fluid from downstream must be pulled upstream along the walls in order to replace that dragged along with the jet. As the jet injects more momentum into the supraglottal cavity, the recirculation gains more momentum. During closure, the jet momentum flux decreases rapidly. If this decrease is not matched by a comparably rapid decrease in recirculation momentum, the recirculation flow may actually act to pinch off the jet before the glottis closes completely. Observations of the flow during glottal closure also indicate that the fluid external to the jet moves with the vocal fold walls as they close, which may enhance this effect. This additional mechanism for jet shutoff is consistent with and complementary to those proposed by Deverge *et al.* (2003), and is advanced here as a supplement to them.

While the ensemble mean volume flow shows little or no frequency dependence, the variability of vortex shedding in the final stages of the shutoff is clearly an inherently unsteady process. Part of the unsteadiness during this interval is likely due to the weakening of the jet, whose two-dimensional structure dominates the flow while it is strong. During the final moments of glottal flow during a cycle, the velocity fluctuation due to the vortex pairs is at its strongest level compared to the ensemble-averaged velocity, so their inherently unstable dynamics will dominate the flow.

Finally, the volume flow is clearly modulated by vortex shedding, and this inherently unsteady process exhibits perhaps the strongest frequency dependence of all the phenomena discussed here. As the cycle frequency increases, the number of vortices per cycle decreases, and the vortex strength increases. Vortex shedding also impacts voiced sound production through the interaction of the jet with the pharyngeal walls, the source of “breathy” sounds (see Krane, 2005). Clearly, the fact that neither of these contributions scales proportionally to cycle frequency suggests that the glottal jet makes an important contribution to voice perturbations and fluctuations.

V. SUMMARY

Experiments using a test rig that allows time- and space-resolved measurements of flow velocity field in a time-varying model glottis have been presented. The model is scaled up ten times and uses water as the working fluid in order to reduce the model flow time scales by a factor of 1500, allowing good time resolution of the flow at the 15-Hz sampling rate characteristic of the digital particle image velocimetry (DPIV) technique used to measure the velocity field.

DPIV measurements were made for four wall motion cycle frequencies. These frequencies range from (in life scale) 30 Hz to 126 Hz, thus bracketing the normal adult male speaking voice. Inspection of sequences of the velocity vector fields show that for up to the first roughly 10% of the open phase, the glottal flow is inherently unsteady. Once the vocal folds begin to close, the combination of closure and flow inertia combine to accelerate and narrow the jet until roughly 75% of the way through the open phase. During this interval, vortex shedding increases both in the intensity of the vortices shed and in the rate of shedding. After the maximum jet speed is reached, the jet rapidly decays in speed, and the timing of vortex pair formation becomes less synchronized to the wall motion. Finally, the jet shuts off at approximately 90% of the way through the open phase, after which the decaying jet remnants are still present for some time.

The most important findings reported here are as follows:

1. Comparison of the spatial structure of a steady jet flow and the flow that occurs during wall motion shows that the steady state configuration is not reached during a phonation cycle, although some jet asymmetry was observed at the lowest frequency wall motion, supporting the notion that a steady-state glottal jet flow downstream of the glottis is not established during a single vibration cycle.
2. The onset and shutoff of transglottal flow do not coincide with glottal opening and closure.
3. The flow through most of the cycle is strongly frequency dependent, and the strongest frequency dependence is associated with vortex formation.
4. A lack of frequency dependence occurs during the flow shutoff phase: shutoff occurs, on average, at the same point in the cycle, independent of cycle frequency, but
5. the precise shutoff time of a particular realization is influenced strongly by cycle-to-cycle variability in vortex shedding during this interval.

These findings not only suggest that glottal flow is unsteady, they have important implications for understanding how the voice is produced and on fundamental limitations in controlling perturbations and fluctuations. As vocal fold vibration frequency increases, the volume flow waveform skewness also increases, so that the rate of change of volume flow waveform is more intense with increasing frequency. In the past, this skewing has been explained by the inertance of the flow upstream and downstream of the vocal folds, but the current results suggest that the inertance is modified by the unsteady behavior of the glottal

jet. In addition, the occurrence of premature volume flow shut-off means that the steepness of that shutoff gradient is larger than would be estimated by observation of glottal area and the Bernoulli equation. All these unsteady flow behaviors directly affect voice power and quality through their influence on the glottal volume flow waveform. Finally, the variability in jet flow shutoff time may account for naturally occurring perturbations and fluctuations in the voice (Hirschberg, 1992; Lous *et al.*, 1998).

ACKNOWLEDGMENTS

The authors gratefully acknowledge support from Grant No. 1R01DC054642-01 and from the Institute for Deafness and Other Communication Disorders, National Institutes of Health. In addition we would like to thank J. Petrowski for invaluable assistance with the motion control and with model fabrication issues. We would also like to thank N. Krane for assistance in machining the model.

References

- Alipour F, Scherer R, Patel V. An experimental study of pulsatile flow in canine larynges. *J. Fluids Eng.* 1995; 117:577–581.
- Barney A, Shadle CH, Davies POAL. Fluid flow in a dynamic mechanical model of the vocal folds and tract. I. Measurements and theory. *J. Acoust. Soc. Am.* 1999; 105(1):444–455.
- Barry, M. M.S. thesis. Department of Mechanical and Aerospace Engineering, Rutgers University; 2005. Unsteady glottal aerodynamics in a scaled up mechanical model of the vocal folds.
- Berke G, Moore D, Monkewitz P, Hanson D, Gerratt B. A preliminary study of particle velocity during phonation in an in vivo canine model. *J. Voice.* 1989; 3(4):306–313.
- Coker, CH; Krane, MH; Reis, BY; Kubli, RA. Search for unexplored effects in speech production; Proceeding of ICSLP '96; Philadelphia, PA: 1996.
- Cranen B, Boves I. Pressure measurements during speech production using semiconductor miniature pressure transducers: Impact on models of speech production. *J. Acoust. Soc. Am.* 1985; 77(4): 1543–1551. [PubMed: 3989109]
- Deverge M, Pelorson X, Vilain C, Lagrée P-Y, Chentouf F, Willems J, Hirschberg A. Influence of collision on the flow through in-vitro rigid models of the vocal folds. *J. Acoust. Soc. Am.* 2003; 114(6):3354–3362. [PubMed: 14714815]
- Hirschberg A. Some fluid dynamic aspects of speech. *Bull. Commun. Parl.* 1992; 2:1–30.
- Hofmans G, Groot G, Rancei M, Graziani G, Hirschberg A. Unsteady flow through *in vitro* models of the glottis. *J. Acoust. Soc. Am.* 2003; 113(3):1658–1675. [PubMed: 12656399]
- Hsu, T-Y. M.S. thesis. Department of Mechanical and Aerospace Engineering, Rutgers University; 2000. Turbulent secondary flow in the mixed boundary corner formed by a free surface and a vertical solid wall.
- Hsu T-Y, Grega LM, Leighton RI, Wei T. Turbulent kinetic energy transport in a corner formed by a solid wall and a free surface. *J. Fluid Mech.* 2000; 410:343–366.
- Ishizaka K, Flanagan JL. Synthesis of voiced sounds from a two-mass model of the vocal cords. *Bell Syst. Tech. J.* 1972; 51:1233–1268.
- Krane MH. Low-frequency aeroacoustic production of unvoiced speech sounds. *J. Acoust. Soc. Am.* 2005; 118(1):410–427. [PubMed: 16119362]
- Krane MH, Wei T. Theoretical assessment of unsteady effects in phonatory aerodynamics. *J. Acoust. Soc. Am.* 2006; 120(3):1578–1588. [PubMed: 17004480]
- Krueger PS. An over-pressure correction to the slug model for vortex ring circulation. *J. Fluid Mech.* 2005; 545:427–443.
- Krueger PS, Gharib M. The significance of vortex ring formation to the impulse and thrust of a starting jet. *Phys. Fluids.* 2003; 15(5):1271–1281.
- Krueger PS, Gharib M. Thrust augmentation and vortex ring evolution in a fully pulsed jet. *AIAA J.* 2005; 43(4):792–801.

- Liljencrants, J. Experiments with analysis by synthesis of glottal airflow; Proceedings of ICSLP '96; Philadelphia, PA: 1996.
- Lous NJC, Hofmans GCJ, Velduis RNJ, Hirschberg A. A symmetrical two-mass vocal-fold model coupled to vocal tract and trachea, with application to prosthesis design. *Acta Acust.* 1998; 84(6): 1135–1150.
- Mongeau L, Franchek N, Coker CH, Kubli RA. Characteristics of a pulsating jet through a small, modulated orifice, with application to voice production. *J. Acoust. Soc. Am.* 1997; 102(2):1121–1133. [PubMed: 9265759]
- Shah P, Atsavapranee P, Hsu TY, Wei T, McHugh J. Turbulent transport in the core of a trailing delta wing vortex. *J. Fluid Mech.* 1999; 387:151–175.
- Story B, Titze I. Voice simulation with a body-cover model of the vocal folds. *J. Acoust. Soc. Am.* 1995; 97:1249–1260. [PubMed: 7876446]
- Teager HM. Some observations on oral airflow during phonation. *IEEE Trans. Acoust., Speech, Signal Process.* 1980; ASSP-28(5):599–601.
- van den Berg J, Zatema J, Doornenbal P. On the air resistance and Bernoulli effect in the human larynx. *J. Acoust. Soc. Am.* 1957; 29:626–631.
- Vilain CE, Pelorson X, Fraysse C, Deverge M, Hirschberg A, Willems J. Experimental validation of a quasi-steady theory for the flow through the glottis. *J. Sound Vib.* 2004; 276:475–490.
- Zhang Z, Mongeau L, Frankel S. Experimental verification of the quasi-steady approximation for aerodynamic sound generation by pulsating jets in tubes. *J. Acoust. Soc. Am.* 2002; 112(4):1652–1663. [PubMed: 12398470]

FIG. 1.

(Color online) Schematic of test model in water channel, showing real dimensions. Channel flow is set to a steady flow rate and moves from left to right, flowing both around and through the model when the model glottis is open. The dotted line box shows a typical camera viewing area for measurements presented in this article.

(a)

(b)

FIG. 2.

(Color online) Photos of the test apparatus. (a) The model placed in the water channel test section, looking upstream. Visible are the model vocal folds, the drive mechanism (located above the model), and the glass walls and floor of the water channel test section. (b) One of the model vocal folds. The half-circular shape of the wall is readily visible. Also visible are the linear bearings, which allow smooth motion of the model, and (at top) the angle through which the linear stages transmit momentum to the model vocal fold.

FIG. 3.

Schematic of experiment control using waveform generator. A new acquisition interval begins every 15 Hz. The waveform generator sends pulses to the camera and lasers to provide proper timing of illumination of the two images in an image pair. During the first cycle, a pulse is sent to the motion controller to initiate the motion of the model vocal folds.

FIG. 4.

Wall motion for the four cases of oscillation frequency studied. Glottal width, h , normalized by maximum glottal width, $h_{\max}$, is plotted versus time, t , from opening, normalized by time, T_o , glottis is open. Frequency is expressed nondimensionally as Strouhal number (St) and as life-scale frequency (f_{ls}). Δ : $St=0.010$, $f_{ls}=30$ Hz; $\circ$: $St=0.018$, $f_{ls}=58$ Hz; $*$: $St=0.035$, $f_{ls}=109$ Hz; and $\square$: $St=0.040$, $f_{ls}=126$ Hz.

FIG. 5. (Color online) Images of jet velocity field from DPIV measurements of a single realization, superimposed on corresponding image of model vocal folds during motion, $St = 0.035$ ($f_{1.5} = 109$ Hz). Arrow length is proportional to local flow speed. Time of each image is given as fraction of time, T_o , that the glottis is open: (a) $t/T_o = 0.15$, $h/h_{\max} = 0.33$, starting vortex visible; (b) $t/T_o = 0.50$, $h/h_{\max} = 0.99$, glottis fully open; (c) $t/T_o = 0.76$, $h/h_{\max} = 0.58$, jet at maximum speed; (d) $t/T_o = 0.93$, $h/h_{\max} = 0.18$, flow has shut off and jet is in decay phase.

FIG. 6. (Color online) Images of jet velocity field from DPIV measurements superimposed on corresponding image of model vocal folds at $t/T_0=0.75$ for all St. (a) $St=0.010$, (b) $St=0.018$, (c) $St=0.035$, and (d) $St=0.040$. Vortex pairs are visible in each image. In the $St=0.017$ case, the jet is seen to divert from the centerline.

FIG. 7.

Maximum axial velocity component at glottal exit plane, $St=0.035$: comparison of (thin line) raw signal, (thick line) low-pass filtered signal, and (dotted line) ensemble average of ten realizations. Maximum jet speed on exit plane, u_{exit} , is normalized by maximum jet speed, u_{ss} , observed in steady flow through fully-open glottis. Time, t , from opening, is normalized by time, T_o , glottis is open.

FIG. 8.

(Color online) Single realizations of maximum axial velocity component at glottal exit plane versus t/T_o for four cycle frequencies studied. Maximum jet speed on exit plane, u_{exit} , is normalized by maximum jet speed, u_{ss} , observed in steady flow through fully-open glottis. Time, t , from opening, is normalized by time, T_o , glottis is open. Frequency is expressed nondimensionally as Strouhal number (St) and as life-scale frequency (f_{1s}): (thin gray line) $St=0.010$, $f_{1s}=30$ Hz; (gray solid line) $St=0.018$, $f_{1s}=58$ Hz; (black dotted line) $St=0.035$, $f_{1s}=109$ Hz; (black solid line) $St=0.040$, $f_{1s}=126$ Hz.

FIG. 9.

(Color online) Ensemble-averaged glottal exit plane volume flow versus t/T_o for four cycle frequencies studied. Glottal volume flow, Q_{exit} , is normalized by the product of the maximum velocity u_{ss} observed in steady flow for a fully open glottis and the maximum glottal width during the cycle. Time, t , from opening, is normalized by time, T_o glottis is open. Frequency is expressed nondimensionally as Strouhal number (St) and as life-scale frequency (f_{ls}): (thin gray line) $St=0.010$, $f_{\text{ls}}=30$ Hz; (gray solid line) $St=0.018$, $f_{\text{ls}}=58$ Hz; (black dotted line) $St=0.035$, $f_{\text{ls}}=109$ Hz; (black solid line) $St=0.040$, $f_{\text{ls}}=126$ Hz.