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AIRFLOW MEASUREMENT IN A DYNAMIC MECHANICAL MODEL OF THE VOCAL FOLDS

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ABSTRACT

A dynamic mechanical model of the vocal folds and tract has been constructed in order to investigate the effect of periodically interrupting a flow of air along a tube.

Hotwire anemometer measurements of the fluid movement within the tract have been made. Behaviour close to the shutters is found to vary greatly across the tract cross-section, having the form of a jet surrounded by a vortex ring which widens as it develops to fill the entire tract cross-section by approximately 4cm downstream of the shutters.

INTRODUCTION

A full understanding of the mechanisms of voiced speech cannot be achieved without the verification of theoretical models with measured data. Although indirect measurement is possible for some parameters, for example measuring glottal area function by laryngograph, [1] in order to obtain aerodynamic or acoustic measurements, transducers must be placed in the airflow. To do so in or around the glottis in a live subject is clearly fraught with difficulty and although instrumentation may be introduced via the oral cavity and trachea, [2] it must be small enough not to significantly disturb the flow field in the area of measurement. Further problems occur in trying to position such equipment accurately and in achieving enough control over the phonatory processes to be certain what, exactly, is taking place to produce the observed results.

In the past many methods have been used to circumvent these problems, one of the more common being static mechanical modelling (e.g. [3], [4]). Such models are useful for determining pressure gradients across the glottis but unfortunately can give no insight into the time dependent behaviour of the flow from which the acoustic wave develops.

This paper describes a dynamic mechanical model of the glottis designed to study the effect of periodically interrupting the flow of air along a pipe. The next section contains a description of the model and its instrumentation. This is followed by measured data from the model and a discussion of the implications of this data.

EXPERIMENTAL METHOD

The dynamic mechanical model is shown in Figure 1. It has approximately the same dimensions as the human male larynx. The tract is circular in cross-section and terminates in a plane circular baffle to give an output radiation impedance equivalent to that of the mouth and face [5].

The shutters are driven by two Ling Dynamics LD202 vibration generators, allowing control of the "glottal area" function. Air passes along the tract in the direction indicated and is modulated by the shutters which act as a driven one-mass model having a rectangular "glottis". Instrumentation can be inserted to measure flow parameters at any point within the tract both upstream and downstream of the shutters.

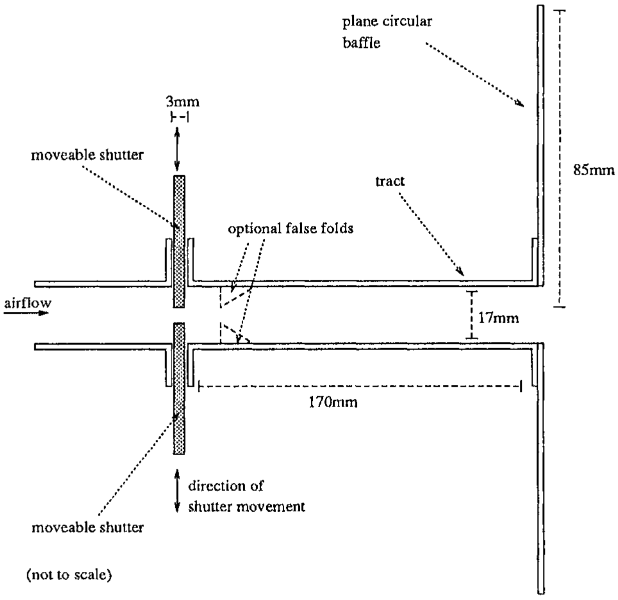

Figure 1: The Dynamic Mechanical Model

Despite the idealised internal profile of the model, experiment has shown that when used as a static model, the pressure drop across the shutters is comparable in magnitude with that measured in other static models [6].

A schematic diagram of the instrumentation of the model is shown in Figure 2. Upstream of the pressure regulating valve is a Hydrovane air compressor which acts as a high impedance pressure source. The regulating valve is used to guarantee a constant volume velocity of air to the model, as measured by a rotameter, to an accuracy of +/- $7cm^3s^{-1}$. Sub-glottal pressure is measured with a pitot-static tube attached to a manometer.

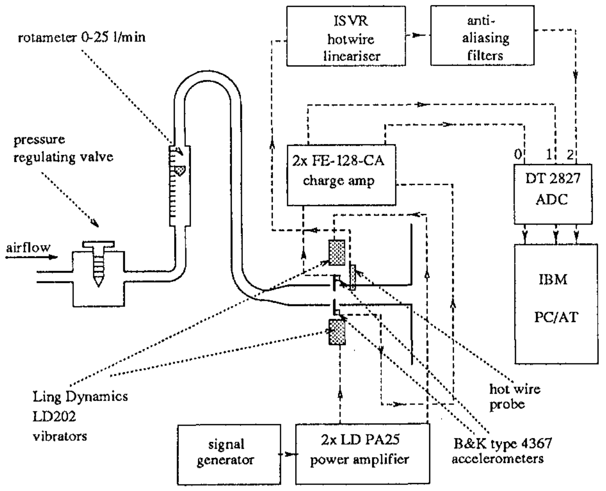

Figure 2: Schematic Diagram of Instrumentation for the Model

The vibration generators which drive the shutters are powered by two Ling Dynamics PA25 power amplifiers which are in turn driven by a variable frequency signal generator. The phonation neutral glottal area is set prior to vibration by means of feeler gauges. Displacement of the shutters from this initial position is measured by a Bruel and Kjaer type 4367 accelerometer attached to each shutter. Each accelerometer signal is amplified by a Fylde FE-128-CA charge amplifier.

Particle velocity is measured at various points in the flow using a constant temperature hotwire anemometer, connected to an ISVR lineariser [7]. A more detailed discussion of this system is given below.

The output signals from the charge amplifiers and the hotwire lineariser pass via an anti-aliasing filter to separate channels of a multichannel Data Translation DT2827 analogue-to-digital converter board in an IBM PC/AT running under Hypersignal data acquisition and signal processing software. The anti-aliasing filter is a cascade of two low pass filters with cut off frequency of 2.5kHz and a roll-off of 96dB per octave in total. The sampling frequency for A/D conversion of 5kHz was found to be adequate.

The constant temperature hotwire anemometer consists of a 5 μm diameter tungsten wire 5mm in length soldered between two prongs of a probe. The probe forms one arm of an automatically balanced Wheatstone bridge contained within the ISVR hotwire lineariser. The electrical output signal from the bridge is proportional to the rate of heat loss from the probe due to it being placed in a moving air flow. The output voltage from the bridge circuit was calibrated by placing the hotwire in a range of known flows between 0 and $12ms^{-1}$. A cubic curve was fitted by the method of least mean squares to the graph of output voltage against flow rate. This calibration curve was then used to convert bridge output signals to particle velocity in subsequent experimental measurements, (the more typical procedure of using the lineariser circuit within the ISVR hotwire lineariser could not be used here since flows of less than $1ms^{-1}$ were expected over much of the glottal cycle [7]).

It should be noted that whilst the rate of heat loss from the probe is a scalar quantity, particle velocity of the flow is a vector quantity and thus data measured in this way can give no information about the direction of flow. Furthermore, should the hotwire be subject to two flow components of opposite direction at different points along its length, the output signal will be proportional to the sum of the magnitudes of these components.

For all data presented in this paper the phonation neutral glottal area was $17mm^2$ and peak glottal area was $34mm^2$ corresponding to glottal widths of 1mm and 2mm respectively. Minimum glottal area was as close to complete closure as mechanical constraints permitted. In all cases the shutters were driven sinusoidally. Measurements were taken at two fundamental frequencies, 80Hz and 100Hz and at two volume velocities, $200cm^3s^{-1}$ and $300cm^3s^{-1}$. Hotwire measurements were made at 1cm intervals along the tract axis at the positions shown in Figure 3. Experiment showed that measurements at positions d and e were of the same magnitude and appearance as those at a and c respectively and thus symmetry across the tract was assumed for all measurements.

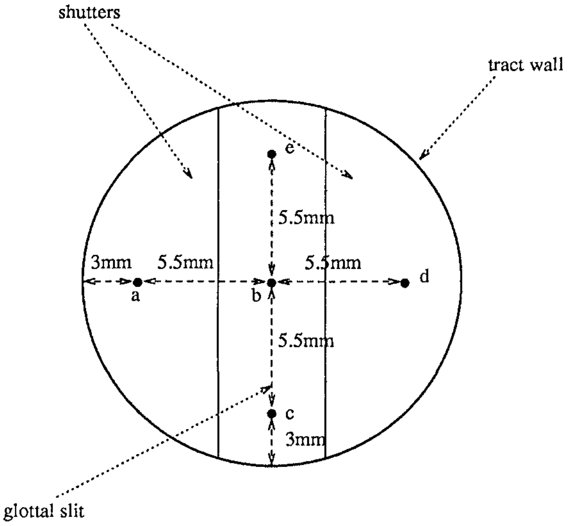

Figure 3: Hotwire Measurement Positions.

Data presented in this paper are representative of flow behaviour at all fundamental frequencies and volume velocities tested, although the magnitude of the flow velocity varies from case to case.

RESULTS AND DISCUSSION

Figure 4 shows the hotwire data for sites a,b and c for a measurement plane 1cm downstream of the shutters for the flow conditions $F_0 = 80Hz$, Volume velocity = $200cm^3s^{-1}$. The displacement of the shutters from phonation neutral position is also indicated. It can clearly be seen that data for site a differ greatly from data for sites b and c which are in line with the gap between the shutters. Mean flows at sites a,b and c, +/- their standard deviations are $151+/-59cms^{-1}$, $100+/-31cms^{-1}$ and $226+/-67cms^{-1}$ respectively. Taking the mean of the mean flows and multiplying by the area of the tract ($2.26cm^2$) gives a rough estimate of the volume velocity as $360cm^3s^{-1}$. This is approximately twice the size of the input volume velocity, suggesting that as well as axial components in a downstream direction, the flow has transverse components and possibly also axial components directed upstream.

The mean flow and its standard deviation at site c are approximately twice as great as the same measurements at site b, suggesting that reflection of flow components is occurring close to the tract walls.

At all measurement sites the trend is towards a sharp peak in flow velocity on shutter opening followed by a more gradual decline as the shutters close. This is

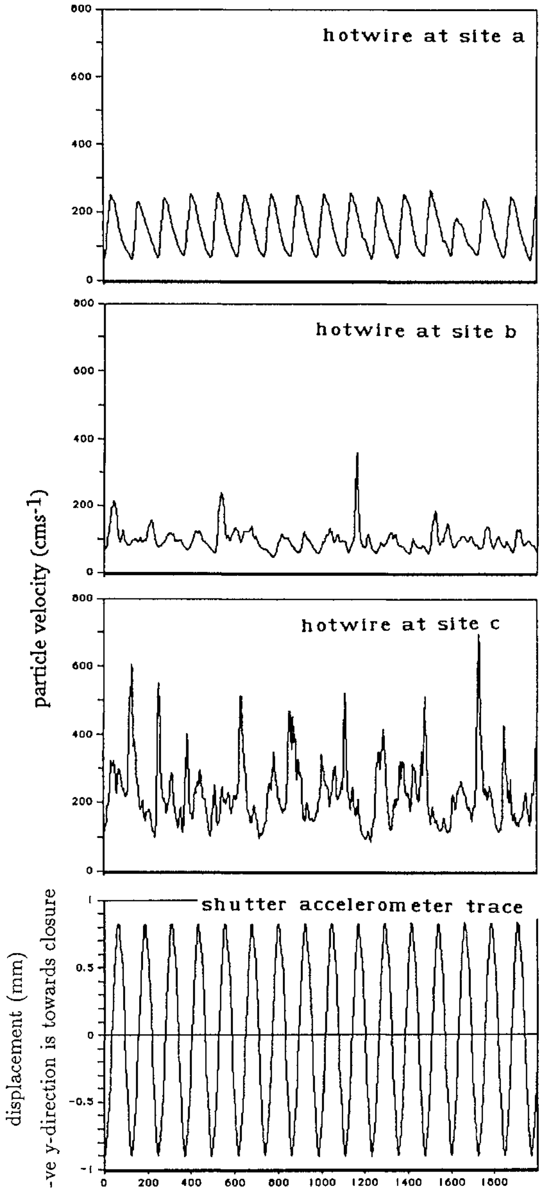

Figure 4: Hotwire Signals at Sites a,b and c at 1cm Downstream of Shutters and Corresponding Accelerometer Trace

consistent with the use of a constant volume velocity source. Pressure builds up behind the shutters while they are closed and is released suddenly as they open causing high flow velocity to occur at this time. As they close, pressure behind them is still low and the flow velocity reduces proportionally to the area between them.

Figure 5 shows hotwire data and accelerometer traces for the same measurement sites and flow conditions, in a plane 4cm downstream of the shutters. Difference in flow behaviour between the sites is less distinct. Calculating the volume velocity from the mean flows as before gives good agreement with the input volume velocity suggesting a reduction in non-axial flow components.

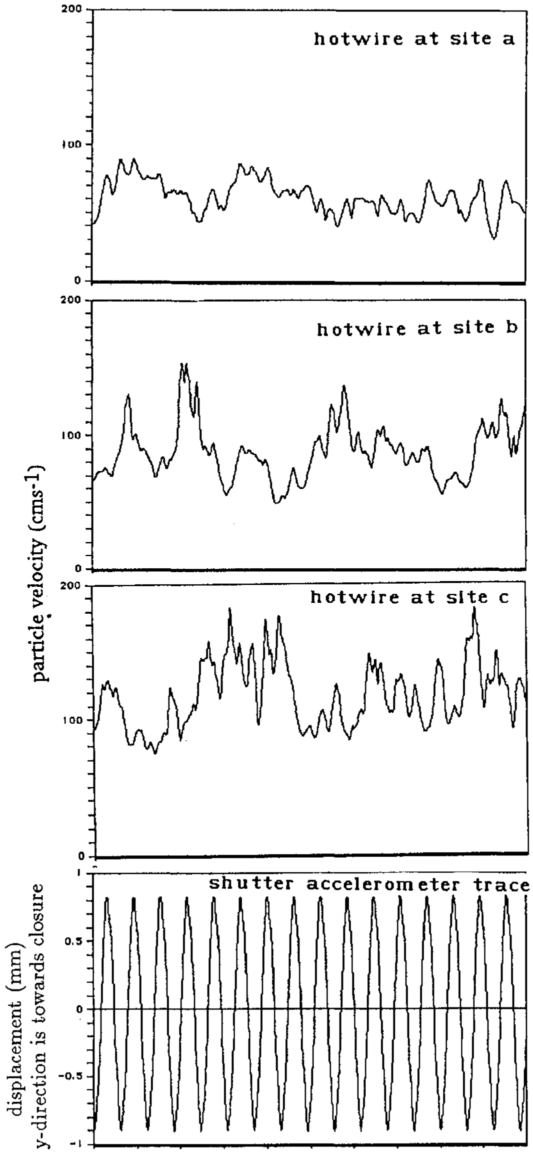

Figure 5:Hotwire Traces for Sites a,b and c at 4cm Downstream of Shutters and Corresponding Accelerometer Trace

Shadle et al. [8], performed flow visualisation experiments on a dynamic mechanical model similar in many respects to the one described here. The formation of a jet was described at the glottal exit which gradually widened, mixing with the surrounding air to fill the whole tract. Comparison of our data with these observations would suggest that the regions of high velocity flow at positions b and c 1cm downstream of the shutters correspond to this jet. Observed turbulence in the jet accounts for the non-axial velocity components measured in the flow. In our model the jet appears to have widened sufficiently to fill the tract by a distance of 4cm downstream of the shutters, comparable with the longest jet reported in the flow visualisation experiments of 3.4cm.

It is likely that the fluid motion observed at site a at 1cm downstream of the shutters is due to vortex shedding from the jet. This is supported by two-dimensional numerical simulations of glottal flow reported by Gauffin and Liljencrants [9] and by Liljencrants [10] in which a vortex ring was shown to develop around the glottal jet. Flow visualisation also showed the formation of vortices some of the time [8].

McGowan [11], postulated the development of such a jet-vortex system during phonation. He further suggested that should such a system be shown to exist in the vocal tract then the three-dimensional nature of the fluid velocity field should be part of the model of the voice source since in that case, in addition to the monopole-type acoustic source due to the volume velocity at the glottis, there would be a dipole-type acoustic source due to the vorticity-velocity interaction.

At 16cm downstream of the shutters, flow in the tract has become approximately uniform. The hotwire signal at site b, for the same flow conditions as previously, is shown in Figure 6 and is also typical of the signals at sites a and c. The mean flow +/- the standard deviation at all three sites is 108 +/- 8cms^{-1}.

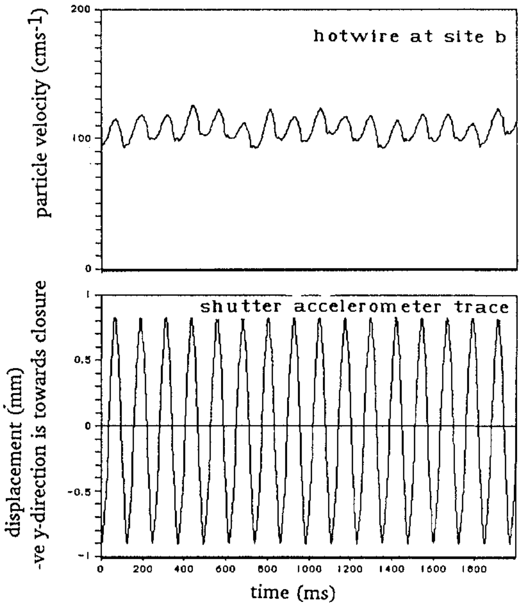

Figure 6: Hotwire Trace for Site b at 16cm Downstream of Shutters and Corresponding Accelerometer Trace. Trace is also Typical of Sites a and c

The signal 16cm downstream of the shutters is similar in appearance to the familiar glottal wave resulting from inverse filtering experiments. All evidence of the three dimensional behaviour observed at the glottis has disappeared as has the spike in the signal as the glottis opens.

CONCLUSIONS

Measurement of fluid particle velocity in our dynamic mechanical model of the vocal folds has shown the pattern of fluid motion between 1cm and 4cm downstream of the glottis to vary widely over the cross-section of the tract. Comparison with flow visualisation experiments suggests that the measured flow velocities correspond to the development of a jet at the glottal exit which spreads out along the tract to fill the whole cross-section by 4cm downstream. Vortex shedding appears to occur from the sides of the jet in the area of the tract not directly in line with the glottal slit. This behaviour corresponds to that predicted by Gauffin and Liljencrants [9], Liljencrants [10] and McGowan [11] in their theoretical models of glottal jet formation and suggests that the aeroacoustic approach to phonation described by McGowan may be a more realistic description of the voice source than current one-dimensional models.

Future work will concentrate on relating these measurements to the waveform observed by inverse filtering experiments and in defining the effect of the false vocal folds on such a jet-vortex system.

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