Fluid flow in a dynamic mechanical model of the vocal folds and tract. I. Measurements and theory

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In this study, aerodynamic and acoustic measurements were obtained in a dynamic mechanical model of the larynx and vocal tract. The model consisted of a uniform duct, intersected by a pair of sinusoidally oscillating shutters. A controlled airflow along the duct was periodically disturbed by the action of the shutters and pressure, and flow velocity measurements were obtained in the region downstream. The velocity field in the duct could be decomposed into three distinct components: a mean flow, a fluctuating acoustic particle velocity, and a fluctuating nonacoustic velocity associated with the transport of vortices along the duct at the local mean flow velocity. Two theoretical models for sound radiation from the duct exit were investigated. The first was based on the in-duct acoustic field alone and was unable to provide a realistic prediction of the measured, radiated sound field except at the first formant of the duct. In the second a simple description of sound generation due to the interaction of vortices with the duct exit was added. In this case much closer prediction of the measured values was achieved, leading to the conclusion that the interaction of the nonacoustic velocity fluctuation with the duct boundaries results in a significant additional source of acoustic energy located in the region of the duct exit. © 1999 Acoustical Society of America.

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INTRODUCTION

Realistic models of the aerodynamic and acoustic events occurring in and around the larynx during the production of vowel sounds are an important prerequisite for natural sounding articulatory speech synthesis. Furthermore, understanding how changes in these events affect the radiated speech signal may allow diagnosis of speech pathologies without recourse to intrusive and potentially dangerous surgical procedures.

Generally, current models of voiced speech production are developed from the basis of the Acoustic Theory of Speech Production (Fant, 1960). This is a one-dimensional plane-wave acoustic model which proposes that the fluctuating volume velocity at the glottal exit constitutes an acoustic source, and that the vocal tract acts as a passive acoustic filter such that the output speech wave is a convolution of the source waveform and the filter response. All acoustic excitation is assumed to occur at the glottal exit and only fluctuating velocity associated with the acoustic disturbance is considered in the model.

To obtain information regarding physiologically realistic values for fluid velocity and pressure within the glottis and around its inlet and outlet, static modeling studies have frequently been used (e.g., Scherer et al., 1983, 1990; Binh and Gauffin, 1983). However, such models can give little information about the location and nature of the acoustic sources present in the tract, or about unsteady fluid motion.

Latterly, Teager and Teager (1983, 1990) and Kaiser (1983) have called for the rejection of the linear one-dimensional model in its entirety, prompted by apparent anomalies observed in fluid velocity measurements which Teager and Teager obtained in the mouth during the phonation of sustained vowels. These anomalies led them to believe that the fluid motion they were measuring was not solely associated with an irrotational, plane-wave, acoustic particle velocity. They suggested that the separation of the flow from the tract walls, leading to the presence of vortices, could result in additional acoustic sources throughout the vocal tract.

McGowan (1988) and Hirschberg (1992), perhaps prompted by the questions raised by Teager and Teager, have made theoretical studies of the fluid motion in the vocal tract using an aeroacoustic analysis. They suggest that the fluid motion in the vocal tract may, in part, be associated with a nonacoustic velocity component due to the generation of vortices at the glottal exit. Although such a nonacoustic velocity field will not, itself, radiate sound, it may result in additional acoustic sources in the vocal tract due to interaction with the tract boundaries at area discontinuities.

Two-dimensional theoretical models of the fluid motion
at the glottal exit (e.g., Liljencrants, 1989; Thomas, 1986; Hergel and Höge, 1991) suggest that the flow in this region consists of an unsteady jet due to the glottal efflux each cycle, together with its associated shear layer. Thus a mechanism for the production of ordered vortical structures in the flow downstream of the glottal exit is predicted by these computational models.

Calibrated in vivo measurements of the time-varying supra- and sub-glottal pressure within the vocal tract close to the larynx were obtained by Cranen and Boves (1985). However, to obtain corresponding fluid velocity measurements seems both hazardous and impracticable, especially when it is noted that a single measurement per plane, as used for the pressure, is unlikely to be representative of the complicated three-dimensional flow pattern expected in this region.

Experiments using excised canine larynges (e.g., Alipour et al., 1996) show some promise for flow measurements, but the complexity of the geometry provides perhaps too much richness of detail for the underlying mechanisms to be easily identified.

Dynamic mechanical models with, initially, simplified geometries offer the opportunity to investigate unsteady fluid motions while maintaining controllability and repeatability of experimental conditions. Shadle et al. (1991) report flow visualization experiments in a model with a single oscillating shutter representing the vocal fold motion and a square duct representing the vocal tract. They observed the development of a jet at the shutter exit for each cycle of the oscillation. Kiritani et al. (1987) investigated the flow through a driven slit in a rubber sheet using hot wires, noting that the flow close to the slit was confined to a region with roughly the same area as the slit, but that further downstream the region of fluid disturbance had expanded. More recently, Mongeau et al. (1997) used a driven, rubber model with a symmetrical oscillation to investigate the validity of the quasi-static assumption.

In this study a Dynamic Mechanical Model (DMM) has been designed to study the acoustic and aerodynamic effects of periodically interrupting a steady airflow (Barney, 1995). The DMM has similar dimensions to the human male vocal tract. It consists of a cylindrical duct (the vocal tract), open at one end, and supplied with a regulated air flow at the other. The flow is modulated by the motion of a pair of electromechanically driven shutters (the vocal folds). In the first instance the simplest possible representative duct geometry was adopted. In-duct pressure and velocity measurements, together with radiated sound measurements, have been used to investigate the nature of the fluid and acoustic fields within the duct.

The model and its instrumentation are described in Sec. I. In Sec. II the far-field radiated sound spectrum outside the model is presented and in Sec. III the acoustic field within the duct is estimated. It will be shown that the acoustic field within the duct cannot alone provide a realistic estimate for the radiated sound field. Section IV details further study of the in-duct velocity field. It will be deduced from hot wire measurements of the fluid velocity within the duct that in addition to an acoustic field, a nonacoustic flow field is also present, dominated by an ordered train of vortices that convent along the duct at the local mean flow velocity. In Sec. V a simplified model for the scaling of the sound generated by the vortices at the duct exit will be developed. It will be shown that predictions of the radiated sound field that incorporate the contribution of both the acoustic and nonacoustic velocity fluctuation provide closest agreement with the measured values.

I. THE MODEL

The DMM is shown schematically in Fig. 1. It is made from a clear plastic, cylindrical duct 28 cm in length, with an interior diameter of 1.7 cm. The duct is intersected 17.8 cm from the open end by a pair of shutters. The shutters are made of a rigid plastic and can slide across the duct such that they meet each other, dividing the duct into two separate sections. The rectangular channel between the shutters has a length \( l_s \) of 1.7 cm, a depth \( d_s \) of 0.3 cm and a width \( w_s \) that is variable according to the degree of opening. At the open end, the duct terminates in a plane circular baffle 12.5 cm in radius.

Instrumentation can be inserted into the duct at any point, both upstream and downstream of the shutters, via a slot of width 0.5 cm extending the entire length of the duct. The slot can be sealed, with modelling clay, along its length and round the measuring instruments to prevent air leakage. The entire duct can be rotated about its axis, allowing the position of the slot relative to the shutters to be varied. This allows measurements to be obtained at any point in the duct.

Each shutter of the DMM is driven by a Ling Dynamic Systems LD202 vibration generator. The seal between the perspex block and the shutters is not airtight. The amount of air leakage around the shutters can be gauged from the reduction of mean flow velocity downstream of the shutters compared to upstream. For all flow rates used, the reduction was found to be of the order of 10%. The effect of this leakage on the pressure and velocity measurements made in the duct is discussed in the companion paper (Shadle et al., 1999).
The amplitude and driver waveform of each shutter may be individually controlled. However, for the measurements reported here, each vibration generator was driven by an identical sinusoidal waveform with a frequency of 80 Hz.

The shutter position during vibration was monitored by a B&K 4367 accelerometer attached to each shutter. The maximum channel width was 2 mm, for all measurements was 2 mm.

Initially, the shutters were constructed of the same hard plastic material throughout. It was found that setting the shutters so as to obtain complete closure across the duct resulted in their meeting with such force that they bounced apart. This was expected to be reflected in the measured pressure and velocity signals and was thus undesirable. A closed-cell foam strip 1 mm thick was attached to the edge of each shutter allowing closure to occur without bounce. As a result, closure was not instantaneous but could be estimated from the pressure measurements (see Sec. III) to last approximately 1/5 of a shutter cycle (2.5 ms).

Air passed along the duct in the direction shown in Fig. 1. The air was supplied by a compressor remote from the model and could be controlled locally by a pressure regulating valve. The air passed from the valve, via a plastic tube, to a Platon rotameter with a range of 33–416 cm$^3$ s$^{-1}$ and a measurement error of ±8 cm$^3$ s$^{-1}$. A valve at the rotameter allowed fine tuning of the flow rate passing through the model. Pressure at the upstream side of the shutters was not pressure at the duct exit at a distance from the duct.

All transducer signals were stored on a 386 PC and were acquired via a four-channel ADC with 12 bits per sample and a voltage range of ±1 V. The sampling error was equivalent to ±0.5 mV. Acquisition was controlled by Hvlab software which had a simultaneous sample-and-hold method for A-to-D conversion. A sampling frequency of 5015 Hz was used unless otherwise indicated. Hvlab includes software controlled anti-aliasing filters which were used for signal conditioning prior to sampling. The in-duct pressure analysis method described in Sec. III placed a limitation on the bandwidth of the measurements. In accordance with this limitation, the cutoff frequency of the anti-aliasing filters was set to 1 kHz for all measurements except where indicated. The sampling time for each data set was of the order of 10 s.

II. RADIATED SOUND MEASUREMENTS

A. Method

The sound radiated from the open end of the duct of the DMM was measured using a B&K 4134 ½-in. condenser microphone connected to a B&K 4230 amplifier, and placed level with the duct exit at a distance $r = 60$ cm from the duct exit plane such that a line connecting the duct exit plane to the microphone position made an angle of 45° to the long axis of the duct. Measurements were made in a semi-anechoic room with a background noise level, measured using a B&K 2203 sound level meter, of less than 10 dB SPL (re: 20 μPa).

In addition to the aeroacoustically generated sound, the DMM made large amounts of mechanically generated noise due to the shutter driver mechanism. In order to minimize the contribution of the mechanical acoustic sources to the measured radiated sound, two strategies were adopted. The DMM was placed in a separate room from the microphone. A hole the size of the duct was drilled in the wall between the rooms and the DMM was placed so that the duct passed through the hole with the duct exit lying flush with the wall of the measurement room. The circular baffle was removed and the wall, which was sealed round the duct, acted as an “infinite” baffle at the duct termination. All measurements in this paper, with the exception of one set of hot wire measurements (see Fig. 5), were obtained using the “infinite” baffle. The isolation of the mechanical parts of the DMM from the measurement room reduced the mechanically generated contribution to the radiated sound to a large degree, but it was found that some mechanically generated sound traveled down the duct. An estimate of this small contribution was obtained by measuring the sound radiated from the duct exit with no air flow through the model. For all airflow measurements of radiated sound, the time domain estimate of zero-flow radiated noise was subtracted from the measured radiated sound. The shutter accelerometer trace was used to determine the appropriate relative phase for the signals prior to subtraction. A more detailed description of the analysis and implementation of the noise reduction procedure may be found in Barney (1995). With the contributions to the radiated spectrum due to mechanical noise sources minimized, the resulting spectral level for each harmonic of the shutter frequency is considered to be primarily that associated with the aeroacoustic sound generation in the duct.

The far-field microphone measurements (see Figs. 2, 4, and 8) are spectral envelopes in dB re: 20 μPa plotted against nondimensional shutter frequency $ff_0$, where $f$ is the frequency of the harmonic and $f_0$ is the fundamental shutter frequency. All spectral envelopes were calculated from an average of 13 4096-point power spectra with an overlap between time windows of 15%. The data were Hanning-windowed prior to the DFT.

B. Results

Figure 2 shows far-field sound pressures for all three volume flow rates. All spectral components were at least 20 dB above the background noise level except for the 7th harmonic where the SPL was at least 9 dB above the background noise. It is clear that, with the exception of the 7th, 8th, 9th, and 12th harmonics, the SPL increases with increasing volume flow rate $U$. The highest level for each volume flow rate occurs at the first harmonic and decreases until the 5th harmonic, where there is evidence of a resonance peak. A second, higher amplitude resonance spanning the 9th, 10th,
A plane-wave acoustic theory is valid within the duct for waves with wave number $ka$ less than $1.84(1 - M^2)^{0.5}$ (where $a$ is the radius of the duct). For $ka$ greater than this value the first circumferential mode will propagate. For the duct of the DMM the Mach number $M = v/c$, where $c$ is the speed of sound.

A uniform duct of finite length, terminating in an open end, the fluctuating pressure at any point in the duct will be a superposition of two waves, one, an incident wave, traveling outward from an acoustic source, and the other a wave reflected from the open end. Thus the time varying pressure $p(x,t)$ and acoustic particle velocity $u_a(x,t)$ at any distance $x$ along the duct axis for each propagating mode, will be given by

$$p(x,t) = p^+(x,t) + p^-(x,t), \quad (1a)$$
$$u_a(x,t) = u_a^+(x,t) + u_a^-(x,t). \quad (1b)$$

where the superscript ‘$+$’ identifies a wave traveling in the positive $x$ direction and the superscript ‘$-$’ identifies a wave traveling in the negative $x$ direction.

In the presence of mean flow, for each spectral component of a periodic disturbance

$$p^+(x,t) = p_0^+ e^{j(at-k^+x)}, \quad (2a)$$
$$u_a^+(x,t) = u_a^+ e^{j(at-k^+x)}, \quad (2b)$$
$$p^-(x,t) = p_0^- e^{j(at+k^-x)}, \quad (2c)$$
$$u_a^-(x,t) = u_a^- e^{j(at+k^-x)}, \quad (2d)$$

where $p_0^+$ and $p_0^-$ are the component pressure wave amplitudes at the $x=0$ plane, $u_a^+$ and $u_a^-$ are the component particle velocity wave amplitudes at the $x=0$ plane, and $k^+ = \omega/(c_0 + v)$ and $k^- = \omega/(c_0 - v)$ are the wave numbers for the positive- and negative-going wave components in the presence of mean flow $v$.

From Euler’s equation and Newton’s second law it may be shown (Davies, 1988) that the acoustic particle velocity $u_a$ and pressure $p_x$ are described by

$$p_0 c_0 u_a = p^+_x - p^-_x, \quad (3a)$$
$$p_x = p^+_x + p^-_x, \quad (3b)$$

where $p_0$ is the ambient fluid density and $c_0$ is the local sound speed of the fluid.

Given two pressure time histories $p_{x1}(t)$ and $p_{x2}(t)$ at the duct wall at positions $x_1$ and $x_2$, respectively, then the wave components for each frequency in the spectrum may be written (Davies et al., 1980)

$$p_{x1} = p_0^+ e^{-jkx_1} + p_0^- e^{jkx_1}, \quad (4)$$
$$p_{x2} = p_0^+ e^{-jkx_2} + p_0^- e^{jkx_2}, \quad (5)$$

forming a set of linear simultaneous equations which can be solved for $p_0^+$ and $p_0^-$. Then using Eqs. (2) and (3), the fluctuating pressure and acoustic particle velocity can be estimated for any position within the duct.

B. Method

In the DMM, the pressure within the duct was measured using 1/4 in. omni-directional electret condenser microphones inserted through the slot in the duct so that they were flush with the duct wall. The microphones have a bandwidth of 20–20 000 Hz with a linear amplitude response for SPLs up to 120 dB (Harrison, 1994). The microphones were calibrated for amplitude and phase in a known acoustic field. Each microphone was connected to one channel of an ISVR four-channel solid state amplifier.

For this acoustic analysis, pressure time histories were obtained at the wall of the duct for two positions, $x = 4$ and $x = 14$ cm, where the $x = 0$ plane corresponds to the downstream face of the shutters and the positive $x$ direction is the direction of mean air flow. In order to carry out the decomposition of the measured pressure into its component pressure amplitudes, it is important that the downstream transducer not be placed overly close to the duct exit, where the pressure is expected to be close to zero. Furthermore, preliminary hot wire measurements (using the system described in Sec. IV) showed that the velocity disturbance within the first three centimeters of the duct downstream of the shutters was extremely complicated and it was deemed best to place the upstream transducer away from this region. Positioning

FIG. 2. Spectral envelope for the radiated sound pressure measured at 60 cm from the duct exit at an angle of 45° to the long axis of the duct for shutter frequency 80 Hz and three mean flow rates: $U = 200$ cm$^3$ s$^{-1}$ (solid), 300 cm$^3$ s$^{-1}$ (dotted), 400 cm$^3$ s$^{-1}$ (dash-dot).
the microphones at \(x = 4\) cm and \(x = 14\) cm gave the largest possible spacing given the above constraints. Harrison (1994) has shown that the low frequency reliability of component pressure amplitude estimates made from pairs of pressure measurements increases as the separation of the transducers is increased. However, the estimates become unrealistic at frequencies where the half-wavelength is of the order of the transducer separation. For a transducer spacing of 10 cm, as used in this study, this gives a band of unreliable estimates for frequencies between 1.5 and 1.9 kHz. With this in mind, a conservative estimate for the usable bandwidth of the pressure measurements was adopted with an upper frequency limit of 1 kHz.

Examination of the spectra of the pressure signals, obtained from a DFT, showed that most of the energy in the spectrum was contained in the harmonics of the shutter frequency. A set of software bandpass filters with center frequency equal to each of the harmonics of the shutter frequency and bandwidth of 20 Hz was designed. The filters were third-order Butterworth filters and a zero-phase distortion filtering algorithm was adopted. The filters were used to break the pressure signal down into its constituent frequency bands.

For each frequency band, Eqs. (4) and (5) were solved to give the component pressure waves for each frequency at the \(x = 0\) plane. Pressures at other points in the duct were found for each frequency component using Eqs. (2). The total fluctuating pressure prediction at any point is given by the sum of the predictions for each spectral component of the pressure. Similarly the total acoustic particle velocity at any point is given by the sum of the acoustic particle velocity estimates for each spectral component. To minimize the contribution due to mechanically generated noise sources, a similar method to that adopted for the radiated pressure measurements was used. The pressure fluctuation with zero flow was measured at the duct wall for each measurement location and subtracted from the with-flow measurement at the same location.

C. Results

The pressure fluctuation measured at the duct wall for \(x = 4\) and \(x = 14\) cm can be seen in Fig. 3(a) for a volume flow rate of \(200\) cm\(^3\) s\(^{-1}\). Here \(0^\circ\) shutter phase is taken as the mid-point of the closed period of the shutters.

The measurements show large, strongly damped pressure oscillations about a depressed mean during shutter closure, followed by smaller, less strongly damped oscillations about a raised mean while the shutter is open. The amplitude of the oscillations at \(x = 4\) cm is about twice that at \(x = 14\) cm, which corresponds to the well-established fluctuating pressure distribution in a tube open at one end. For larger volume flow rates the amplitude of the fluctuations is greater, but the overall pattern throughout the shutter cycle shows the same features.

The acoustic particle velocity estimate derived from the pressure measurements is shown in Fig. 3(b) for all three volume flow rates at \(x = 14\) cm. The amplitude of the fluctuating acoustic particle velocity increases with increasing volume flow rate and is positive during shutter closure, becoming negative as the shutters open and remaining so until they close again.

The acoustic power, \(W(u_a)\), radiated from the open end of the duct due to the acoustic field within, may be predicted for each frequency component by the well known piston-in-a-plane-baffle model (e.g., Kinsler et al., 1982). The acoustic power at the duct exit is related to the mean square pressure \(p_r^2\) in the hemispherical acoustic far field a distance \(r\) from the duct exit by

\[
W(u_a) = 2\pi r^2 \frac{p_r^2}{\rho_0 c_0} = \rho_0 c_0 (u_a(17.8, t))^2 \pi a^2 \sigma, \tag{6}
\]

where \(a\) is the duct radius, \(\sigma = (ka)^2/2\) is the asymptotic value of the radiation efficiency of the duct exit, \(ka \rightarrow 0\), and \(u_a(17.8,t)^2\) is the time-averaged acoustic particle velocity at the duct exit plane, which may be obtained by using the acoustic particle velocity estimates for the \(x = 0\) plane together with Eqs. (2) to obtain an acoustic particle velocity estimate for \(x = 17.8\) cm and then taking a time average. For a far-field position not on the duct axis, a directivity factor \(2J_1(ka \sin \theta)/(ka \sin \theta)\) must be included on the right hand side of Eq. (6), where \(J_1(ka \sin \theta)\) is a Bessel function of the first kind of order 1 for cylindrical coordinates and \(\theta\) is the angle between the duct axis and the line from the duct exit to the point at which \(p_r\) is measured.

Equation (6) was used to make a prediction for each spectral component of the far-field radiated pressure a distance of \(60\) cm from the duct exit at an angle of \(45^\circ\) to the duct axis. In Fig. 4, this prediction is compared to the mea-
sured radiated pressure obtained at the same location for each volume flow rate.

It is clear that while the predicted and measured values are similar for the 4th, 5th, and 6th shutter harmonics, elsewhere the measured signal is underpredicted by at least 10 dB.

The acoustic field within the duct presumably had significant contributions from one or more acoustic source mechanisms (McGowan, 1998) in the region of the shutters. However, a prediction based on this acoustic field alone was unable to account for the far-field measured spectrum. To investigate further, a more detailed picture of the velocity field within the duct of the DMM was required.

IV. HOT WIRE MEASUREMENTS IN THE DUCT

A. Method

The velocity field at a sequence of selected points in the duct was measured using an ISVR constant temperature hot wire anemometer system (Davies and Mason, 1974), which had a measurement bandwidth of approximately 0–17 kHz. The prongs of the hot wire were 0.5 cm apart with an active wire length of 0.2 cm. The hot wire was calibrated in the duct of the DMM in the following way: The wire was located parallel to the y axis at x = 14, y = 0, z = 0 and the shutters were opened to a width of 1 cm. The rotameter was used to supply volume flow rates measured as 0–416 cm$^3$ s$^{-1}$ in steps of 16 cm$^3$ s$^{-1}$. For each volume flow rate the output voltage of the hot wire was recorded and then paired with the flow velocity calculated from the dynamic pressure measured by a 2-mm pitot-static tube attached to a manometer. The pitot-static tube was located with its tip 1 cm downstream of the hot wire. The voltage recorded by the hot wire was found to be insensitive to the presence or otherwise of the pitot-static tube and, similarly, the dynamic pressure recorded by the pitot-static tube was found to be insensitive to the presence or otherwise of the hot wire. A least-mean-squares fit of a cubic curve was made to the voltage-velocity data pairs to give a calibration curve for the hot wire. A software calibration program applied the calibration curve to each time history recorded by the hot wire. Note that generation of the calibration curve relies only on measurements made in the duct and is thus independent of any error in the volume flow rate as measured at the rotameter due to leakage around the shutters.

B. Results

In Fig. 5 typical velocity time histories are plotted for the lowest volume flow rate for x = 1, 4, and 17 cm downstream of the shutters for three positions on each plane as
indicated in the figure. For the measurements in Fig. 5 only, the sampling frequency was 5 kHz and the anti-aliasing filter cutoff frequency was 2 kHz; also the finite baffle of Fig. 1 was used to facilitate access of the hot wire to locations close to the duct termination. When examining the velocity time histories it is important to remember that none of the time histories was acquired simultaneously, but were later aligned with reference to the observed shutter phase using the shutter accelerometer trace. For the \( x = 1 \) cm plane, the flow pattern varies greatly with time and position across the duct. At \( x = 4 \) cm, the signals are almost periodic for all positions and by \( x = 17 \) cm, the three signals have settled down to an effectively periodic fluctuation superimposed on an almost one-dimensional mean flow. The same general pattern of an approximately uniform flow was observed for the higher volume flow rates although the mean and fluctuating amplitudes were proportionately larger.

Positions \( y = 0, z = 0 \) and \( y = 0, z = 0.6 \) are directly downstream of the opening between the shutters. At \( x = 1 \) cm a symmetric jet exiting the shutters might thus be expected to impinge on the hot wire during every cycle resulting in a periodic hot wire signal. However, shear layers tend to roll up to form vortices which can be expected to result in a periodic hot wire signal over the \( x = 1 \) plane, the flow pattern is symmetric about the plane of the opening at any instant and thus the jet may be expected to flap (like the flapping waves seen in a flag). The observed lack of uniformity of the hot wire signal over the \( x = 1 \) plane seems to correspond to this flow regime.

By 20 jet-widths downstream, it is known from the literature (e.g., Davies, 1981) that a shear layer will have rolled up into a succession of well-formed vortices which, as they move further downstream, will become progressively more diffuse and regularly spaced. This is in accordance with the observed development in both the uniformity and periodicity of the hot wire signals with increasing distance downstream from the shutters (Davies et al., 1995). The observed vorticity distribution corresponds to the field obtained by the appropriate superposition of a one-dimensional acoustic field with that produced by a succession of axially symmetric vortices with their images (Davies, 1996).

It is apparent from the measurements shown in Fig. 5 that a mean flow is always present at all positions, including those at the plane \( x = 1 \). The observations show that the instantaneous velocity at any radial position seldom falls below (and normally remains well above) half its mean value, even when the shutters are closed.

In Fig. 6(a), the amplitude of the measured velocity fluctuation is compared with the acoustic particle velocity estimate for \( x = 14 \) cm for a volume flow rate of \( U = 200 \text{ cm}^3 \text{s}^{-1} \). For these measurements, the “infinite” baffle was once again in place. The time histories for the acoustic velocity and the velocity measured with the hot wire, although not acquired simultaneously, were aligned with reference to the observed shutter phase using the shutter accelerometer trace. It is evident that the hot wire measurements and the acoustic particle velocity estimate are dissimilar in both amplitude and phase, suggesting that the acoustic particle velocity may be only one contribution to the total measured velocity fluctuation. A corresponding discrepancy in amplitude and phase was observable in the higher volume flow rate cases.

In Fig. 6(b), the amplitude of the total velocity fluctuation is compared with that of the acoustic particle velocity estimate on a harmonic-by-harmonic basis for a volume flow rate of \( U = 200 \text{ cm}^3 \text{s}^{-1} \). At the 4th, 5th, and 6th harmonics, the two have approximately equal amplitude and, furthermore, were found to be in phase. Thus for these frequencies the total fluctuating velocity is dominated by the contribution from the acoustic particle velocity. This corresponds to the frequencies where the measured radiated pressure field outside the duct was well predicted using the acoustic field within the duct. Elsewhere the amplitudes (and phases) differ, with the greatest difference in amplitude being at the first harmonic [as can be seen from Fig. 6(a)]. For harmonics 8–12 the acoustic particle velocity is larger than the total measured velocity, but here the total fluctuation was in anti-phase with the acoustic particle velocity estimate. Thus for all harmonics with the exception of the 4th, 5th, and 6th, there appears to be a fluctuating velocity component in addition to the acoustic field within the duct.

It seemed reasonable to assume that this additional fluctuating component might be associated with vortices, generated at the shutter exit and propagating along the duct. To
determine whether this was the case it was necessary to find the convection velocity for this fluctuating contribution. Acoustic disturbances propagate at the local sound speed in the duct, but vortices may be convected at speeds of the order of the local mean flow speed. In the DMM, the local mean flow speeds, determined from the hot wire measurements, were 80 and 120 cm s⁻¹ for volume flow rates measured at the rotameter of 200 and 300 cm³ s⁻¹, respectively.

C. Determination of convection velocity

Velocity measurements obtained using a single hot wire at a fixed position x within the duct of the DMM may contain components due to the convection of spatial variations past the measuring point, and further components due to temporal variations at that fixed measuring point. If two velocity measurements can be obtained with a spatial separation Δx between the measurement positions, then the general dependence of each on the other may be estimated by finding their cross-correlation function. Their cross-correlation coefficient, R, is defined as

$$R(Δx, τ) = \lim_{T→∞} \frac{1}{T} \int_0^T u_A(t)u_B(t+τ) \frac{u_A^2}{u_B^2} \, dt,$$

(7)

where the subscripts A and B denote measurements at positions A and B, respectively, and the overbar denotes a time average. One useful attribute of this function is that it can be used to find the average convection velocity of flow disturbances over the path Δx (Davies and Bose, 1968).

In the duct of the DMM, the velocity was measured simultaneously at two points using two hot wire systems. Note that these measurements were made using the “infinite” baffle. Two volume flow rates were investigated: $U = 200$ cm³ s⁻¹ and $U = 300$ cm³ s⁻¹. Hot wire A was placed at $x = 14$ cm and hot wire B was placed at $x = 14.7$, 14.9, 15.1, and 15.3 cm successively to give four different separation values of Δx: 7, 9, 11, and 13 mm, respectively. The spacing between the wires was maintained by a series of shims corresponding to the spacings Δx, which were clamped between the two probes.

A hot wire loses heat to the air passing by it and thus for some distance downstream of it there exists a thermal wake. If two wires are placed directly behind each other, the downstream wire (hot wire B) will lie in the thermal wake of the upstream wire (hot wire A) and its measurements will be contaminated by the presence of the upstream wire. To reduce the cross-talk between the wires during this study, hot wire B was offset in the z direction with respect to hot wire A, by a distance $Δz = 5$ mm. The hot wires were inserted into the duct such that hot wire A was at $x = 14$, $z = 0.25$. Hot wire B was thus at $x = 14 + Δx$, $y = 0$, $z = -0.25$. Both the spacings Δx and the offset $Δz$ were measured using a traveling microscope.

If one assumes a “smoke ring” vortex traveling down the duct such that it is axially symmetric, then the offset between the wires $Δz$, being itself axially symmetric, should cause no error in the measurement of the time-of-flight of such a vortex from hot wire A to hot wire B. Unfortunately, vortices are seldom so symmetrically distributed and thus errors may be introduced into the convection velocity estimates. It can be argued that the presence of the duct boundaries in the DMM, with the resultant image vortices, would encourage the migration of vorticity toward an axially symmetric distribution, minimizing such errors. Examination of Fig. 5 suggests that an axially symmetric assumption may be valid from about 4 cm downstream of the shutters onward. Any discrepancies in the relative axial displacements of the hot wires would similarly introduce errors. However, Davies and Bose (1968) have shown that for convection velocity measurements in a nonacoustic flow, the estimates of the convection velocity, $u_E$, converge to the convection velocity, $u_x$, as the wire separation, Δx, increases in part because the discrepancies due to positioning of the wires becomes less significant as the overall separation increases. Hence, by taking successive spacings one will arrive at a good estimate of the true convection velocity.

It is possible that different harmonic components in the flow will have different convection velocities. Thus cross-correlation analysis was performed for each successive harmonic component of the fluctuating signals after the corresponding local contribution from the estimated acoustic field had been subtracted from the total measured velocity fluctuation, taking due account of the relative phase between the signals.

For all measurements for the cross correlation, the sampling rate was raised to 10 kHz to provide greater time resolution, while the anti-aliasing filter cutoff frequency was maintained at 1 kHz. The resulting time history extended over 20 shutter cycles for each measurement location.

Figure 7 shows the ratio of the convection velocity estimate $u_E$ for each hot wire spacing to the mean flow velocity within the duct for the fundamental frequency. It may be seen from Fig. 7 that as the hot wire separation increased, the convection velocity estimate tended toward the mean flow speed, indicating that the component of the measured fluctuating velocity not associated with the estimated acoustic field was likely to be due to nonacoustic disturbances or vortex transport along the duct.
A corresponding analysis at the other harmonics of the shutter frequency gave results for the convection velocity estimates which did not differ significantly from those reported for 80 Hz, with the exception of the 4th, 5th, and 6th harmonics where the residual velocity waveform, after subtracting the acoustic particle velocity estimate, were too small to obtain realistic cross-correlation functions. Care had to be taken to ensure the correlations always referred to an individual disturbance.

V. VORTEX SOUND GENERATION

A. Theory

A picture emerges of the field within the duct consisting of an acoustic standing wave field, presumably generated by some combination of sources due to the fluctuating mass and fluctuating aerodynamic force at the exit to the shutters (and possibly the open end), together with a train of vortices, one generated during each shutter cycle, drifting down the duct at the mean flow speed. Thus an expression for the total velocity disturbance within the duct may be written

\[ u = v + u_a + u_n, \]  

where \( u \) is the total velocity, \( v \) is the mean flow velocity, \( u_a \) is the fluctuating acoustic particle velocity for which \( \nabla \times u_a = 0 \), and \( u_n \) is the fluctuating nonacoustic velocity due to vortex transport along the duct for which \( \nabla \cdot u_n = 0 \).

For a mean flow rate \( v \) of 80 cm s\(^{-1}\), a vortex generated at the shutters at time \( t_0 \) travels a distance of 1 cm in time \( t_s \), where \( t_s \) is equal to the period of the shutter cycle. Similarly, for a mean flow velocity of 120 cm s\(^{-1}\), a vortex will travel 1.5 cm over a shutter cycle. Hence for a mean flow velocity of 80 cm s\(^{-1}\) there will be within the duct at any instant, approximately 17 vortices, each with a length of approximately 1 cm. For a mean flow velocity of 120 cm s\(^{-1}\) there will be approximately 11 vortices within the duct, each with a length of approximately 1.5 cm.

Periodically generated vortices are not themselves good radiators of sound. However, it is well known that where they interact with solid boundaries they provide significant acoustic sources and in particular can excite resonators very strongly, as in wind instruments (Davies, 1981). A fluctuating nonacoustic flow generated at an area expansion can thus provide a source of acoustic excitation for a duct. In the DMM where the duct geometry is uniform along its length, the first major area expansion after the shutters is at the open end.

For the DMM it has been demonstrated that the measured fluctuating velocity has contributions from both acoustic and nonacoustic flow fields. The nonacoustic part of the velocity disturbance, incident at an area discontinuity, will cause pressure and velocity fluctuations which will be transported in the acoustic flow field as sound and thus may be expected to contribute to the radiated spectrum. The mechanism by which the nonacoustic flow produces sound is, in general, rather complicated as is the interaction of the two velocity fields; however, a simplified model of the appropriate scaling for vortex noise generation at a duct area discontinuity (e.g., the open end) may be developed (Davies, 1996).

Consider, for simplicity, the vortex motion in the duct to be comprised of an axially symmetric vortex of radius \( R \), where \( R = a/2 \) and \( a \) is the radius of the duct. The circulation \( \Gamma \) of each vortex is given by

\[ \Gamma = \oint u_n \cdot R \, d\theta = 2\pi R u_n, \]  

with a corresponding vorticity of

\[ \Omega = \frac{\Gamma}{\pi R^2} = \frac{2 u_n}{R}. \]  

According to Doak (1995), who described the source in terms of the total fluctuating enthalpy [see also Powell (1964), Howe (1975), and McGowan (1988)], the relationship between the acoustic mean intensity vector \( \mathbf{J} \) and the nonacoustic fluid motion at the boundary discontinuity may be expressed, for the case of small amplitude, adiabatic fluctuations, in an otherwise static and uniform fluid where the convection velocity of the vortices \( v \ll c_0 \), as

\[ \nabla \mathbf{J} = -\rho_0 c_0 (\nabla \times u_n), \]  

where the overbar indicates a time average, and which for the duct becomes

\[ \nabla \mathbf{J} = -\rho_0 c_0 \left( \frac{2 u^2_n}{R} \right) = -\rho_0 c_0 \left( \frac{4 u^2_n}{a^2} \right). \]

The generated acoustic power associated with the vortices is then

\[ \int_{V_S} \nabla \cdot \mathbf{J} \, dV_S = 4 \pi a^2 \rho_0 c_0 \overline{u_n^2}, \]  

where \( V_S \) is the volume enclosing each vortex and the vorticity is assumed to be uniformly distributed through \( V_S \).

From conservation of energy considerations an expression relating the radiated acoustic power at the duct exit to the mean square pressure in the acoustic far field, which is analogous to Eq. (6), may be written for a source in an “infinite” baffle

\[ W(u_n) = 2 \pi a^2 \frac{p^2}{\rho c_0} = 4 \rho_0 c_0 \left( u_n(17.8, i) \right)^2 \pi a^2 \sigma, \]  

where the radiation efficiency \( \sigma = (ka)^2/2 \) was defined with Eq. (6).

One should be cautious about the application of Eq. (14); while it will be valid for the simplified geometry of the DMM, it cannot be strictly relevant for the vocal tract in vivo.

B. Predictions from theory

The same method used for the cross-correlation measurements in Sec. IV was used to estimate the fluctuating nonacoustic fluid velocity amplitude for each harmonic. The acoustic velocity for each harmonic, as predicted from pressure measurements, was subtracted from each harmonic of the total velocity measured by the hot wire, taking due account of the relative phase of the two signals in each case. Since the acoustic velocity is associated with plane-wave
propagation in the duct and the measured velocity close to the open end of the duct was found to be approximately uniform across the duct area, $u_n$ will also be approximately uniform across the duct area. Thus a value for $u_n$ obtained at a single measurement position within the duct may be used to estimate the net volume flux over any plane close to the duct exit. The nonacoustic velocity was estimated at the $x=14$ plane. To obtain the nonacoustic velocity estimate at the open end ($x=17.8$), each harmonic component must be translated along the duct in the positive $x$ direction. This is achieved using an appropriate time shift for the fluctuation at $x=14$. It was shown in Sec. IV that the nonacoustic velocity fluctuation convected along the duct in the positive $x$ direction at approximately the mean flow velocity $\bar{U}$. Consequently, an appropriate time shift to translate the disturbance estimated at $x=14$ cm the short distance to the open end is

$$u_n(17.8,t) = u_n\left(14, t - \frac{x_1}{\bar{U}}\right), \quad (15)$$

where $x_1=3.8$ cm is the distance between the $x=14$ plane and the open end.

A prediction of the far-field sound pressure level for each spectral component at a distance of 60 cm from the duct exit and an angle of 45° due to the contributions to the radiated sound from both the acoustic and the nonacoustic fields is shown in Fig. 8. The contributions from the two velocity fields have been treated as independent since analysis of the relative amplitudes and phases of each harmonic of the two velocity disturbances indicated that contributions from the cross terms $(u_a \cdot u_n)$ were negligible.

The predictions of Fig. 8 demonstrate that combining the contribution associated with the nonacoustic field with the acoustic contribution to the pressure results in much improved agreement between the measured SPL and the predicted SPL. When $U=200 \text{ cm}^3 \text{ s}^{-1}$, the two curves are closely similar except at the 3rd harmonic where the new prediction is 9 dB lower, and at the 10th harmonic where the prediction is 4 dB higher. When $U=300 \text{ cm}^3 \text{ s}^{-1}$ the prediction is closely similar to the measurement except at the seventh harmonic where it is 12 dB higher. When $U=400 \text{ cm}^3 \text{ s}^{-1}$ the predicted levels lie around the measured levels except at the 7th harmonic where the prediction is 14 dB above the measurement. The discrepancies between the measured and predicted levels may be primarily attributable to a combination of the neglect of the cross terms as noted previously and the assumption in the vortex sound model of an axially symmetric vortex with neglect of the effect of any nonuniformity of flow local to the core region. Additionally, implicit in Eq. (15) is the assumption that the vorticity conveys in a nondispersive manner. In general such convection will be dispersive; however, comparison of the hotwire measurements at $x=14$ cm (Fig. 6) and $x=17$ cm (Fig. 5) together with the evidence of the cross-correlation analysis suggests that, far from the shutters and over short distances at least, this assumption of nondispersive convection will lead to a reasonable estimate for the rms value of the nonacoustic velocity fluctuation at the duct exit plane. Clearly there is much better agreement between the measured and predicted SPLs in Fig. 8 than was found for the prediction based on the acoustic velocity component acting in isolation.

Thus one concludes that the nonacoustic velocity field within the duct constitutes a significant part of the sound generation mechanism, providing the dominant sound source except at the 4th, 5th, and 6th harmonics, where the acoustic field was dominant.

VI. CONCLUSIONS

We have described a simple Dynamic Mechanical Model (DMM) of the vocal folds and tract, where the folds are represented by a pair of driven, sinusoidally oscillating shutters.

Measurements of the fluctuating pressure at two points along the duct wall of the DMM, downstream of the shutters, were found to exhibit the characteristic amplitude distribution of an acoustic standing wave field. The energy in these pressure fluctuations was found to be predominantly concentrated at the harmonics of the shutter oscillation frequency, and thus a time domain, plane-wave, harmonic analysis allowed an estimate of the fluctuating acoustic particle velocity field within the duct to be obtained.

Measurements of the velocity field within the duct using hotwire anemometry showed a pattern characteristic of an unsteady jet downstream of the shutters due to the passage of
air through the shutter channel. Over the first 4 cm or so the jet became more diffuse and mixed with the air in the downstream duct. The velocity field was highly three-dimensional at 1 cm downstream of the shutter exit and became gradually more uniform as distance from the shutters increased.

At no position within the three-dimensional flow field close to the shutter exit or the more uniform flow field further downstream did the acoustic particle velocity estimate compare well either in amplitude or in phase-relationship-to-the-shutter-cycle to the measured velocity fluctuation. This is unsurprising, since to assume that the entire fluctuating velocity field within the duct is associated with the fluctuating acoustic field is to assume an acoustic source distribution at the shutter exit with unrealistically high efficiency. It is well known that the shear layer associated with an unsteady jet is inclined to roll up, eventually forming ordered vortical structures in the flow. It seemed probable that the measured velocity fluctuation was the resultant of contributions from both the acoustic particle velocity and from a fluctuating nonacoustic velocity field.

Cross-correlation analysis of dual hot wire measurements confirmed that the component of the measured velocity fluctuation not associated with the acoustic particle velocity estimates had a propagation velocity comparable to the mean flow speed in the duct. Such a nonacoustic, fluctuating velocity field is characteristic of the convection of a train of vortices along the duct.

McGowan (1988) has proposed that the generation of acoustic energy at the glottal exit may be due to two mechanisms: the fluctuating volume flow through the glottal channel as modeled by Fant (1960), and the fluctuating force due to the interaction of the vorticity with the fluid velocity. In the DMM, no information as to the type or number of acoustic source mechanisms, close to the shutter exit or elsewhere, which contribute to the acoustic field within the duct can be obtained from the pressure measurements made at the duct wall. In McGowan’s model, the vorticity is assumed to decay downstream of the glottis. In general, in the absence of strong damping mechanisms, vorticity is known to persist for strong distances. Hirschberg (1992) and Teager and Teager (e.g., 1990) have noted that the interaction of a nonacoustic velocity with abrupt expansions in a duct area function may result in the transfer of energy from the nonacoustic velocity field to the irrotational acoustic field. In the vocal tract this could occur at the epiglottis, palate, teeth, and lips. In the DMM the only abrupt area expansion downstream of the shutters is the duct exit.

For the DMM, a model of the sound radiation at the duct exit based on the irrotational acoustic particle velocity fluctuation in the duct cannot alone account for the measured radiated pressure field except at the first formant of the duct. A model that includes additional contributions to the radiated sound field due to the interaction of the nonacoustic flow field with the area change at the duct exit is much more successful at predicting the observed sound field despite the simplicity of the model of the vorticity distribution and its relation to the acoustic field. One is led to conclude that the nonacoustic flow field within the duct provides a significant additional source of acoustic energy located in the region of the duct exit.

The spectral distribution of a nonacoustic velocity field depends strongly on the geometry of the region where it is generated. The spectral distribution of sound from any acoustic sources due to the interaction of the nonacoustic velocity field with the duct boundaries will also be geometry dependent. One should not therefore expect that the results obtained in the DMM will map directly to the vocal tract. A companion paper (Shadle et al., 1999) compares measurements made in the DMM to in vivo measurements made during voiced speech production and considers the implications of including a nonacoustic velocity field in speech production models.

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