Dynamics of temporal variations in phonatory flow^{a)}

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This paper addresses the dynamic relevance of time variations of phonatory airflow, commonly neglected under the quasisteady phonatory flow assumption. In contrast to previous efforts, which relied on direct measurement of glottal impedance, this work uses spatially and temporally resolved measurements of the velocity field to estimate the unsteady and convective acceleration terms in the unsteady Bernoulli equation. Theoretical considerations suggest that phonatory flow is inherently unsteady when two related conditions apply: (1) that the unsteady and convective accelerations are commensurate, and (2) that the inertia of the glottal jet is non-negligible. Acceleration waveforms, computed from experimental data, show that unsteady and convective accelerations to be the same order of magnitude, throughout the cycle, and that the jet flow contributes significantly to the unsteady acceleration. In the middle of the cycle, however, jet inertia is negligible because the convective and unsteady accelerations nearly offset one another in the jet region. These results, consistent with previous findings treating quasisteady phonatory flow, emphasize that unsteady acceleration cannot be neglected during the final stages of the phonation cycle, during which voice sound power and spectral content are largely determined. Furthermore, glottal jet dynamics must be included in any model of phonatory airflow.

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I. INTRODUCTION

This paper addresses the following question: Is phonatory airflow inherently unsteady? The answer to this question is relevant because it determines the volume of air forced through the glottis during a phonation cycle, and hence the level of sound produced. Given that the flow is strongly time-dependent, the question may seem peculiar. However, many investigators (Pelorson *et al.*, 1994; Story and Titze, 1995; Lous *et al.*, 1998) have assumed glottal flow to be quasisteady. Others (Mongeau *et al.*, 1997; Zhang *et al.*, 2002; Vilain *et al.*, 2004) have presented experimental evidence that phonatory is, at least in part, quasisteady. If these studies are correct, phonatory airflow is able to adjust essentially instantaneously to changes in geometry (vocal fold wall motion) or driving forces (transglottal pressure gradient), regardless of the inertance and compliance of the subglottal and supraglottal regions. There are at least two important practical implications of such a situation. First, the volume flow rate for a given transglottal pressure is maximum. Second, mathematical modeling of phonatory flow is greatly simplified. These implications explain the attention given this question over the last 20 years.

A comprehensive answer to the question posed above can be found by reference to the equation of motion. Newton's second law, written for a fluid, contains two terms describing the acceleration of fluid particles: One (the unsteady acceleration) describes the acceleration due to local time variations in fluid velocity, and the other (the convective acceleration) describes accelerations due to spatial variations such as those found in a duct flow (such as the contraction formed by the vocal folds at the exit of the trachea). If temporal variations are dynamically relevant, then the former effect will be at least commensurate with the latter. Conversely, a quasisteady flow is one in which the former is negligible compared to the latter.

The Strouhal number argument outlined by Hirschberg (1992) is a first-order approach to estimating the relative strengths of the two accelerations. The Strouhal number St is a non-dimensional parameter which in principle measures the relative strength of the unsteady acceleration relative to the convective—the larger St , the more unsteady effects are important to the dynamics of phonatory flow. Hirschberg (1992) argued that $St \sim f_0 L / U$ where f_0 is the vibration frequency, L the glottis length, and U the maximum jet speed. Because St defined in this manner is $O(10^{-2})$ for glottal flow, it was argued, time variations have no dynamic relevance in phonatory flow. Hirschberg (1992) did present physical arguments that during the jet flow initiation, for example, time variations may play a dynamic role. McGowan (1993) built

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on this idea, citing the inherent unsteadiness of the separated flow in the upper reaches of the glottis, particularly the motion of the separation point.

Implicit in McGowan's (1993) arguments is the realization that the dynamic relevance of time variations may vary during 1 cycle, depending on the spatial and temporal structure of the flow. In fact, the experimental studies of Mongeau *et al.* (1997), Zhang *et al.* (2002), and Vilain *et al.* (2004) all show that any agreement between their measurements and a quasisteady flow model is only valid for limited time intervals of the cycle. In particular, the flow in the initiation and shutoff intervals shows marked departures from a quasisteady description. Thus the idea that a single non-dimensional parameter (such as St) can characterize the unsteadiness of the flow for the whole cycle finds little empirical support.

The empirical studies cited above all focused on measurement of glottal impedance, using measures of transglottal pressure and volume flow, rather than a direct comparison the acceleration terms. The experiments of Kucinski *et al.* (2006) also estimated glottal impedance from flow and pressure measurements. Their study showed evidence that glottal aerodynamic impedance varies with vibration frequency. While this result might suggest that flow unsteadiness may become more important as frequency increases, it is not an unambiguous test, because the pressure gradient depends on the inertance and compliance of the model vocal tract and subglottal region.

The theoretical study of Krane and Wei (2006) compared the order of magnitude of terms in the equation of motion for phonatory airflow, in particular, making a distinction between unsteady and convective acceleration mechanisms. They developed a generalized Bernoulli equation which relates transglottal pressure to volume flow, and which includes mediating factors such as friction, wall motion, and the movement of the point of separation. Using the scales of motion, they showed that, with the exception of the separation point, most of the additional terms are negligible in phonatory flow, at least for an interval in between flow initiation and flow shutoff interval. These conclusions were tempered by the caution that in their analysis, the pressure in the jet region was assumed uniform, i.e., that the jet inertia is zero. Beyond the order of magnitude arguments of Hirschberg (1992) and Krane and Wei (2006), the relationship between the two acceleration terms in phonatory airflow, especially in the jet region, has not been systematically addressed, by theoretical, experimental, or computational means.

As just noted, another untested assumption in the traditional phonatory aerodynamic model is that the glottal jet's only contribution to phonatory aerodynamics is a quasisteady pressure loss, the primary mechanism of glottal flow resistance. As Krane and Wei (2006) noted, this approach assumes that the jet immediately diffuses its momentum into the ambient stagnant fluid just downstream of the vocal folds, and that this process is a quasisteady one. The traditional analysis, first advanced by van den Berg *et al.* (1957), and built upon by Ishizaka and Flanagan (1972), locates the jet-diffusion loss at the glottal exit (or, more generally, at the separation point—see, e.g., Pelorson *et al.*, 1994; Story and

Titze, 1995; or Lous *et al.*, 1998 for more recent modeling examples that directly address this issue). This approximation is useful when the jet flow is steady, despite the fact that jet diffusion takes place over an extended region, because the jet is in equilibrium with the ambient air. As pointed out by Titze (1994), there is no guarantee that this equilibrium, which allows the lumped-loss approximation advanced by van den Berg *et al.* (1957), is continually re-established during the large excursions in jet momentum that occur during a single vibration cycle. Several results gleaned from literature strongly suggest that it does not. First, Hofmans *et al.* (2003) indicates that the pressure downstream of the separation point (i.e., along the jet) is non-uniform. For the jet to play the limited role it has been assigned, the pressure along the jet must be uniform. Second, recent work (for example, Kruger *et al.*, 2005) indicates that the forces driving a time-varying jet must overcome not only the inertia of the fluid in the jet, and that of the air entrained into it, but also the “added mass” of the fluid pushed into motion by jet initiation, or by alteration of the jet's momentum. These effects should be associated with a non-uniform pressure distribution along the jet. Finally, the pressure measurements used in impedance tests of quasisteady flow are taken far downstream of the model vocal folds (Zhang *et al.*, 2002), or the models vent into the open atmosphere, which is used for the downstream pressure reference (Mongeau *et al.*, 1997; Deverge *et al.*, 2003; Vilain *et al.*, 2004). As a result, the assumption of uniform pressure along the jet is not rigorously tested. The dynamics of glottal jet flow downstream of the separation point and how it compares to that in the contraction region have yet to be addressed in terms of the flow acceleration. A non-uniform pressure distribution along the jet should be reflected as a nonzero net acceleration (inertia) along the jet. Thus an assessment of jet inertia is an important part of assessing the dynamic relevance of time variations in phonatory flow.

Previous work has thus addressed the issue of phonatory flow unsteadiness under the following implicit assumptions.

- (1) The flow dynamics are uniform over the whole vibration cycle, and over the entire length of the flow between the vocal folds, and can thus be characterized by a single non-dimensional parameter St of order 10^{-2} .
- (2) The glottal jet inertia is negligible (i.e., the jet flow is quasisteady).

Further, previous empirical tests of the quasisteady assumption approached the issue by comparing measured glottal flow impedance to an expression that obtains if the flow were, in fact, quasisteady. This paper takes a different approach, based on a more fundamental definition of flow quasisteadiness. Instead of comparing the transglottal pressure-volume flow ratio, this work compares the level of the two acceleration terms (convective and unsteady) using measurements of the velocity field of the flow between moving model vocal folds. Because the acceleration terms are estimated from data only in the region of interest, and because the relative magnitude of the two terms is the basis for comparison, the result is independent of the dynamics of the adjoining regions.

FIG. 1. (Color online) Sketch of phonatory flow showing coordinates defined in the text. Also shown are the contraction and jet flow regions, in which the dynamics of the flow are qualitatively distinct, as discussed in Sec. II C.

The paper proceeds as follows. First, a definition of quasisteady flow is given in terms of the relative magnitudes of the two acceleration terms. The behavior of these terms in the contraction and jet regions are discussed, and the relevant scales of motion are identified and used to interpret the meaning of non-dimensional parameters such as the Strouhal number and the reduced frequency of vibration. Second, measurements of the flow between two moving walls moving in a manner consistent with vocal fold vibration, are used to assess the two implicit assumptions identified above that underlie quasisteady flow. These data are used to show that the flow evolves at smaller time scales than those of the wall, establishing that the dynamics of the flow changes during 1 cycle. The acquisition of a new data set in the region between the model vocal folds is described, and the data are used to show how the acceleration terms behave differently in the contraction and jet regions of the flow. It should be emphasized that this approach does not require the measurement of pressure. As described below, the definition of quasisteady flow denotes that the two mechanisms of air acceleration have a particular relationship, allowing a direct assessment of the quasisteady assumption. It is important to stress that this test focuses on the value of the acceleration terms in the volume between the vocal folds, independent of the inertance of the rest of the physical model.

II. THEORETICAL CONSIDERATIONS

A. Geometry

Figure 1 shows a sketch of the geometry of phonatory flow. The coordinates x_A , x_S , and x_C denote the axial locations of the entrance of the contraction (at the intersection of the conus elasticus and the trachea), the separation point, and the glottis exit, respectively. The separation point location x_S is of particular importance because upstream of x_S , in the *contraction region*, the flow is attached and conforms to the shape of the walls. Downstream of x_S , in the *jet region*, however, the jet flow does not follow the shape of the passage.

The cross-sectional area of the region bounded by the vocal fold walls is denoted S , with subscripts indicating axial location, e.g., $S_A = S(x_A)$, is the cross-sectional area at $x = x_A$. The cross-sectional area of the jet is denoted S_j . As discussed below, the flow in each region displays qualitatively different dynamics, so that time variations of flow may have qualitatively different dynamic impact.

B. Quasisteady flow: Definition

A definition of quasisteady phonatory flow begins with the axial momentum equation (Newton's second law) along the centerline of the glottis (Krane and Wei, 2006)

$$\rho \frac{\partial u}{\partial t} + \rho \frac{1}{2} \frac{\partial u^2}{\partial x} = - \frac{\partial p}{\partial x}, \quad (1)$$

where flow has been assumed to be essentially symmetrical about the centerline. The left-hand side is rate-of-change of momentum (per unit volume) of the airflow at a particular location in the fluid, and the right-hand side is the sum of the forces (per unit volume) on the airflow at the same location. From left to right, the first term is the unsteady axial acceleration, the second is the axial convective acceleration, and the third is the net axial pressure force. A fluid flow is *steady* if the *unsteady acceleration is identically zero*.

An unsteady flow is one where the unsteady acceleration is nonzero. *Quasisteady* flow is essentially a time-varying flow where the *unsteady acceleration is negligible compared to the convective acceleration*. This occurs when the acceleration of the flow due to time-dependent boundary conditions, such as boundary motion, or time-varying inlet and outlet pressure, is much smaller than the acceleration that takes place due to changes in area of the flow stream. As such, the unsteady acceleration is a measure of the inertive resistance of the flow to a change in pressure gradient and wall shape.

Integrating Eq. (1) along the centerline of the glottis, between two axial locations x_1 and x_2 , results in

$$\rho \int_{x_1}^{x_2} \frac{\partial u(x,t)}{\partial t} dx + \frac{\rho}{2} (u_2^2 - u_1^2) = p_1 - p_2 + h_0(t), \quad (2)$$

where h_0 is the head loss due to friction in the glottis. The left-hand side, as in Eq. (1), is the net acceleration (flow inertia), equal to the sum of the unsteady and convective accelerations (times mass per unit volume). The right-hand side is the pressure force per unit volume acting on the flow along the streamline from x_1 to x_2 .

Note that Eq. (2) is essentially Bernoulli's equation for an unsteady flow. The more familiar, steady flow version of Bernoulli's equation does not include the unsteady acceleration term. Deverge *et al.* (2003) and Krane and Wei (2006) have shown how this term may be further decomposed to show explicitly the contributions of vocal fold wall motion and axial excursions of the separation point, so it should be recognized that these effects are also lumped into this term. For the present study, the unsteady term will be treated as a unit.

Since “quasisteady flow” is an approximation, an identically zero unsteady acceleration is not necessary. Instead, the unsteady term should be negligible compared to the convective acceleration

$$\frac{\rho \int_{x_1}^{x_2} \frac{\partial u(x,t)}{\partial t} dx}{\frac{\rho}{2}(u_2^2 - u_1^2)} \ll 1, \quad (3)$$

defining a general criterion to assess the degree of unsteadiness of a flow. Note that this criterion is defined over a finite axial distance (from x_1 to x_2), and is thus in this form not a comparison of local quantities, but instead defined for the region of interest $x_1 < x < x_2$ as a whole, and only for that region of interest, independent of the dynamics of the adjoining regions. It should be emphasized in that the formulation used here, relative magnitudes of the two acceleration terms are defined for the entire region of interest (e.g., between $x_1 = x_A$ and $x_2 = x_C$, the contraction entrance and glottis exit, respectively). Quasisteady phonatory flow adjusts more or less instantaneously to changes in its environment (due to, e.g., transglottal pressure and vocal fold shape). In other words, the flow inductance is negligible. In such a situation, the condition defined in Eq. (3) is satisfied. If the condition in Eq. (3) is not satisfied, then the flow in the region of interest cannot adjust rapidly to changes in its environment, and the unsteady acceleration cannot be neglected compared to the convective acceleration, in the region of interest. Estimation of the acceleration terms in a particular region using a velocity field measured in the same region is thus an unambiguous assessment of the dynamic relevance of time variations of flow in that region, independent of the inductance and compliance of adjacent regions. Furthermore, this test does not require measurement of pressure.

C. Order of magnitude arguments for neglecting unsteady acceleration

The traditional argument for quasisteady phonatory flow, following a “Strouhal number criterion” (see [Hirschberg, 1992](#); [Krane and Wei, 2006](#)), is now revisited in light of the above discussion. The Strouhal number, St , is generally a measure of the ratio of unsteady acceleration to convective acceleration. It is typically estimated for phonatory flow to be (see, e.g., [Hirschberg, 1992](#))

$$St \approx \frac{f_0 L}{U} \sim \frac{L}{UT}, \quad (4)$$

where U is the velocity at the minimum area location of the glottis, $L \sim x_S - x_A$ is the length of the glottis, f_0 the fundamental frequency of vibration, and $T = 1/f_0$ the vibration period.

In the traditional argument, the relative strengths of the ratio of unsteady to convective acceleration are found by estimating the order of magnitude of each term as follows:

$$\rho \int_{x_A}^{x_S} \frac{\partial u(x,t)}{\partial t} dx \sim \rho \frac{U}{T_o} L, \quad (5)$$

FIG. 2. (Color online) Single realization of maximum axial velocity component at glottal exit plane vs t/T_o for $f^* = 0.035$ and $f_{ls} = 109$ Hz. Three dynamically distinct flow intervals are indicated, as are the time scales associated with each, as described in the text. 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. Data are from [Krane et al., 2007](#).

$$\frac{\rho}{2}(u_S^2 - u_A^2) \sim \rho U^2, \quad (6)$$

where $x_1 = x_A$ (the location of the contraction entrance), $x_2 = x_S$ (the location of glottal flow separation), and T_o is the time that the glottis is open. Note that this time scale is more fitting than the vibration period T for estimating $\partial u / \partial t$ because flow occurs only when the glottis is open. These two time scales are related by $T_o = Q_o T$, where Q_o is the open quotient ([Titze, 1994](#)).

Note that implicit in the estimates (5 and 6) is not only that $u_S \approx U$, but also that $u_A \ll u_S$ due to the large change in area from the trachea (at x_A) to the separation point (at x_S). The ratio of the unsteady term to the convective term then has an estimated order of magnitude

$$St \sim \frac{L Q_o}{UT_o}, \quad (7)$$

which is greater than the estimate given in Eq. (4) by a factor of $1/Q_o$. For the scales observed in phonatory flow, St , defined thusly, ranges from 0.01 to 0.1, suggesting that the flow is, in fact, quasisteady.

Implicit in such arguments is that the dynamics of the flow do not change during 1 cycle, and that the flow changes at time scales commensurate with the wall motion time scale T_o . Experimental evidence ([Berke et al., 1989](#); [Alipour et al., 1995](#); [Mongeau et al., 1997](#); [Barney et al., 1999](#); [Zhang et al., 2002](#); [Krane et al., 2007](#)) suggests that these assumptions are not correct. For example, Fig. 2 shows the maximum velocity at the exit of a model glottis ([Krane et al., 2007](#)), as a function of percent of the open period T_o of the wall motion cycle. Note that the velocity rises rapidly as the flow initiates, then plateaus, then rises again, beginning roughly halfway through the open interval, before falling rapidly just prior to closure. We expect the ratio of the unsteady and convective accelerations to be higher during the startup and shutoff intervals than during the middle interval, because the time scales of these intervals are so much shorter. This strongly suggests that we cannot treat the flow

dynamics uniformly throughout 1 cycle; there are dynamically distinct intervals during a single cycle.

A time scale, and hence, a Strouhal number, can be defined for each of these dynamically distinct intervals. The first time scale, T_a , denotes the duration of initiation and shutoff, as shown in Fig. 2. The second, T_m , the duration of the middle interval, is given by $T_m \sim T_o - 2T_a$. Flow measurements (Berke *et al.*, 1989; Alipour *et al.*, 1995; Mongeau *et al.*, 1997; Barney *et al.*, 1999; Zhang *et al.*, 2002; Krane *et al.*, 2007) shows the ratio T_o/T_a can be as high as 6. The unsteady acceleration during the flow initiation and shutoff intervals, estimated using the flow time scale T_a , then becomes

$$\rho \int_{x_A}^{x_S} \frac{\partial u(x,t)}{\partial t} dx \sim \rho \frac{U}{T_a} L \sim \rho \frac{U}{T_o} \frac{T_o}{T_a} L. \quad (8)$$

The ratio of the unsteady term to the convective term then has an estimated order of magnitude

$$\text{St}_a \approx \frac{L}{UT_a} \sim \frac{L}{UT_o} \frac{T_o}{T_a} \sim f^* \frac{T_o}{T_a}, \quad (9)$$

where St_a denotes the Strouhal number for the startup and shutoff intervals. The new parameter $f^* = L/(UT) = LQ_o/(UT_o)$ is the reduced frequency of vibration, identical in appearance to the “Strouhal number” defined in Eqs. (4) and (7), ranges from 0.01 to 0.1. Equation (9) then suggests that the Strouhal number can, in fact, exceed 0.1 in those intervals of the vibration period during which the velocity changes rapidly, even when $f^* \sim 0.01$. In these rapidly changing intervals, then, the flow is clearly unsteady. Contrast this with a Strouhal number estimate St_m for the remainder of the open part of the vibration cycle, where the flow time scale is now $T_o - 2T_a$,

$$\begin{aligned} \text{St}_m &\sim \frac{L}{UT_m} \sim \frac{L}{U(T_o - 2T_a)} \sim \frac{L}{UT_o} \frac{T_o}{(T_o - 2T_a)} \\ &\sim f^* \frac{1}{\left(1 - 2\frac{T_a}{T_o}\right)}. \end{aligned} \quad (10)$$

The smaller T_a/T_o , the closer St_m is to f^* for the middle flow interval, suggesting that this interval is less unsteady than the startup and shutoff intervals. These arguments are consistent with the results of Mongeau *et al.* (1997), Zhang *et al.* (2002), and Vilain *et al.* (2004), who all showed substantial intervals in the middle of the open period during which the measured glottal flow and transglottal pressure were consistent with a quasisteady flow assumption. At the same time, these studies also reported brief intervals at the beginning and end of the open period in which the flow was not consistent with such an assumption. Even finer time scales, identified by Krane *et al.* (2007) to be associated with vortex shedding, are evident in the velocity traces of Fig. 2. Yet another Strouhal number can be defined for this process, which is a subject of current investigation.

The above discussion emphasizes that a Strouhal number estimated using the cycle period [as in Eq. (4)] is not a useful assessment of phonatory flow unsteadiness. Instead,

each dynamically distinctly different time interval of 1 cycle should be assessed separately using a Strouhal number estimated with its appropriate time and velocity scales. While it should not be interpreted as a measure of phonatory flow unsteadiness, the parameter $f_o L/U$ is still useful as a non-dimensional frequency of vibration. It is thus recommended that $f^* = f_o L/U$ be denoted as a *reduced vibration frequency*, to distinguish it from the Strouhal number, which has the specific dynamic interpretation as the relative strengths of the unsteady and convective accelerations, which f^* cannot address. For example, when reading Krane and Wei, 2006 and Krane *et al.*, 2007, f^* should be substituted for St in all cases.

D. Effect of flow geometry on acceleration terms

The discussion in Sec. II C suggests that phonatory flow does not in general exhibit just one type of dynamical behavior in a single cycle. Rather, it transitions between dynamically distinct regimes (unsteady to quasisteady, and then back) in a single vibration cycle. In the same way, the flow may exhibit dynamically distinct spatial regions, depending on the flow geometry. In other words, the geometry of the flow can also affect the dynamic relevance of the phonatory flow time variations. The sketch in Fig. 1 shows two distinct flow regions: a contraction region and a jet region. The dynamical distinction between the flows in these regions arises primarily from whether the cross-sectional area of the flow changes rapidly in space, compared to how rapidly the flow changes speed in time. The spatial variation in the flow is in turn controlled by how the flow cross-sectional area matches that of the walls. In the contraction region, the two areas are identical, while in the jet region the flow cross-section is narrow and focused, even as the walls diverge rapidly. In what follows, the effect of this simple qualitative change in flow geometry will be considered separately for the contraction and jet regions, and finally, for the combined region comprising both.

How flow geometry impacts the flow dynamics in each region is illustrated through further development of Eq. (2). In Eq. (2) (see Deverge *et al.*, 2003; Krane and Wei, 2006), the convective term may be re-written in terms of the velocity at x_2 as

$$\rho \int_{x_1}^{x_2} \frac{\partial u(x,t)}{\partial t} dx + \frac{\rho u_2^2}{2} \left(1 - \left(\frac{S_2}{S_1}\right)^2\right) = p_1 - p_2, \quad (11)$$

where S_1 and S_2 are the cross-sectional areas of the flow at x_1 and x_2 , respectively. [Here, h_0 has been neglected, relative to $p_2 - p_1$, after Krane and Wei (2006).] Inspection of Eq. (11) shows immediately that, when $S_1 = S_2$, the convective acceleration is zero. In this situation, a time-varying flow is inherently unsteady. Note in addition that a steady flow with $S_1 = S_2$ experiences no pressure variation along its axis.

The flow in the attached region ($x_A < x < x_S$, where $S_1 = S_A$ and $S_2 = S_S$) between the vocal folds (sketched in Fig. 1) is characterized by large changes in cross-sectional area ($S_S/S_A \ll 1$), so it might be expected that the convective acceleration dominates there. With these consideration in mind, the traditional argument for quasisteady phonatory flow es-

sentially proceeds as follows: If the unsteady acceleration is negligible, then the pressure forces (and hence, forces on the vocal fold walls) are determined by the flow in the contraction, which by virtue of its large area change, is dominated by convective acceleration. This argument implicitly assumes the pressure along the jet is negligible, which is equivalent to stating the inertia of the jet (sum of the unsteady and convective acceleration terms in the jet) is negligible.

The convective acceleration behaves very differently in the jet region ($x_S < x < x_C$, where $S_1 = S_S$, $S_2 = S_C = S_j$, and $S_j/S_S \approx 1$). Here, the jet flow is focused in a compact region near the centerline, so that the flow area no longer tracks the vocal fold wall shape. At first glance, it appears that the convective acceleration is small. As a result, any time variations should result in an inherently unsteady flow. However, changes in the flow speed and area at the separation point convect along the jet at a finite speed to the glottis exit (see, e.g., Blake, 1986; Zhang and Johari, 1996; Krane, 2005), providing a mechanism for a nonzero convective acceleration in the jet. In any case, Eq. (11) in the jet region shows explicitly the relationship between jet inertia (the net acceleration, the sum of the unsteady and convective terms) and the pressure distribution along the jet—a nonzero net acceleration is also associated with a pressure gradient along the jet.

Since phonatory flow is time varying, and since convective delay provides a mechanism for nonzero convective acceleration even when the flow area change is small, it is unlikely that that jet inertia can be zero (or small) unless the unsteady and convective accelerations have the same magnitude, but opposite sign, so they offset one another. This can occur if the acceleration due to time variations is offset by the convective delay in transporting a temporal change in u along the jet axis from the separation point to the glottis exit. This is analogous to the following conditions under which Taylor's hypothesis is valid (see, e.g., Tennekes and Lumley, 1972):

$$\rho \int_{x_1}^{x_2} \frac{\partial u(x,t)}{\partial t} dx = -\frac{\rho u_2^2}{2} \left(1 - \left(\frac{S_2}{S_1} \right)^2 \right).$$

This condition holds when flow disturbances are “frozen;” i.e., the time evolution of the flow at any point is due solely to the transport of the disturbance past the point in question. For such a situation, jet inertia (and, further, $p_1 - p_2$) is zero as follows:

$$A_{\text{net}} = \rho \int_{x_1}^{x_2} \frac{\partial u(x,t)}{\partial t} dx + \frac{\rho u_2^2}{2} \left(1 - \left(\frac{S_2}{S_1} \right)^2 \right) = 0. \quad (12)$$

Considering the combined region ($x_A < x < x_C$), comprising both the attached and separated flow regions, the relative magnitudes of convective and unsteady acceleration depend on the relative lengths of each region, and the behavior of the jet. For example, during flow initiation, the leading edge of the jet takes a finite time to pass out of the glottis (Mongeau et al., 1997; Krane et al., 2007). In this interval, prior to jet development, the flow at the glottis exit follows the shape of the wall, so $S_1 = S_A$, $S_2 = S_C$, and $S_j/S_C = 1$, and convective

acceleration is identically zero. In contrast, once the jet passes out of the glottis, so $S_1 = S_A$, $S_2 = S_j$, and $S_j/S_C \ll 1$, the convective acceleration becomes appreciable, for the combined region. Finally, as discussed above, the possibility exists that even if the unsteady acceleration contribution from the jet region is appreciable, it may be offset in the jet region by convective acceleration of opposite sign. If this offset occurs, jet inertia is negligible, and the net acceleration in the combined region is determined by the relative strengths of the flow accelerations in the contraction region. If this offset does not occur, then the dynamics of the jet cannot be neglected in phonatory aerodynamic modeling, as has been the case heretofore.

E. Summary of theoretical considerations

The above discussion proceeds by first recognizing that phonatory flow during a single vibration cycle consists of dynamically distinct regions and intervals. As such, a blanket assessment of flow quasisteadiness over the whole spatial extent of the flow, over the entire cycle period, is an oversimplification. A Strouhal number based on time and length scales characterizing the flow as a whole is thus not a meaningful estimate of the relative strengths of the unsteady and convective accelerations. Instead, because temporal variations in phonatory flow are much larger and more rapid at the beginning and end than in the middle of the cycle, defining a Strouhal number for each of these intervals more accurately reflects the flow dynamics. In addition, the qualitatively different behavior of flow in the contraction and jet regions suggests that (1) the contraction flow is dominated by convective acceleration over much of the cycle, because of the large area change in the contraction, and (2) the unsteady acceleration in the glottal jet is likely as large as the convective because the jet flow area changes little, but that (3) the two acceleration terms may offset each other in the jet region, resulting in a zero net acceleration along the jet.

Taken together, these observations form a series of criteria for quasisteady phonatory flow, amenable to measurement: *Quasisteadiness occurs only over distinct intervals of the vibration cycle, during the following.*

- (1) Convective acceleration dominates in the contraction region flow.
- (2) In the jet region, even if the unsteady and convective accelerations are commensurate, they offset each other, so that the net acceleration (and, thus, the pressure change) along the jet is small compared to the transglottal pressure gradient.

If these conditions are satisfied, the dynamics of the contraction flow, dominated by convective acceleration, determine the dynamics of phonatory flow as a whole.

The experiments reported in Secs. III and IV of this paper directly address the validity of these criteria.

III. METHODS

A. Model and data acquisition

The physical model experiments performed for this study use the same model and methods as those described in

(a)

(b)

FIG. 3. (Color online) (a) Photo of model vocal fold. Model is made from clear cast acrylic and has a rectangular prismatic shape, except for the medial surfaces, which in cross-section are a half-circle. The axial length of the model fold is 12.7 cm, its transverse dimension is 14 cm, and the dimension along the length of the “fold” is 28 cm. (b) Schematic of flow rig, installed in water channel, as viewed from above. Vocal folds are installed in a 3.66 m long, 28×28 cm² acrylic duct, 46 cm downstream of the duct inlet. The tunnel is set to a steady flow rate, and flow moves through the model glottis when the folds open. Note the two fields of view used for data acquisition in this study, as shown in Fig. 2.

Krane *et al.*, 2007. These measurements used a set of rigid model vocal folds that were moved in the primary (open-close) mode of vibration. Motion of the model vocal folds was performed using stepper motors under computer control. The model vocal folds themselves have a cross-sectional shape shown in the photo in Fig. 3(a), which is similar to that used in the measurements of Deverge *et al.* (2003) and Vilain *et al.* (2004). The vocal folds were mounted in a 28×28 cm² square-cross section, 3.66 m long duct fabricated from clear cast acrylic. This duct was placed in a water channel whose flow was set to a constant steady rate, as shown in the schematic of Fig. 3(b). When the model vocal folds were closed, there was no flow through the duct, and the volume

flow through the duct when the model glottis was open was at most 5% of the total volume flow in the water channel. The steady flow around the model set up a steady pressure distribution around the model. This pressure distribution included a positive gradient between the inlet and outlet of the model vocal tract duct. The flow through the model thus mimics the pressure-driven flow of real speech. Further details of the experimental setup may be found in Krane *et al.*, 2007. The current study uses not only the data from the previous study, which focused on the jet region of the glottis, but also a new set of measurements which include the entire glottis, as described below.

The velocity field on the plane of symmetry of the glottis was measured using digital particle image velocimetry (DPIV). This technique provides a series of snapshots of the velocity field evolution.

The Redlake ES-1 digital camera used in these experiments allows acquisition of 15 velocity vector fields per second, far too low a sampling rate to resolve a life-scale phonatory flow. In order to improve both temporal and spatial resolution, the model was scaled up ten times, and water was used as the working fluid. Dynamic similarity between the model and life-scale flows is ensured by matching the Reynolds number Re and reduced frequency of vibration f^* of the model and life-scale flows, where these are defined as $Re = U h_{\max} / \nu$ and $f^* = L Q_0 / (T_o U)$. Here, L is the axial length of the glottis, measured from the trachea to the pharynx (typically 1 cm, life-scale), U is the maximum velocity in the glottis (typically 20–40 m/s, life-scale), T_o is the time the glottis is open, and ν is the kinematic viscosity (approximately 1.5×10^{-5} m²/s for air). Because the period of wall motion was prescribed such that the model glottis was open for half the period T , this estimate of f^* also uses $Q_0 = 0.5$. The ratios of 10 in size and 15 in kinematic viscosity result in an experiment whose flow speed is reduced by a factor of 150, and whose time scales are increased by a factor of 1500. Thus the cycle period of the model corresponding to a 100 Hz (cycle period of 0.01 s) has a cycle period of 15 s, allowing ample temporal resolution of the velocity field. Details of the DPIV system, its control, acquisition, and processing may be found in Hsu *et al.*, 2000 and Krane *et al.*, 2007.

B. Calculation of acceleration terms from data

The calculation of the convective acceleration for any region is obtained using the form of the term given in Eq. (2). Because the data are discretized in both time and space, the terms in Eq. (2) need to be re-written in discrete form. Accordingly, we define the velocity in terms of the discretized time and spatial location as

$$u(x, t) = u(m\Delta x, n\Delta T_s) = u_m^n,$$

where $n = 0, 1, 2, \dots, N$ and $m = 1, 2, 3, \dots, M$. Here, M and N being the number of time and space steps, respectively, and Δx (approximately 0.13 cm) and ΔT_s (1/15 s) are the spatial and temporal discretization, respectively.

The convective acceleration is computed as one-half of the difference of the squares of the centerline axial velocity

components at the end points of the region in question as follows:

$$A_{\text{conv}} = \frac{1}{2}(u_{m_2}^{n+1} - u_{m_1}^{n+1}), \quad (13)$$

where m_2 is the index of the location of the downstream (superior) edge of the region of interest, and m_1 is the upstream (inferior) location. For example, for the contraction region, $x_{m_1} = x_A$ (contraction inlet) and $x_{m_2} = x_S$. The waveforms of the velocities at these locations are given in Fig. 5, as described below. For each case studied, ten realizations of a single cycle were measured. The convective acceleration was calculated for each case and the ten resulting waveforms were ensemble averaged.

Calculation of the unsteady acceleration from velocity data is more involved. First, the axial velocity at each point along the centerline of the region of interest is differentiated in time using a central difference scheme

$$\frac{\partial u}{\partial t}(x, t) = \frac{\partial u_m^n}{\partial t}(m\Delta x, n\Delta T_s) \approx \frac{u_m^{n+1} - u_m^{n-1}}{2\Delta T_s}, \quad (14)$$

where m and n are integers. Then, at every instant, these derivatives are integrated along the centerline. The numerical estimate of this integral is made using a simple sum of the local value of $\partial u / \partial t$ times the spacing Δx between the points at which the data are defined as follows:

$$A_{us} = \int_{x_1}^{x_2} \frac{\partial u}{\partial t}(x, t) dx \approx \sum_{m=m_1}^{m_2} (u_m^{n+1} - u_m^{n-1}) \frac{\Delta x}{2\Delta T_s}. \quad (15)$$

IV. RESULTS

A. Cases studied

The current study uses the measurements from [Krane et al. \(2007\)](#), as well as a new, previously unreported set of measurements. The previously reported measurements cover ten realizations each of a single cycle of vocal fold motion, for Reynolds number $Re = U_{SS}L/\nu = 8000$ and reduced frequency $f^* = 0.010, 0.018, 0.035$, and 0.040 . Here, L and f^* are defined in Sec. II C, and ν and U_{SS} are the air kinematic viscosity and the steady flow jet speed with the model vocal folds held open to their maximum width. These reduced frequencies correspond to life-scale voice frequencies (for open quotient=0.5) of 30, 60, 108, and 126 Hz, respectively. The field of view of these measurements, which focuses on the jet region of the flow, is shown in Fig. 4(a). The new set of measurements consists of ten realizations of a single cycle for the same Reynolds number, at $f^* = 0.035$, but covers a wider field comprising the length of the combined region, as shown in Fig. 4(b). [Krane et al. \(2007\)](#) showed that in this geometry the flow separates just downstream of the axial location corresponding to the minimum glottal width, hereafter referred to as the *throat*. These convenient references are used to divide the flow between the model vocal folds into the *contraction region*, which extends from the contraction entrance to the throat, and the *jet region*, which extends from the throat to the glottis exit. The flow in the former region is characterized by attached, converging flow, and in the latter by separated jet flow. [Each of these regions is

FIG. 4. (Color online) (a) Example image showing narrow-angle field of view for data acquisition. Flow is from left to right. Ends of model vocal folds are visible at the top and bottom of the image. Model folds are fully open in this image. This view contains only a portion of the entire length of the glottis, mostly the jet region. Data for this field of view are for $Re = 8000$, and $f^* = 0.010, 0.018, 0.035$, and 0.040 . These correspond, in life-scale, to $f_0 = 30, 58, 108$, and 126 Hz, respectively. (b) Example image showing wide-angle field of view for data acquisition. Flow is from left to right. Ends of model vocal folds are visible at the top and bottom of the image. Model folds are fully open in this image. This view contains the entire length of the glottis. *Contraction region* is considered for purposes of this study to extend rightwards from the left-hand edge of the image (the *inlet*) until the location (the *throat*) of the minimum distance between the two model folds. The *jet region* extends rightwards from the throat to the glottal exit plane just over half the horizontal distance along the image. Data taken in this field of view are for $Re = 8000$ and $f^* = 0.035$, as defined in the text.

denoted in Fig. 4(b).] Below, the flow in the contraction, jet and combined regions are below examined separately, and the frequency dependence of the flow in the jet region is also observed.

B. Velocity waveforms

The centerline velocity waveforms at three axial locations: the glottis entrance, throat (axial location of minimum glottal opening), and exit, shown in Fig. 5, show the changing behavior during a single cycle of wall motion, and how these temporal variations differ in the contraction and jet

FIG. 5. Waveforms of centerline velocity at three axial locations, for a single “vibration” cycle, for $f^*=0.035$: the contraction inlet (solid line), the throat (dashed line), and the glottal exit (dashed-dotted line). Velocity amplitude has been normalized by $U_{ss}=28$ cm/s, the speed of a steady state jet through a fully open glottis. Time has been normalized by the time T_o the glottis is open.

regions. In the figure, the velocity has been normalized by the steady state, full-open glottis value $U_{ss}=28$ cm/s (as in Krane *et al.*, 2007). The velocity traces presented are the ensemble average of ten realizations of a single cycle of wall motion. The time axis is the time from the opening of the glottis, normalized by the time the glottis is open during 1 cycle of wall motion. The data presented in Fig. 5 are for $f^*=0.035$, corresponding to a life-scale voice frequency of 108 Hz.

The inlet velocity rises relatively smoothly to reach its maximum value roughly 40% through the open part of the cycle. The velocity then appears to remain at a plateau of roughly 23% of the steady state velocity, until approximately $0.75T_o$, when the velocity begins to fall off to zero. Note that the waveform is not symmetrical—the acceleration of the initial stages is much weaker than the deceleration at the end. By contrast, the velocity at the minimum gap location rises very rapidly and reaches its plateau of $0.8U_{ss}$, which it maintains until $t=0.5T_o$, when the flow accelerates again as the model glottis begins to close. The acceleration continues until roughly $0.75T_o$, when the velocity falls off rapidly to zero prior to closure of the glottis. Finally, the exit velocity rises more slowly than either the inlet or throat velocity, slowing its rate of increase at approximately $0.30T_o$. The exit velocity then rises slowly until approximately halfway through the open part of the cycle. Then, from $0.60T_o$ to $0.75T_o$, the flow accelerates rapidly, exhibiting several oscillations each of which corresponds to the passage of a jet vortex pair through the glottis exit plane (Krane *et al.*, 2007). These oscillations continue and intensify during the period of rapid decrease. This period is of particular importance because it coincides with the volume flow shutoff (Krane *et al.*, 2007) which has been shown to determine voice power and spectral content (see, e.g., Titze, 1994).

It is interesting to note that the velocity traces at the minimum area and the exit do not match except for $t/T_o \approx 0.75$. Prior to this instant, the throat velocity is greater than the exit velocity. The opposite relation is observed for $t/T_o > 0.75$. The change-over essentially coincides with the maxima of the three waveforms shown in Fig. 4. Prior to the

change-over, when the flow as a whole is increasing, the velocity at the minimum glottal area exceeds that at the exit. Afterwards, when the flow is decelerating, the velocity at the minimum area is less than that at the exit. This behavior is suggestive of a convective delay, in which changes in the momentum at the jet formation point are transported down the length of the jet at the speed of the jet. This behavior also suggests that for $t/T_o < 0.75$, the jet is convectively decelerated, and convectively accelerated after. A nonzero convective acceleration in a region where the flow area changes little is also consistent with a convective delay, as described in Sec. II C.

C. Acceleration terms, by region

Figures 6(a)–6(c) show the unsteady, convective, and net accelerations for three regions: the contraction region [Fig. 6(a)], the jet region [Fig. 6(b)], and the glottis as a whole [Fig. 6(c)].

In all cases, the acceleration terms are normalized by U_{ss}^2 , and the time coordinate is normalized by the time T_o that the glottis is open, as in Fig. 5.

The flow in the contraction [Fig. 5(a)] shows behavior described in Sec. II C— A_{conv} is dominant from roughly $0.30T_o$ to $0.75T_o$. The unsteady acceleration term is positive during the acceleration phase and negative during the flow deceleration. The high-frequency oscillations again correspond to vortex pair motion in the glottal jet region. These results are consistent with those reported by Mongeau *et al.* (1997), Deverge *et al.* (2003), and Krane and Wei (2006), in which the effects of wall motion are expected to become commensurate with those associated with transglottal pressure, resulting in unsteady flow during those intervals. It should be noted that because the greatest unsteady acceleration occurs during the flow decay interval. As a result, in this acoustically and perceptually relevant interval is arguably unsteady.

The flow in the jet region [Fig. 6(b)] also shows behavior similar to that expected according to the reasoning given in Sec. II D of this paper. While the flow area in the jet region does not show much axial variation, there is a significant convective acceleration due to the time delay between the throat and exit velocity waveforms. The unsteady acceleration has qualitatively the same behavior as in Fig. 5(a), but in the jet region it attains a much larger magnitude, by as much as a factor of 3. In addition, the initial unsteady acceleration occurs later in the cycle than it does in the contraction region, because of the convective delay in the jet. The result is that in the jet the unsteady acceleration is never negligible compared to the convective acceleration. The flow in the jet region is in that sense inherently unsteady.

The acceleration terms [Fig. 6(c)] for the combined region are simply the sum of the contributions from the contraction and jet regions. From these data, it is clear that there are but a few, brief instants during which the convective acceleration is much larger than the unsteady acceleration. The high-frequency peaks, again, are associated with fluctuations due to the convection and growth of vortex pairs on the

FIG. 6. Comparison of convective (solid, black) and unsteady (dashed, gray) acceleration calculated from DPIV velocity data, for three regions, for $f^*=0.035$: (a) the contraction, (b) the jet region, and (c) the entire length of the glottis. Acceleration has been normalized by the square of U_{ss} , the speed of a steady state jet through a fully open glottis. Time has been normalized by the time T_o that the glottis is open. Data correspond to same case as in Fig. 4(b).

jet boundary. Again, the largest unsteady acceleration occurs during the decay phase of the cycle.

Figure 7 shows net acceleration (inertia) $A_{net}=A_{conv}+A_{us}$ for each region. The jet inertia appears to be small in the interval $0.30 < t/T_o < 0.70$. As a result, the net acceleration for the glottis, as a whole, follows closely the net acceleration for the contraction region, for the middle 40% of the cycle. It should be noted that the jet inertia is not negligible during the rest of the cycle, especially during the acoustically important shutoff interval. For this reason, models of phonatory flow dynamics that do not incorporate jet inertance may be neglecting an important effect.

FIG. 7. Net acceleration (inertia) for three regions, corresponding to the cases in Fig. 6: contraction region (heavy solid line), jet region (light solid line), and whole glottis (dashed line). Coordinates are normalized as in Fig. 6. Negligible jet inertia in the middle interval means that the dynamic behavior of the glottis as a whole is determined by the behavior in the contraction from $0.3 < t/T_o < 0.70$.

D. Frequency dependence of acceleration terms in jet region

Figure 8 shows the net acceleration terms in the jet region, respectively, as a function of cycle frequency. The acceleration and time coordinates are normalized as in Figs. 6 and 7. In Fig. 8, the overall shape of the net acceleration waveform does not change much with frequency. For all cases, the jet inertia is roughly zero in the interval $0.3 < t/T_o < 0.70$. Two pronounced differences are observed, however. The first is that the magnitude of the acceleration increases monotonically with frequency. The second is the high-frequency oscillations associated with vortex shedding. As shown in Krane *et al.*, 2007, the amplitude of centerline velocity fluctuations due to vortex pair motion was shown to increase with frequency. In addition, the vortex shedding rate seems to be determined more strongly by local conditions (jet speed, glottal width, and boundary layer thickness), than on the timing of the wall motion. The result is that more vortex pairs are shed during a single cycle for the low-frequency vibration than for 1 cycle with a shorter open period, and that the amplitude of vortex-induced fluctuations increases monotonically with cycle frequency. These trends

FIG. 8. Comparison of net accelerations in the jet region for three reduced frequencies. Data here correspond to the cases taken in the narrow field view, as shown in Fig. 3(a): $f^*=0.010$ (dark, solid line), $f^*=0.018$ (dashed gray line), and $f^*=0.040$ (dotted line). Coordinates are normalized as in Fig. 6.

result in net acceleration fluctuations which increase with cycle frequency.

V. DISCUSSION

The experimental results presented in Sec. III might appear contradictory. On one hand, the unsteady acceleration is seen to be non-negligible throughout the cycle, suggesting, according to the Strouhal number criterion that the flow is inherently unsteady. In contrast, during the middle interval (excluding startup and shutoff), the net acceleration for the flow in the combined contraction and jet regions is nearly equal to that of the contraction alone. During this interval, the convective acceleration is predominant. Essentially, for the middle interval between startup and shutoff, in the frequency range studied, there is a dynamic equivalence between the flow in the combined regions and that in the contraction. Thus a quasisteady flow model, based on the assumed predominance of convective acceleration in the contraction and zero jet inertia is accurate (again, only in the middle interval), despite the fact that the unsteady acceleration is non-negligible. This apparent contradiction is resolved by noting that (1) the accelerations in the contraction and jet regions are not in phase, and (2) during the middle interval, the convective and unsteady accelerations in the jet region essentially offset so that the net acceleration in that region is nearly zero. This behavior is consistent with the theoretical findings of Krane and Wei (2006), who showed that quasisteady glottal flow requires zero jet inertia (net acceleration). Measurement shows that jet inertia is *not* negligible in the startup and shutoff intervals, however, consistent with the theoretical work of Howe and McGowan (2007). In fact, the inertial contributions of the jet region are at least as large as those of the contraction.

The experimental results in Sec. III are also consistent with the theoretical discussion presented in Sec. II. The temporal behavior of phonatory flow shows qualitatively different dynamics during a vibration cycle, confirming the argument that a Strouhal number based on cycle frequency cannot accurately classify flow dynamics through an entire cycle. Measurement also gives credibility to arguments based on the dynamical distinction between the flow in the contraction and jet regions, in which (1) the flow in the contraction is dominated by convective acceleration, (2) the jet is inherently unsteady because the flow area change is small, and (3) the net acceleration in the jet region may be small due to offsetting unsteady and convective accelerations arising from the convection of slowly varying disturbances.

The present experimental results, and their interpretation, also appear to buttress the conclusions of Mongeau *et al.* (1997), Zhang *et al.* (2002), and Vilain *et al.* (2004) which showed quasisteady flow for the middle interval of the phonation cycle, but unsteady startup and shutoff. The degree to which this unsteadiness is dominated by displacement of air by the motion of the walls (Zhang *et al.*, 2002; Deverge *et al.*, 2003; Krane and Wei, 2006) is currently under investigation. Thus, for a good portion of the cycle, it seems that the dynamics of glottal flow and the forces driving vocal fold vibration can be estimated assuming the net

acceleration is equivalent to the convective acceleration in the contraction. It should be cautioned, however, that this interval comprises but 40% of the time the glottis is open. Furthermore, the flow during the shutoff interval, where the largest changes occur, and which determines the acoustic power and spectral content, is inherently unsteady, with a large contribution from the glottal jet. The aerodynamic behavior of this crucial, final interval is thus still not fully resolved.

It might be argued that the shape of the model vocal folds in this study is not sufficiently realistic. The model shape is rigid, though its motion mimics the first mode of vibration; the real vocal folds also change shape during phonation. These same objections could be made to previous studies as well (Mongeau *et al.*, 1997; Zhang *et al.*, 2002; Vilain *et al.*, 2004). The narrowest region of the model glottis has a shorter axial extent than is physiologically realistic. These are real concerns, and experiments of the kind presented here should be repeated in a more physiologically realistic model. However, it can be argued that what is relevant in determining phonatory flow unsteadiness is the length over which the jet extends. In phonatory flow, the jet forms near the glottal exit while the glottis is converging. In that case, the results for the contraction region alone may be more relevant. During the later stages of a vibration cycle, however, the jet formation point moves upstream, so that the glottal geometry is more similar to that used in the current experiment. That this moving separation point behavior was not observed in the model used in the current study is attributed in part to the model's unchanging shape. In any case, movement of the separation point only increases the level of the unsteady acceleration (Krane and Wei, 2006). Clearly, the effects of glottis shape change and separation point motion need further investigation.

VI. SUMMARY

This paper describes an experimental study of the dynamic role of time variations in phonatory flow. Quasisteady flow was defined to occur when unsteady acceleration in a region is negligible compared to the convective acceleration in the same region of the flow. Each of these terms was defined clearly for flow along the centerline of the flow between the vocal folds. A measure of the convective acceleration was shown to be the difference in half the squares of the velocity at the end points of the centerline through the region in question, while a measure of the unsteady acceleration was calculated by integrating $\partial u / \partial t$ along that centerline. Thus the calculation of the unsteady term required simultaneous measurement of the velocity along the centerline. The question was also addressed in terms of the distinctly different dynamics in two regions: the contraction region, where the flow follows the shape of the vocal fold walls, and the jet region, where the flow does not conform to the shape of the walls. It was shown that convective acceleration is likely to dominate the contraction region, and that quasisteady phonatory flow is a valid approximation when the flow in which this region dominates the dynamics because glottal jet inertia is negligible.

Measurements of the flow in a scaled-up model of the human glottis were performed using DPIV during several cycles of model vocal fold motion. DPIV provides simultaneous measurements of velocity in all points on a plane, so that the data contain spatial as well as temporal information. The experimental model was scaled up ten times life size and water was used as the working fluid to enable adequate temporal and spatial resolution. Dynamic similarity between these measurements and life-scale phonatory flow was established by matching its Reynolds number and reduced frequency of vibration to those of the model flow. This experimental setup allows both temporally and spatially resolved flow measurements.

The measurements were used to calculate the unsteady and convective acceleration terms in the contraction region and jet regions, as well as the “combined region” comprising both regions. In addition, the acceleration terms were calculated from data for the jet region for three additional cycle frequencies. The results show that for the contraction region, the convective acceleration is dominant in the middle 45% of the cycle, while the flow is unsteady during the initial and final intervals of the cycle. In the jet region, however, the two acceleration terms were of comparable magnitude throughout the cycle, but appear to offset one another from $0.30 < t/T_o < 0.70$, but not in the initial 30% and final 30% intervals of the cycle. For the combined region, while the convective acceleration from the large area change in the contraction was high, the unsteady acceleration due to rapid changes in velocity in the jet region resulted in the unsteady acceleration being commensurate with the convective throughout 1 cycle. As a result, according to the definition given in Sec. II, phonatory flow is inherently unsteady, because the unsteady acceleration is never really negligible compared to the convective acceleration.

However, because the net acceleration in the jet region is nearly zero (except during the initial and final stages), the predominant contribution to the net acceleration comes from the contraction region. During those initial and final intervals, the jet also makes a non-negligible contribution to the net acceleration. In this sense, the quasisteady phonatory flow approximation is again verified in the middle interval of the cycle, with the proviso that the conclusion is offered only for the frequency range in which the results cover (< 125 Hz fundamental frequency). Thus, while quasisteady flow appears to obtain in the middle of the cycle, it holds for less than half the time the glottis is open. It should be emphasized that, during the start-up and shutoff temporal regimes, the flow is inherently unsteady, and that the dynamic contribution of the glottal jet cannot be neglected. This suggests that the traditional model for glottal aerodynamic resistance must be supplemented by an additional inertance associated with the unsteady transverse diffusion and added mass of the time-varying glottal jet. This is especially important during flow shutoff, during which the primary contributions to voice sound power and spectral content are developed.

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