The occurrence of the Coanda effect in pulsatile flow through static models of the human vocal folds

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(Received 3 August 2005; revised 12 May 2006; accepted 12 May 2006)

Pulsatile flow through a one-sided diffuser and static divergent vocal-fold models is investigated to ascertain the relevance of viscous-driven flow asymmetries in the larynx. The models were 7.5 times real size, and the flow was scaled to match Reynolds and Strouhal numbers, as well as the translaryngeal pressure drop. The Reynolds number varied from 0–2000, for flow oscillation frequencies corresponding to 100 and 150 Hz life-size. Of particular interest was the development of glottal flow skewing by attachment to the bounding walls, or Coanda effect, in a pulsatile flow field, and its impact on speech. The vocal folds form a divergent passage during phases of the phonation cycle when viscous effects such as flow separation are important. It was found that for divergence angles of less than 20 degrees, the attachment of the flow to the vocal-fold walls occurred when the acceleration of the forcing function was zero, and the flow had reached maximum velocity. For a divergence angle of 40 degrees, the fully separated central jet never attached to the vocal-fold walls. Inferences are made regarding the impact of the Coanda effect on the sound source contribution in speech. © 2006 Acoustical Society of America. [DOI: 10.1121/1.2213522]

PACS number(s): 43.70.Aj [BHS] 

I. INTRODUCTION

This paper addresses the development of the Coanda effect and its potential influence in phonation. Henri Coanda, a Romanian engineer, is credited with discovering that fluid issuing forth from a slot has a tendency to adhere to a surface placed adjacent, and at some acute angle, to the slot. He attributed this phenomenon to an imbalanced suctioning force caused by entrainment of the ambient fluid between the jet and the adjacent surface (Coanda, 1936). This phenomenon is commonly referred to as the Coanda effect, and is evident in many common engineering applications involving fluid mechanics.

The Coanda effect arises when a jet of fluid strikes a surface placed adjacent to the jet, and at some acute angle to the jet. The jet is deflected by the surface, and the flow is attached to the surface. This effect is important in many engineering applications, including aircraft design and fluid mechanics.

The Coanda effect has been shown to exhibit many of these qualities that are expected to contribute to the production of sound in voiced and unvoiced speech. Investigating a two-dimensional turbulent jet exhausted over an inclined adjacent flat plate, Borque and Newman (1960) observed a separation of the flow at the lip, followed by a reattachment point downstream. Newman (1961) later provided a comprehensive theoretical and experimental investigation of the Coanda effect, using an inclined adjacent flat plate for flow at moderately high Reynolds number. Basing his theory on conservation of momentum and undeflected jets, he determined that flow separation and reattachment lengths were a function of the angle of the plate to the flow axis. Furthermore, they showed that an imbalance in entrainment between the two sides of the jet results in the jet asymmetry that characterizes the Coanda effect.

Unfortunately, this previous work is limited to flows which are steady and are characterized by Reynolds numbers higher than those exhibited in speech. Both of these factors affect the entrainment rate of the jet, and hence, the occurrence of the Coanda effect. Turbulent shear layers have increased entrainment (Hussain, 1986) i.e., quicker formation of the Coanda effect, but shorter attachment lengths. Furthermore, in a study of fully pulsed axisymmetric jets with a...
no-flow period, Bremhorst and Hollis (1990) found the entrainment rate to be nearly double that for steady jets. These findings suggest that there are many variables that may contribute to, or inhibit, the formation of asymmetric flows in the dynamic environment of speech.

The possibility of asymmetric flow configurations in speech has been proposed in the past. Initially suggested by Teager (1980), Teager and Teager (1981, 1983), and Kaiser (1983), their work was largely disregarded due to a lack of theoretical underpinning relating their observations to sound production. Furthermore, their inability to conclusively address issues of repeatability and reproducibility of their measurements, as well as the inherently invasive nature of the hot-wire measurements on which their findings were based, limited the acceptance of their work. Despite this controversy, inspection of their data and others is highly suggestive that glottal jet flows are often asymmetrical. It is widely accepted that the Coanda effect will form in steady vocal-tract flow investigations, as mentioned by Hirschberg (1992) and Krane and Alipour and Scherer (1992, 1995a, 1995b) showed lateral spatial variations in the maximum glottal jet velocity. Although not explicitly investigating glottal flow asymmetries, Alipour and Scherer (1995) and Alipour et al. (1995a, 1995b) spatially reconstructed the nature of the flow from point-wise, temporal, hot-wire measurements. While spatial variations in the mean velocity field were evident, the inability to capture an instantaneous full-field realization prevented definitive characterization of the flow behavior. Furthermore, the spatial variability of the flow may have been influenced by interference of the relatively large-sized probe with the flow, when placed close to the excised larynges.

Due to the impetus of Teager and Teager (1983) and Kaiser (1983), considerable efforts have been directed to resolve the question of whether or not the Coanda effect will occur in the dynamic, high-frequency oscillations of phonation. Early work was performed by Pelorson et al. (1994, 1995) and Hirschberg et al. (1996) in impulsively started flows in three times life-size static vocal-fold models of varying geometric configurations. Unsteady flow was generated by abruptly opening a pressurized reservoir placed upstream of the models. A picture of the glottal flow dynamics was constructed by acquiring velocity measurements at the minimal constriction of the vocal-fold models, as well as measuring the static pressure time history on the facing vocal-fold models at the same location. Flow visualization was also employed to observe the spatial development of the glottal jet. By measuring the time necessary for the Coanda effect to fully establish in their models, they concluded that there was insufficient formation time available during the high-frequency oscillations inherent in phonation. Their conclusions were based on the assumption that the development of the Coanda effect takes a finite period of time to develop, and that this formation interval is proportional to the fundamental frequency. These results have been confirmed, recently, by Hofmans et al. (2003).

Using the same experimental setup of impulsively started flow through divergent glottal models, pressure measurements were obtained on both vocal-fold walls at the minimum constriction. The development of the Coanda effect was identified by a marked divergence in the pressure magnitude between the opposing walls. Again, the same necessary time scaling for the development of the Coanda effect was reported. These studies concluded that the Coanda formation time was longer than that afforded by the high-frequency oscillations of voicing. However, the results of Mongeau et al. (1997) suggest the importance of flow acceleration within the glottis when investigating the flow-field behavior. While they did not obtain spatial flow-field measurements, time-resolved hot-wire velocity measurements of flow through a modulated life-size rubber model of the vocal folds revealed that the flow largely behaved in a quasisteady manner, except during the opening one-fifth of the duty cycle when the flow was accelerating. While the experiments of Pelorson et al. (1994, 1995), Hirschberg et al. (1996), and Hofmans et al. (2003) have provided significant contributions to flow development and behavior within the glottis, they are all limited by their inability to accurately represent the flow dynamics (i.e., truly pulsatile flow) that occurs in voiced speech, as well as the inability to obtain the velocity time history in a nonintrusive manner. In particular, the duration of the flow acceleration resulting from the impulsively started flow is a significant fraction of a typical period of a glottal cycle. Consequently, there remains an unresolved issue regarding the development of the Coanda effect in phonation under pulsatile flow conditions.

An obvious advancement of previously performed work (as suggested by Pelorson et al., 1995) is to investigate glottal flow behavior in the more physiologically applicable situation of a truly pulsatile flow field. The purpose of this study was to investigate the development of the Coanda effect in static models of the human glottis, subject to pulsatile flow, with a waveform comparable to physiological phonation conditions, and to determine which parameters govern its formation. Particle image velocimetry (PIV) was used to investigate flow through the glottal airspace. This noninvasive technique provides full-field, planar mean velocity statistics with high spatial resolution, an advancement over techniques previously employed in laryngeal flow investigations.

The choice of pulsatile flow through static vocal-fold models (rather than dynamic models) allows a focus on how time variations in glottal flow affect the occurrence of the Coanda effect, using a flow field that evolves in a dynamically similar manner to physiological flows. In this manner, the present study builds upon the previous work of Pelorson et al. (1994, 1995), Hirschberg et al. (1996), and Hofmans et al. (2003), adding only a single additional degree of complexity. The results reported herein provide insight into what factors are important in the development of the Coanda effect during phonation. Not only is the in vitro model used more physiologically accurate than those in previous similar studies, but the experimental technique provides accurate spatial distributions of the velocity field, obtained in a noninvasive manner. From these measurements, the time required for the formation of the Coanda effect, relative to a physiologically relevant pulsatile flow period, can be determined.
II. METHODS

A. Experimental apparatus

All experiments were performed in a low-speed, open-circuit suction wind tunnel, as shown schematically in Fig. 1. The optically clear polycarbonate test section measured 30.5 cm (12.0 in.) by 30.5 cm (12.0 in.) in the spanwise directions (out of the page) and 122 cm (48.0 in.) in the streamwise direction (left-to-right).

An unsteadiness generator, consisting of five equally spaced rotating shutters placed downstream of the test section, was used to provide the periodic free-stream velocity fluctuations in the test section to replicate the unsteady physiological flow parameters. Matching the physiological flow required that an ellipsoidal cross-sectional geometry be used for each shutter so that the total area obstruction of the shutters varied in the streamwise direction throughout one rotation, producing a pulsatile flow with a zero mean flow component for part of the cycle. The shutter frequency, $f_s$, adjustable from 0–5 Hz, was controlled by a variable speed motor (Oriental Motors, 60 W, model US560-501W), with a 7.5:1 gear box (model 5GU7.5KA).

An optical encoder (US Digital, model E5s-360) with 0.5° resolution quadrature output was placed on the shutter shaft, and the quadrature output was sent to a digital frequency counter (Data Precision, model 5740) which recorded the shutter frequency with a resolution of ±0.001 Hz. The TTL output wave of the optical encoder also served as a variable external trigger based upon shutter phase, which was used for reference in the phase-averaged data acquisition. Shutter position, or phase $\phi$, was defined as zero when the shutters were oriented such that the major diameter was vertical, and the shutters were fully closed. One flow pulse is produced by the shutters rotating 180°, from fully closed to open and then fully closed again.

Two devices were constructed to investigate the Coanda effect. The first was a one-sided diffuser, schematically shown in Fig. 2. The diffuser apparatus created a modified test section by dividing the existing wind tunnel test section into a top and bottom plane spanning the width of the original test section. The top half measured 16.23 cm (6.39 in.) high, while the bottom half measured 13.77 cm (5.41 in.) high. As flow passed through the top half of the modified test section it was accelerated through a fifth-order polynomial inlet contraction, with a contraction ratio of 22:1. The exit of the contraction formed the slot width of interest, and measured 7.5 mm (0.30 in.) high. Extending from the lower edge of the slot was an adjacent plate which was angled at 20° away from the streamwise direction. The plate had a length-to-diameter ratio of 18.5. The total length of the apparatus was 42.0 cm (16.5 in.). The bottom half of the modified test section served as the bypass. Four stretched wire mesh screens were placed across the bottom section, mimicking the dynamic pressure drop across the modified test section. The screens were equally spaced 2.54 cm (1.00 in.) apart. All four screens had a porosity of 59%, and mesh size of 42, where mesh size is defined as the number of openings per linear inch.

The second apparatus, the glottal flow test section, was physiologically representative of the glottal airspace, based on dimensions reported by Scherer et al. (2001). A schematic showing its positioning in the wind tunnel is shown in Fig. 3. This apparatus, constructed of 1.27-cm (0.500 in.)-thick clear acrylic sheet, divided the original wind tunnel test sec-
tion into three separate horizontal channels. The total length was 61.0 cm (24.0 in.). The top and bottom channels both measured 28.0 cm (11.0 in.) wide by 7.52 cm (2.96 in.) high, and served as bypasses to allow sufficient air flow to the fan. The middle channel acted as the vocal-tract test section. The opening was 30.5 cm (12 in.) wide by 12.9 cm (5.08 in.) high. A two-dimensional contraction, with a contraction ratio of 3.4:1, in the spanwise direction narrowed the middle channel to a constant width of 9.00 cm (3.54 in.). Three 7.5 \times \text{scale} \ = 40^{\circ} \text{model pairs with divergence angles of} 10, 20, \text{and} 40^{\circ} \text{were machined according to the specifications of Scherer et al. (2001). Figure 4 shows (one-half of) one of the vocal-fold models with a divergence angle of} 40^{\circ}. \text{Data were acquired with models positioned in the vocal-tract channel such that the exit plane of the models was located} 33.0 \text{cm (13.0 in.) downstream of the vocal-tract inlet, and} 28.0 \text{cm (11.0 in.) upstream of the exit. The height of the vocal-tract channel dictated that the glottal gap be decreased as} 1 \text{.} \text{Wire mesh screens were used along the top and bottom bypasses to increase flow resistance so that the pressure drops were identical to the pressure drop across the center channel containing the vocal-fold models, thereby eliminating any undesirable pressure gradients when the flow exits the vocal-tract model. Seven screens were placed normal to the streamwise direction along the top and bottom bypasses, spanning the whole width and height. The mesh size of the screens was} 80 \text{ (openings per linear inch), porosity was} 19.4\% \text{, and wire diameter was} 0.018 \text{ cm (0.0070 in.). They were spaced} 5.08 \text{ cm (2.00 in.) apart, centered about the middle of the channels.}

B. Data acquisition

The spatial flow field through the one-sided diffuser, and vocal-fold models, was measured using Particle image velocimetry (PIV). PIV is a noninvasive technique that provides detailed, spatially resolved flow fields. A particle-laden flow is illuminated with a thin laser sheet, formed by a pulsed Nd:YAG laser. The light scattered by the particles is captured by a charge-coupled device (CCD) camera creating an image of the particle cloud. With the time between each laser pulse, \( \Delta t \) (and therefore each image) precisely controlled, successive images are then cross correlated using a fast Fourier transform (FFT) algorithm to find the displacement, \( \Delta x \), of the particles. Velocity vectors can then be determined according to \( U = \Delta x / \Delta t \). Ensemble averages allow detailed statistics of the flow to be computed. See Grant (1997) and Raffel et al. (1998) for more details concerning the PIV technique.

Dynamic similarity between the measured model flow and glottal flow was established by matching the Reynolds number (Re), Strouhal number (St), and pressure distribution \( (C_p) \) to the physiological values inherent in phonation, where

\[
\text{Re} = \frac{Ud}{\nu},
\]

\[
\text{St} = \frac{fd}{U},
\]

\[
C_p = \frac{\Delta P_{\text{trans}}}{1/2 \rho U^2}.
\]

In the above equations, \( U \) is the fluid velocity, \( d \) is the characteristic length scale, \( \nu \) is the kinematic viscosity of the fluid, \( f \) is the frequency of the flow pulsations, \( \Delta P_{\text{trans}} \) is the transglottal pressure drop, and \( \rho \) is the fluid density. The length scale, \( d \), was chosen to be the height of the minimal constriction in the apparatus of interest, as shown in Fig. 3. Solving for \( U, f \), and \( \Delta P_{\text{trans}} \) results in \( U \) scaling as \( 1 \) over the model size, while \( f \) and \( \Delta P_{\text{trans}} \) both scale as \( 1 \) over the model size squared. The life-size and scaled values for both apparatus can be found in Table I. The larger model size \( (7.5 \times \text{life-size}) \) was chosen to allow easier optical access, and better spatial resolution of the flow.

PIV data were taken in the anterior-posterior midplanes \( (Y-Z \text{plane}) \) in experimental setup of Figs. 2 and 3. The flow was seeded using an olive oil atomizer (TSI, model #2) which incorporates six Laskin nozzles, and emits nearly monodisperse seed particles with diameters on the order of 1 \( \mu \text{m} \). The seeding particles were inserted into the upstream flow.

![FIG. 4. Vocal-fold model, 7.5 \times \text{scale} \ = 40^{\circ}.](image)

### Table I. Life-size and model parameters.

<table>
<thead>
<tr>
<th>Apparatus</th>
<th>Flow conditions</th>
<th>Physiological</th>
<th>One-sided diffuser</th>
<th>Glottal-flow</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flow</td>
<td>Pulsatile</td>
<td>Pulsatile</td>
<td>Pulsatile</td>
<td></td>
</tr>
<tr>
<td>( d ) (mm)</td>
<td>( -0–1 )</td>
<td>7.5</td>
<td>3.0</td>
<td></td>
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<tr>
<td>( U ) (m/s)</td>
<td>( -0–30 )</td>
<td>4.0</td>
<td>7.40</td>
<td></td>
</tr>
<tr>
<td>( f_p ) (Hz)</td>
<td>( -100–250 )</td>
<td>1.78, 2.67</td>
<td>1.78</td>
<td></td>
</tr>
<tr>
<td>( \nu ) (Ns/m²)</td>
<td>( 1.51 \times 10^{-5} )</td>
<td>( 1.51 \times 10^{-5} )</td>
<td>( 1.51 \times 10^{-5} )</td>
<td></td>
</tr>
<tr>
<td>( \Delta P_{\text{trans}} ) (cmH₂O)</td>
<td>( -0–20 )</td>
<td>N.A.</td>
<td>0–0.267</td>
<td></td>
</tr>
<tr>
<td>Re</td>
<td>( -0–5000 )</td>
<td>0–1987</td>
<td>0–1470</td>
<td></td>
</tr>
<tr>
<td>St</td>
<td>( -10^{-3} )</td>
<td>3.3 \times 10^{-3}, 5.0 \times 10^{-3}</td>
<td>7.22 \times 10^{-3}</td>
<td></td>
</tr>
<tr>
<td>( \Psi ) (Divergence angle, deg)</td>
<td>( -40 ) to ( -40 )</td>
<td>40</td>
<td>10, 20, 40</td>
<td></td>
</tr>
</tbody>
</table>
section of the wind tunnel via a flow loop which ran from the
atomizer through a plenum chamber, before being drawn into the
wind tunnel, 2.0 m (6.6 ft.) upstream of the test section, via two 2.54-cm (1.00 in.)-diameter perforated pipes placed
along both side walls of the wind tunnel.

The area of interest was illuminated using a 500-
ml/pulse laser (New Wave, Nd: YAG) with a 532-nm wave-
length and pulse duration of 5 ns. Images were captured by a
digital camera (TSI PowerView 4MP, model 630051) with a
2000 × 2000 pixel CCD array. The image plane varied in
size from ~30 mm square to ~60 mm square depending on
the area of interest. The images were processed using an FFT
correlator on a Nyquist grid, with 32² or 64² pixels, and 50%
overlap. With peak-finding accuracy of ~0.1 pixels (Peterson,
2001) and subregion shifting of 8 to 16 pixels, the un-
certainty in the mean velocity measurements was ~6%. The
spatial resolution ranged from ~0.24 to 0.48 mm. The
phase-averaged unsteady flow measurements were externally
triggered from the optical encoder on the unsteadiness gen-
erators and thereby depended on the shutter frequency. The
repeatability of the optical encoder was ±1/30th of a degree,
which for a shutter frequency of 1.78 Hz results in a vari-
ation of ±0.104 ms. The number of image pairs (realizations)
acquired for each data set varied between 100 and 1000. The
number of realizations was chosen to ensure convergence of
the ensemble mean, which was determined by comparing the
average of N realizations to the average of N+1 realizations.
The mean was considered converged when increasing N by 1
resulted in a minimal change in the average value. The num-
ber of realizations to be acquired at subsequent shutter posi-
tions was then chosen such that the average representation of
the flow converged within 3% of the mean stationary value,
thereby minimizing the amount of data that needed to be
acquired, while still maintaining a sufficient level of accu-
cacy. Vector validation was achieved by applying maximum,
minimum, mean, median, and standard deviation statistics.
Care was taken to not employ any interpolation, or “filling” pro-
cesses that would alter the data sets.

The time history of velocity through the one-sided dif-
fusor in pulsatile flow was measured using hot-wire an-
emometry (TSI, model IFA-300). The probe (TSI, model
1201-20) measured 0.20 cm (0.09 in.) wide, with a film di-
diameter of 50.8 µm (2.0 µm). The velocity was acquired at
the throat by inserting the hot-wire wand from above, normal
to the flow, such that the probe was flush against the upper
diffuser wall, with the tip extending halfway across the dif-
fuser throat, oriented so that the cross wire was normal to the
flow direction. The maximum measured frequency response
of the hot wire was ~100 kHz. The data samples were ac-
quired at a rate of 600 Hz.

The unsteady time history of the flow velocity through
the vocal-fold models was measured by laser Doppler veloc-
metry (LDV) (Dantec Dynamics Flowlite 1D). LDV has the
added benefit over hot-wire anemometry of being a noninva-
sive technique which allows point-wise temporal resolution
of the flow field. The interrogation volume was formed by
two 1.38-mm-diameter beams produced by a helium-neon
laser (λ=632.8 nm), with a frequency shift of 40 MHz. At
the exit pupil of the focal lens the beam spacing was 38 mm
with a divergence angle of 13.54°. The focal length of the
beams was 160 mm, and the beam diameter at the focal length
was ~0.1 mm, which corresponds to an ellipsoidal measurement volume of ~4.5×10⁻³ mm³. The measure-
ment volume was positioned in the minimal glottal airspace
between the two vocal-fold models, allowing capture of the
streamwise velocity component. Signal processing was per-
formed by flow-processing software (Dantec Dynamics
BSA). Flow seeding specifications were the same as those
used for the PIV measurements. The resulting acquired
sample rate was on the order of 1 kHz for all of the mea-
surements.

III. RESULTS

A. One-sided diffuser

Due to its simplicity, a one-sided diffuser design was
chosen as a first approach to investigate the development of
the unsteady Coanda effect. The simplified configuration
allowed a broad investigation of the unsteady Coanda effect,
while having the added benefit that the flow always attaches
to one side, thereby simplifying spatial averaging of the
mean velocity field. It also allows the flow conditions to be
benchmarked with previous experiments performed on the
The results of this initial study were used to guide the ap-
proach taken in the subsequent investigation of the Coanda
effect through more physiologically representative vocal-fold
models. The frequency dependence of the Coanda effect was
investigated by measuring the velocity field of pulsatile flow
in the one-sided diffuser using phase-averaged PIV at two
shutter frequencies (fₛ); 1.81 and 2.67 Hz (102 and 150 Hz
life-size). Figures 5(a) and 6(a), respectively, are temporal
velocity traces at the slot (diffuser throat), plotted versus
shutter phase, φ, in degrees, for the two aforementioned fre-
cuencies of interest. The location of the shutter positions,
depicted as shutter phase φ, at which the PIV data were
acquired is indicated on each plot by vertical lines, and is
labeled as: (A) 20°; (B) 40°; (C) 60°; (D) 80°; (E) 95°; (F)
105°; (G) 115°; (H) 130°; (I) 145°; (J) 160°; and (K) 180°. Re-
Regions of acceleration (φ=40–105°), maximum velocity
(φ=105–115°), and deceleration (φ=115–160°) are indi-
cated on each figure.

The temporal flow behavior is best explained by exam-
ining the time derivative of the velocity traces, or accelera-
tions, plotted in Figs. 5(b) and 6(b) (fₛ=1.81 and 2.67 Hz,
respectively). As shown in Figs. 5(a) and 5(b), for a shutter
frequency of 1.81 Hz the flow velocity begins accelerating
shortly before point B, when the shutter phase is ~35°. Max-
imum acceleration of the flow occurs for a shutter phase of
~52°, after which the flow acceleration slowly dimin-
ishes, until the point of maximum velocity, and zero accel-
eration, is reached at point F. The flow then immediately
decelerates, reaching maximum deceleration at a shutter
phase of ~137°, before finally coming to rest at point J, φ
=160°. Figure 6(b) shows the time derivative of the velocity
trace for a shutter frequency of 2.67 Hz. In comparison to
Fig. 5(b), there is a slight lag between the two shutter posi-
tions arising from a small misalignment in the initial trigger.
position, although this difference does not affect the waveform characteristics. The flow initially accelerates slightly after point B, \( \phi \approx 45^\circ \). It follows the same pattern as described previously, with the maximum acceleration occurring for a shutter phase of \( \approx 57^\circ \), followed by a decline in the acceleration to the maximum velocity, and zero acceleration, at point G, where \( \phi = 115^\circ \). Deceleration reaches a maximum at a shutter phase of \( \approx 142^\circ \), before the flow is brought to rest at a shutter phase of \( 155^\circ \). The magnitude of the maximum acceleration and deceleration is about 25% greater for the 2.67-Hz case [Fig. 6(b)] than the 1.81-Hz case [Fig. 6(a)] due to the shorter opening and closing times inherent in the higher shutter frequency.

Phase-averaged PIV images were acquired at the previously specified shutter positions for a shutter frequency of 1.81 Hz (102 Hz life-size). The images are shown in Figs. 7(a)–7(c), representing a progression of the spatial flow field in time. The temporal location of the velocity field is referenced to the shutter positions, specified as points A through J in the velocity and acceleration waveform plots [see Figs. 5(a) and 5(b)], and is also represented as a vertical line, superimposed on the waveform plot, in the lower left corner of each image. Velocity magnitude is plotted, normalized by the maximum velocity \( U_{\text{max}} = 4.10 \text{ m/s} \) throughout the cycle. The contour plots range in color from blue to red, which corresponds to a normalized velocity of 0.0 to 1.0, respectively. White streamlines are superimposed on the plots. The spatial coordinates have been normalized by the maximum glottal gap \( d = 7.5 \text{ mm} \).

In Figs. 7(a)–7(c), \( f_s = 1.81 \text{ Hz} \), a leading vortex is observed for \( \phi = 65^\circ \). As it is convected downstream, the jet skewers down toward the adjacent plate, and attachment occurs at a shutter phase of \( \phi = 155^\circ \), point F on the velocity and acceleration waveform graphs. Complete flow attachment was defined to be when the reattachment lengths of the pulsatile flow were equal to the reattachment lengths of the steady-flow measurements. The steady-flow measurements are not presented here, but can be found in Erath (2005). This point in time corresponds to the flow reaching maximum velocity, and the acceleration being zero [see Figs. 5(a) and 5(b)]. The streamwise reattachment length is approximately 5 diameters downstream of the slot. The jet remains attached to the surface throughout the remainder of the flow cycle, even after the maximum deceleration in the flow at \( \phi \approx 145^\circ \). The observation that the flow first attaches to the plate at the point of zero acceleration in this case as
well as others to be presented suggests that the occurrence of the Coanda effect may be a function of the temporal velocity derivative, i.e., the flow acceleration.

Next, the development of the Coanda effect was investigated for a shutter frequency of 2.67 Hz (150 Hz life-size). If the time required for the development of the Coanda effect, as proposed by Pelorson et al. (1994), Hirschberg et al. (1996), and Hofmans et al. (2003), is constant (i.e., independent of pulsation frequency), then the phase at which the flow attaches will depend upon the pulse period. For example, when the flow is driven at 2.67 Hz, the phase at which it attaches would be 50% later in the pulse period, than for the case of 1.81 Hz. However, as shown in Fig. 8, the spatial and temporal behavior of the Coanda effect at the higher frequency (2.67 Hz) was identical to the flow field presented at the shutter frequency of 1.81 Hz. For brevity, only the velocity fields at the shutter phases of greatest interest (φ=65, 115, and 145°) are plotted for this frequency. For a complete account of the velocity fields at the higher frequency shutter phases, see Erath (2005). As in the lower frequency case, the initial leading vortex is observed at point C, where φ=65°. The jet is then skewed toward the plate in the subsequent images, before initially attaching to the surface at point G, a shutter phase of 115°. Referring back to the plots of the velocity and acceleration waveform [see Figs. 6(a) and 6(b)], this point again corresponds to the location of the flow where the velocity is a maximum, and the acceleration is zero. These results further confirm that the attachment of the Coanda effect is dependent upon the time derivative of the velocity waveform rather than an absolute time scale based on frequency.

B. Vocal-fold models

The velocity-dependent deflection of the Coanda jet was examined in the more physiologically relevant case of unsteady flow through the static vocal-fold models, at a shutter frequency of 1.81 Hz (100 Hz life-size). The model vocal-
tract apparatus was placed in the wind tunnel, and the velocity waveform was acquired from LDV measurements for the pulsating flow conditions. The LDV measurements allowed noninvasive temporal resolution of the velocity. The waveform is shown in Fig. 9, with the corresponding plot of the acceleration shown in Fig. 9b.

The location of the phase-averaged PIV data acquisition points is labeled on the plots as: (A) 45°; (B) 52.5°; (C) 60°; (D) 75°; (E) 90°; (F) 105°; (G) 120°; (H) 135°; (I) 150°; (J) 155°, $f_s=1.78$ Hz (100 Hz life-size). Areas of acceleration, maximum velocity, and deceleration are labeled on both graphs. The flow accelerates quickly, reaching a maximum at point A, before decelerating to zero at point D, where the maximum velocity occurs. The flow remains steady until point F, where it begins to decelerate, eventually reaching a maximum deceleration at a shutter phase of $\sim 145^\circ$, before the velocity is brought to rest at point J.

Phase-averaged PIV measurements of pulsatile flow through the 7.5× scaled static vocal-fold models with divergence angles of 10, 20, and 40° were acquired, with 1000 velocity field realizations captured at each shutter phase. It was observed that, for each shutter phase, the jet deflection angle, i.e., the angle that the glottal jet deflected from the streamwise direction, varied significantly for the 1000 realizations. In some realizations the jet was deflected toward the lower wall, whereas in others it was skewed toward the upper wall. Typical phase-averaged analysis entails averaging all of the realizations for a given phase angle to achieve statistical convergence of the average flow representation. This method was inappropriate because the random behavior (flip flopping) of the jet deflection angle for a given phase, $\phi$, would smear out any asymmetries or unsteadiness in the flow. To alleviate this concern, the inclusion of a particular vector field in the phase average was determined based on a
calculation of the jet deflection angle for that image pair. After calculating the jet deflection angle for each image pair (at constant shutter phase), a histogram of the distribution was plotted for each data acquisition set, and each vocal-fold model, with a resolution of ±0.0625\(\Psi\), where \(\Psi\) is the total glottal divergence angle. The glottal jet trajectory at each shutter phase, represented by a histogram plot of the jet deflection angle for each data acquisition set, was observed to have a Gaussian-type distribution centered about the peak location (see Erath, 2005; Erath and Plesniak, 2006). The most prevalent jet deflection angle histogram bin contained ~75% of the total realizations at each shutter phase. The PIV velocity fields are presented as the average of the realizations corresponding to the dominant location of the glottal jet at each divergence angle and shutter phase. This method minimized the smearing of flow features due to over averaging, while allowing statistical convergence of the velocity field to be achieved. The result is a detailed representation of the velocity field for the “most probable” location of the glottal jet at any given shutter phase for each divergence angle.

While the complete sequence of velocity fields for each shutter phase is presented for a divergence angle of 10°, only the critical shutter phases are plotted for divergence angles of 20 and 40°. The complete sequence of velocity fields at all of the shutter phases for these two divergence angles can be found in Erath (2005).

1. Ten-degree divergence

The phase-averaged PIV images are shown in Figs. 10(a)–10(c) for a vocal-fold divergence angle of \(\Psi = 10^\circ\). In these figures, the spatial coordinates have been normalized by the minimal glottal diameter, \(d = 0.30 \text{ cm} (0.40 \text{ mm life-size})\), and the velocity magnitude has been nondimensionalized by the maximum fluid velocity \(U_{\text{max}} = 7.40 \text{ m/s}\), for the complete cycle. The results are plotted as contours of normalized velocity magnitude from 0.0 to 1.0, ranging in color from blue to red, respectively. White streamlines are overlaid to highlight the flow patterns.

An initial leading vortex is evident during the acceleration of the flow. As the flow reaches its maximum velocity at point D, \(\phi = 75^\circ\), the Coanda effect is manifested as the jet deflects towards and attaches to the vocal-fold wall [see Fig. 10(b)]. This shutter phase corresponds to the instant when the velocity waveform reaches its maximum value, and the acceleration is zero [see Figs. 9(a) and 9(b)]. This again confirms that the formation of the Coanda effect is dependent upon the acceleration of the flow to maximum velocity. Once attached to the vocal-fold wall the flow remained attached throughout the remainder of the cycle, as in the case of the one-sided diffuser.

2. Twenty-degree divergence

The relevant flow-field behavior can be represented by the critical points of the flow, points B, D, and I, in the forcing waveform. These locations correspond to the initial acceleration of the flow, the point of maximum velocity, and deceleration of the flow preceding complete stoppage. For brevity, the velocity fields through the 20° divergent vocal-fold models are plotted at these critical shutter phases in Fig. 11. At point B (\(\phi = 52.5^\circ\)) the flow accelerates through the slot, and a large leading vortex is formed. The velocity reaches a maximum and the acceleration of the flow goes to zero at point D (\(\phi = 75^\circ\)). As with the smaller divergence angle, the flow attaches to the vocal-fold wall at this phase. It remains attached to the wall through the closing phases of the shutter as the flow decelerates (point I).

Note that for a divergence angle (\(\Psi\)) of 20° the attachment length of the flow along the vocal-fold models is greater for point I than for point D (see Fig. 11), showing a propensity for the point of flow separation to move downstream throughout the cycle. Consequently, the jet also deflects further from the streamwise direction. For \(\Psi = 10^\circ\) the separation point of the flow from the vocal-fold model remained relatively steady throughout the cycle once the flow initially attached, separating at the onset of the exit radius.

3. Forty-degree divergence

The flow behavior is significantly different for a vocal-fold divergence angle of 40° (Fig. 12). Again, the velocity fields are only shown at the critical points (B, D, and I). While the flow initially behaves similarly to the previous cases, with a leading vortex, the flow remains unattached throughout the entire flow cycle, never skewing far enough towards a wall for the jet to completely attach. This can be seen at point D, where the velocity has reached a maximum, yet the flow remains symmetric about the midline. A slight deflection in the jet deflection angle is observed at point I; however, it is believed that this small skewing is a result of very slight geometrical asymmetries in the 40° divergent models. It was found that minimal variations of ~25 \(\mu\text{m} (0.001 \text{ in.})\) in the surface finish, as well as geometric variations between the two facing vocal-fold models of ~100 \(\mu\text{m} (0.004 \text{ in.})\), resulted in the flow preferentially skewing towards a particular wall. If not for slight imperfections in the 40° divergent model, the flow would be expected to remain symmetric throughout the complete cycle. A more in-depth discussion of the flow stability resulting from geometric variations can be found in Erath and Plesniak (2006).

IV. DISCUSSION

The investigation of pulsatile flow through a one-sided diffuser and static vocal-fold models has resulted in the identification of important flow structures that are expected to influence sound production in the vocal tract. Most notable is the flow asymmetry that arises due to the formation of the Coanda effect at divergence angles of 10 and 20°. The occurrence of the Coanda effect was shown to depend on the local unsteady acceleration rather than the cycle frequency, thereby emphasizing its importance in voiced as well as unvoiced speech. While these results seem to contradict the findings of Pelorson et al. (1994, 1995), Hirschberg et al. (1996), and Hofmans et al. (2003), they are actually consistent. As previously mentioned, a major shortcoming of their work was that the flow acceleration, generated by the impulsively opened valve, comprised a large portion...
(about one-fourth) of the total scaled glottal cycle. An inspection of their work reveals that the point at which the Coanda effect develops corresponds to the flow reaching maximum velocity and zero acceleration. In other words, had the impulsively started flow accelerated to maximum velocity quicker, as expected in the physiological case where the flow is pulsatile, the Coanda formation times would have been shorter also, and on the order of those reported in this work.

While no quantitative data have been presented regarding contribution of the Coanda effect to vocal-tract sound, the interaction of the jet with the vocal-fold walls is expected to contribute to the dipole sound source resulting from the unsteady force exerted on the fluid by the walls (see Zhang, 2002). It also follows that the observed downstream deflection of the glottal jet towards the larynx walls may cause an interaction with the false vocal folds, as reported by Shadle (1985), C. Zhang et al. (2002), Krane (2005), and Howe and McGowan (2005). The moving separation point is expected to be of greatest consequence since flow separation is responsible for the varying flow resistance through the glottis, and ultimately, the production of voice (Titze, 1988; Hirschberg, 1992; McGowan, 1993). Furthermore, the presence of the Coanda effect would give rise to pressure differences between the two walls of the vocal folds, thereby directly affecting the forcing functions that drive the motion of the vocal folds (Scherer et al., 2001).
There are several shortcomings of the present simplified model with respect to the complex process of phonation. In particular, the dynamic motion of the vocal folds contributes to the flow velocity in the glottal airspace. Berke et al. (1989) observed that the velocity time history in excised canine larynges exhibited a small acceleration when the vocal folds began to close, a phenomenon which was attributed to flow displacement arising from the vocal folds’ interaction with the fluid as they began to close. Furthermore, in the moments immediately following and preceding glottal opening and closure (when the glottal airspace is small) the dominant mechanism driving the fluid velocity is the motion of the vocal fold walls (Deverge et al., 2003).

V. CONCLUSIONS

The development of the Coanda effect in pulsatile flow was investigated in an idealized one-sided diffuser, and in the more physiologically representative case of flow through static models of the vocal folds. The scaling of the Reynolds and Strouhal number and the pressure coefficient to physiological values lends confidence that these results are reasonable representations of in vivo laryngeal flows.

It was observed that the establishment of the Coanda effect in pulsatile flow depends more strongly on the local unsteady acceleration than on the pulsation frequency, as has been previously reported by Pelorson et al. (1994, 1995), Hirschberg et al. (1996), and Hofmans et al. (2003). These findings result from a more physiologically relevant scenario of a fully pulsatile flow field, and they are not contradictory to previous results (Pelorson et al., 1995; Hofmans et al., 2003) if those results are interpreted by using the findings presented here. The attachment of the Coanda jet to the adjacent wall consistently occurred when the forcing velocity waveform reached its maximum value, and the acceleration was zero, for glottal divergence angles $\Psi = 20^\circ$. For a postcritical divergence angle of $40^\circ$, the flow never attached to a wall.

The separation point of the flow from the vocal-fold models also varied as a function of divergence angle, consistent with the findings of Newman (1961). For $\Psi = 10^\circ$, the flow detached from the vocal-fold models at the onset of the exit radius. Increasing $\Psi$ to $20^\circ$ resulted in the flow staying attached halfway around the exit radius. The presence of the Coanda effect in phonation is expected to influence sound production due to the drastic change in the separation point.
of the flow, as well as the interaction of the skewed jet with the ventricular folds. The pressure distribution on each vocal fold arising from an asymmetric separated flow will also result in a difference in the aerodynamic forces acting on the two folds.

ACKNOWLEDGMENTS

This research was funded by the National Institutes of Health Grant RO1 DC03577. The authors would like to acknowledge Alison Templin for her assistance in data acquisition on the project.


