AN INVESTIGATION OF AIR FLOW THROUGH THE LARYNX BY COMPUTER
AND MECHANICAL MODELLING

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ABSTRACT
A computer model of the larynx has been developed, based on the two-mass model [1] but including some of the more recently observed flow phenomena in the glottis.

In order to test the validity of the output of the computer model and the assumptions on which it is based, a mechanical model has been constructed in which the vocal folds are modelled by vibrating shutters. Measurements have shown that the pressure-flow relations for the model, when the shutters are stationary, are comparable with published data for other static models.

INTRODUCTION

The long term aim of research into laryngeal mechanics is to produce a comprehensive phonatory theory which includes all the subsystems of the voicing mechanism, namely the biomechanical, fluid mechanical and acoustic properties which act together to produce speech sounds. However, the inaccessibility and delicacy of the larynx currently preclude a comprehensive multivariable study in live subjects. A further problem with in vivo studies is lack of control over the parameters of phonation. Even a trained subject such as a singer is unlikely to be able to reliably reproduce a given sound a number of times without variation in pressure, flow rate or geometric configuration of the tract.

To overcome these problems, many researchers have developed computer models of laryngeal activity [1,2,3]. Here data from studies of the individual subsystems are combined to try to give a whole picture of the operation of the voice source. Unfortunately, owing to the incompleteness of the data in each of the separate areas, a complete theory which accounts for all the processes involved has not yet been achieved.

Modelling studies have the advantage that control of the parameters of phonation can be built into the model and thus by holding one variable constant whilst changing others, the inter-relation between parameters can be observed. However, data from a model must be compared with data obtained in the larynx or in a physical model of the larynx to test its validity before it can be assumed that the computer model is behaving as the larynx would behave.

We have developed a two-mass model of the larynx, identical in its mechanical formulation to that of Ishizaka and Flanagan[1], but with a more complex flow regime that takes into account some of the more recently observed phenomena from static modelling studies such as a variable entry loss coefficient and a variation in translaryngeal pressure drop that is dependent in part on glottal geometry[4]. Output from this model compares well with published data from in vivo studies of glottal profile variation during voicing[5] and with volume velocity data obtained from inverse filtering [6]. However, we also wish to verify some parameters for which little data has been published and to determine the validity of the assumptions on which our model is based, in particular, the quasi-static approximation.

Many computer models of the larynx ( e.g. [1,7]), including our own, are based on an assumption of quasi-stasis for the flow through the larynx. The use of static mechanical model studies to gain information about pressure-flow relationships in the larynx is likewise dependent on the quasi-static approximation.

Flanagan[8] suggested that a quasi-static approximation could be used for the air flow through the larynx for oscillation frequencies less than about 300 Hz. This is supported by a formula presented by Meyer[9], which generally accepted in the fluid mechanics literature. In essence, it states that a disturbance must convect through a glottis-equivalent in a time much shorter than the time it takes for the area of the glottis to change appreciably. Thus,

\[ \frac{2T}{u_{av}} \ll 1 \] (1)

Where \( T \) = thickness of glottis
\( f \) = fundamental frequency
\( u_{av} \) = particle velocity

Approximate values of these variables are \( T=0.3 \) cm, \( u_{av}=1000 \) cm/s, \( f=60-300 \) Hz where particle velocity is calculated from values for volume velocity and glottal area of 500 cm²/s and 0.5 cm² respectively. This leads to a range of \( 2T/u_{av} \) of 0.04 - 0.2.

It is obviously important to experimentally verify the range of validity of the quasi-static approximation...
before placing confidence in data from static model studies or assuming that our computer model is a valid representation of laryngeal airflow.

We have constructed a mechanical model of the voice source, described in the next section, from which to obtain quantitative measurements of air flow velocities in the vocal tract. The mechanical model will be used to verify the behaviour of the computer model. Once the computer model is verified the mechanical model will be used to provide more data to extend the computer model to cover a wider range of voicing phenomena.

Our mechanical model is not the first mechanical model of the larynx to be produced. Kiritani et al. [10] described an experiment in which a thin rubber membrane is used to model vocal fold. The second vocal fold is stationary and is modelled by a thick rubber sheet. A stepper motor drives the rubber membrane in such a way that a thin slit opens and closes between the membrane and the sheet. Compressed air is passed through this slit and particle velocity of the air flow is measured by a hotwire anemometer at a number of points above the slit. They found that air passed through the slit in the form of a jet and that even at distances of 15 and 25 mm above the slit, little diffusion of the jet had occurred.

Shadle et al. [11] have described flow visualisation experiments in a mechanical model with one oscillating shutter. They too observed the formation of a jet at the glottal exit and noted that all jet activity was confined to the latter half of the glottal cycle. An increase in the supra-glottal impedance resulted in the jet appearing earlier in the cycle.

Our model differs from the models described above in that it has two oscillating shutters representing the vocal folds and, unlike that of Kiritani et al., it includes the vocal tract in the model. The next section describes the design of the mechanical model and its ranges of operation. This is followed by experimental results for static measurements of the pressure-flow relationship in the model.

THE MECHANICAL MODEL

The mechanical model, based on a model with one moving shutter described by Shadle et al. [11], is designed to share some selected properties of the voice source, but has the advantage that it is more accessible to instrumentation than the human vocal tract. In addition the parameters of oscillation are controllable in a way not possible in a human subject.

A schematic diagram showing a longitudinal cross-section of the model is given in Figure 1. The model consists of a clear cylindrical tube representing the vocal tract, which is bisected by two shutters modelling the vocal folds. The vocal tract tube terminates in a plane circular baffle, 20 cm in radius, giving the model an output acoustic impedance approximately equivalent to that of the mouth and face [12]. Air is passed along the tube from a compressed air supply in the direction indicated in Figure 1. The pressure of the air at the entrance to the model is set by a pressure regulating valve. Following the valve there is a diffuser nozzle and 5 cm further downstream are the shutters. This means that the flow will not be fully developed by the time it reaches the shutters. According to Miller [13], this is similar to the situation in the human trachea. Current apparatus allows a range of pressures from 0 to 30 cmH₂O.

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Driving power for the shutters is provided by two Finnell LMF2 signal generators, which are coupled directly to each shutter. These drive the shutters 180° out of phase with each other as indicated in Figure 1. Frequency of oscillation of the Vibration Generators can be controlled by means of a pair of Finnell LMF2 signal generators.

The shutter and tube dimensions have been chosen to be approximately equivalent to those for a typical adult male. The shutter thickness is 0.3 cm and the tube diameter is 1.7 cm. The length of tube from the shutters to the baffle is 17.5 cm. Volume velocity of the air flow through the model has a range of 0 to 500 cm³/s and the Vibration Generators have a frequency range of 0 to 13 kHz which more than adequately encompasses the oscillation frequencies of vocal fold vibration. Vibration amplitudes vary with frequency and have a value of 0.5 cm for each shutter at 80 Hz.

Instrumentation can be inserted into the vocal tract tube of the model at any point up or downstream of the shutters. This is done by means of a slot, of width 0.5 cm, which runs along the length of the tube. If the slot were left open this would cause a major air leak in the model. To solve this problem, a piece of acetate sheet is cut to fit exactly the internal circumference of the tube. The sheet is inserted into the tube and as a result the slot is blocked and no air leaks out. A hole the size of the instrument to be inserted can be pierced in the sheet with a hot needle at the point where measurement is to be made. Tests have shown the model to be completely air tight.
STATIC MEASUREMENTS

Measurement of pressure drop across the glottis of the model has been made for four glottal areas \( (A_g = 6, 12, 18 \text{ and } 24 \text{ cm}^2) \) with the shutters stationary. The experimental set-up is shown in Figure 2. Glottal area was set with feeler gauges and pressure difference across the glottis was measured using two pitot tubes, one on each side of the shutters, connected to an inclined manometer. Volume velocity was controlled using the pressure regulating valve and measured using a rotameter. Volume velocities for the experiment were in the range 50 - 400 cm\(^3\)/s.

Pressure recorded by the upstream pitot tube was found to be constant for a given volume velocity provided it was a distance of at least 1.3 cm away from the glottis. The downstream pitot tube was placed a distance of 8.5 cm from the glottis since pressure recovery was found to be complete by this point.

Pressure difference was plotted against volume velocity for each glottal area investigated and the results for the translaryngeal pressure drop in our model were compared with those of other researchers. The graph of results is shown in Figure 3.

It can be seen that although some of the other models have more physiologically exact internal profiles, the static pressure loss across the glottis for our model compares well with data collected in other models.

CONCLUSION

Despite its somewhat idealised internal profile, the laryngeal model described in this paper has been shown to have static pressure-flow characteristics comparable to more physiologically exact static models. This gives weight to the theory that measurements taken in this model in its dynamic state will have an equivalence to the measurements which would be taken in the human larynx under the same conditions. Initial tests with the model suggest that it will prove a useful tool for investigating aerodynamic and acoustic events in the vocal tract.

In the future the mechanical model will be used for three investigations:
1) To test the validity of the quasi-static approximation for the larynx.
2) To study the relation of particle velocity downstream of the shutters varies to glottal area during an oscillation cycle.
3) To study the effects of supraglottal impedance on the development of a jet at the glottal exit.

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REFERENCES


