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# MODELLING THE AIR FLOW IN THE GLOTTIS

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The inaccessibility of the laryngeal system does not allow direct in vivo measurements and aerodynamic theories are not accurate enough to let us calculate the aerodynamic forces for arbitrary vocal fold shapes. Therefore we have to rely on empirical measurements using models, mechanical facsimiles or computational.

There has been a few attempts to derive formulas for the air flow through the glottis by using static models of the larynx. The first to make such measurements in a model was probably Wegel in 1930. He derived an empirical formula for the air resistance of the glottis. Later van den Berg, Zantema, and Doornenbal (1957) performed measurements of the pressure within the glottis and the glottal resistance. They used a static model designed from moulds made from a human larynx. The glottis of their model was constructed to form a rectangular duct. The only variable that was systematically varied was the duct diameter. It was controlled by placing closing strips of different size between the two model halves.

The concept of van den Berg's theory of vocal fold vibration is that the air pressure in the glottis can be negative compared to the pressure immediately above and below the glottis. This negative pressure was supposed to be caused by the so-called "Bernoulli effect" created by the acceleration of the air in the narrow glottis. This idea was probably first applied to the glottis by Tondorf, already in 1925.

Ishizaka and Matsudaira (1972), made a more theoretical analysis and suggested two formulas for the glottal resistance, one for turbulent flow and one for laminar flow. With turbulent they meant the possibility of a vena contracta (a contraction of the flow) at the glottal entry. Their turbulent equation was similar to van den Berg's equation but with a different estimate of the recovery of kinetic energy at the glottal exit.

All this pioneering work on glottal aerodynamics has been restricted to uniform glottal ducts although already in his first article van den Berg pointed out the importance of the phase difference between the vibrations of the upper and lower part of the vocal folds.

In more recent model experiments, performed by Sherer et al (1980, 1981) and Binh and Gauffin (1983), both diverging and

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converging glottal ducts have been used. The reasons why so few experiments on the aerodynamics of the glottis have been performed are easy to understand. First, it is difficult to determine the exact dimensions and shapes of the folds and, second, the small physical dimensions pose extreme difficulties to make reliable measurements of the flow pattern and the pressure distribution within an unscaled mechanical model. In order to determine the pressure on the surface of the vocal folds, small holes have to be drilled in the model. The diameter of these holes can hardly be much smaller than 0.5 mm, which is not small compared to the glottal width for a narrow glottis. It is also difficult to make the openings of the holes smooth and regular, which will influence the measurements. These practical difficulties probably have discouraged many experimenters.

In order to circumvent this a five times scaled up model was used in the above mentioned experiments. Scaling is an accepted method in aerodynamics but it has the disadvantage that pressures are reduced by the square of the scale up factor. This implies that pressures of a few mm water column have to be measured with good accuracy in a five times scaled up model.

PRESENT THEORIES

Van den Berg et al, (1957) gave the following expression for the pressure drop, $P_d$, across the larynx:

$$P_d = 1.37P_k + 12T\rho\mu V/W^2 - 0.5P_k$$

where

$P_k = \rho U^2/2A^2$ is the Bernoulli pressure at entry to the glottal duct with uniform velocity distribution across the area A.
$A$ = glottal area, $cm^2$
$T$ = glottal thickness (vertical length), cm
$U$ = volume velocity, $cm^3/s$
$V$ = air velocity in the glottal duct, cm/s
$W$ = glottal width, cm
$\rho$ = air density, 0.00119 $g/cm^2$
$\mu$ = kinematic viscosity of air, 0.15 $cm^2/s$

The first term on the right hand side of the equation represents the pressure drop from the trachea to the glottis entry. The factor 1.37 was motivated by the pressure measured at the glottis entry. In the idealized case this pressure drop should be equal to the kinetic energy of the flow in the glottis. The deviation from this ideal case was explained to depend on turbulent losses at entry and uneven distribution of the velocity across the glottis width. The second term represents the estimated pressure drop along the glottal rectangular duct. This term is the Poiseuille expression for laminar flow between parallel plates, and accounts for the viscous losses within the glottis. The third term, which is negative, represents the recovery of kinetic energy when the air expands at glottal exit.

Ishizaka and Matsudaira (1972) proposed two expressions for the translaryngeal pressure drop: the laminar equation

$$P_d = (1 - 2n(1-n) + 2.2\sqrt[3]{\frac{T\mu}{VW^2}} + 20\frac{T\mu}{VW^2})P_k$$

and the turbulent equation

$$P_d = 1.37P_k + 12\frac{T\rho\mu V}{W^2} - 2n(1-n)P_k$$

where n = glottal area/pharyngeal area

Ishizaka and Matsudaira used the term "turbulent" to mean that there is a "vena contracta" at the entrance.

The value 1.37 of the entry loss coefficient given by van den Berg et al is accepted by Ishizaka and Matsudaira for the "turbulent" formula, but the exit loss coefficient of -0.5 was modified. In the "laminar" equation the entry losses and the losses in the duct were reformulated. The first term to the right is the ideal pressure drop. The second term is assumed to be the hydrodynamic pressure development due to momentum exchange and wall shear stress, from the entrance to the exit of the glottis. The recovery factor after glottal exit is the same as in the turbulent equation. In practice these two formulas give rather similar results.

In order to model glottal shapes that are not rectangular, Ishizaka and Matsudaira (1972) suggested that the non-rectangular shape could be approximated by abutting rectangular ducts having different diameters. One example of this is the so called "two-mass" model.

The formulas proposed by Ishizaka and Matsudaira represent the present state of the theories of the aerodynamics of the larynx. The formulas are based on one-dimensional flow theory in an effort to match experimental data. These formulas have been extensively used in reporting experiments with models of the vocal folds.

Several static model experiments have been performed by different authors in order to validate the formulas. A relatively good match for the flow resistance was generally found for uniform glottal ducts but variations occurred depending on vocal fold shapes and glottal width. However, the pressure distribution on the vocal folds cannot be accurately described by the proposed formulas based on one-dimensional flow theory.

## DIFFERENT FLOW PATTERNS IN THE GLOTTIS

In Fig. 1, cross sections of four different vocal fold configurations are shown with indication of the flow pattern. The shapes of the vocal folds are a little extreme but they are good for illustrating different flow patterns that can occur in the glottis. In Fig. 2 the pressure drop as a function of the volume flow is shown, using the same minimum area for all models. The data are normalized to the ideal case with even distribution of velocity over the glottis area and no friction, that is, they show $P_d/P_k$. The measurements were made with the glottis models coupled to a vocal tract model consisting of a 17 cm long tube with a diameter of 1.8 cm. All data remained the same if this tube was removed, except for the divergent model. For this glottal shape the resistance was 4% higher without the vocal tract tube, because the tube had a stabilizing effect on the jet that would otherwise oscillate.

For the converging glottis in Fig. 1a, the equivalent area is the area of the laminar jet above the glottis, which in this case is 5% smaller than the actual area. The area of the jet is a function of the angle of the convergence (and glottal diameter). In Fig. 1b, where the glottis is divergent, the angle of convergence can be considered to be 90 degrees. The abrupt entry prevents the air from attaching to the walls of the expanding glottis. If the divergence angle is small, as in this case, the air jet will oscillate from one side of the glottis to the other. For the parallel glottis in Fig. 1c the flow separates at the entry but reattaches before glottal exit. Compared to the converging model the friction term makes the resistance higher for low velocities but lower for high velocities because then reattachment of the flow makes the equivalent area bigger. Fig 1d represents a streamlined case. The smooth entry makes it possible for the flow to partly follow the walls in the expanding portion of the glottis, and thus an improved pressure recovery makes the equivalent area greater than the minimum area. Since the glottis is short and the particle velocity high, pressure recovery in the glottis is limited and we can not expect a lower flow resistance than about 0.8 times the ideal case.

## CONVECTIVE ACCELERATION IN THE GLOTTIS

It is clear that a single formula cannot model all these different types of flow. Two-dimensional flow theory is needed but there is no established method for designing the flow lines. An additional problem is that flow separation and unstable flow are difficult to treat mathematically. Separation is caused by convective acceleration. In acoustics it is customary to neglect the convective acceleration (centrifugal force) term in order to linearize the equations. In the glottis, on the other hand, the effect of convective acceleration is important because of the

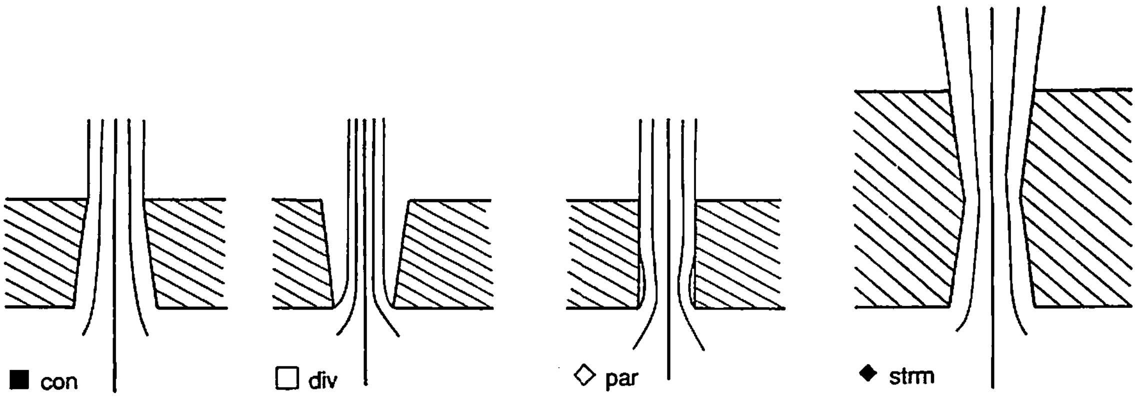


*Fig. 1. Outline shapes of four different models of the glottal passage, all with the same minimum area. The pattern of the upward going flow is indicated.*

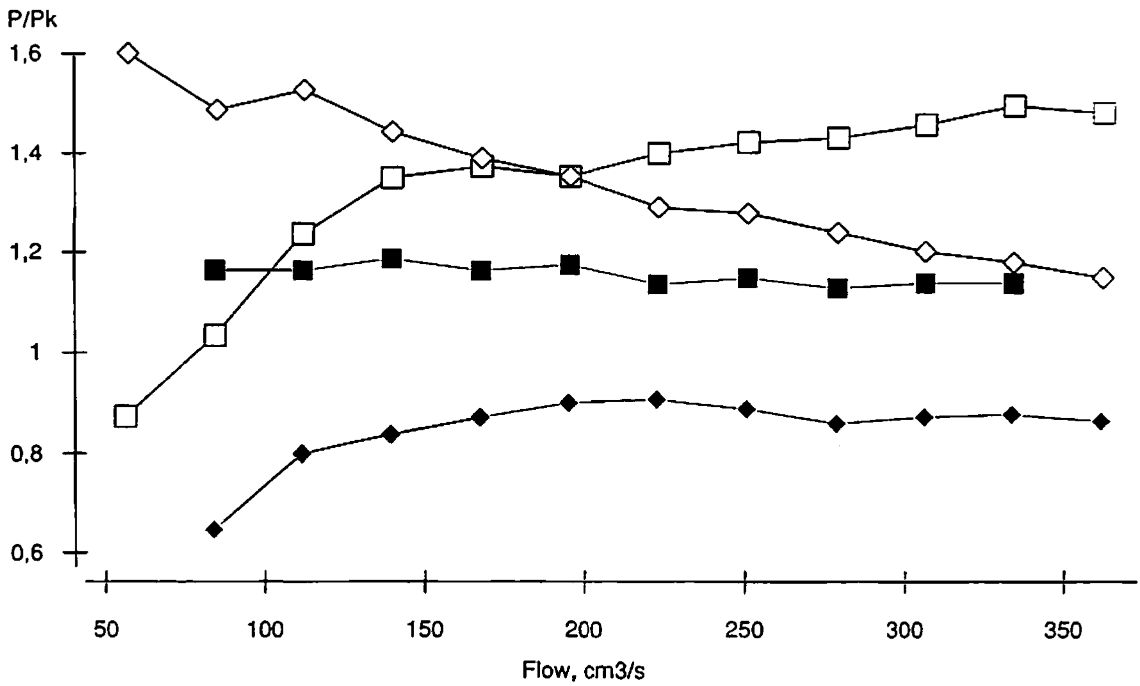


*Fig. 2. Measured pressure-flow relationship in the models of Fig.1. The ordinate represents the relative deviation from the Bernoulli pressure, assuming uniform distribution of velocity across the minimum glottal area.*

small size of the glottis and the high particle velocity, this can easily reach 50 m/s.

The effect of the convective acceleration can be estimated by making some simplified assumptions about the flow pattern. A streamlined case is illustrated in Fig. 3. For our calculation we assume that the streamlines are evenly distributed across the glottal width witch implies that the velocity across the glottal width also is evenly distributed. The radius of curvature of the vocal folds at the narrowest part of the glottis is $r_o$, and the radius of the flow lines is assumed to increase to infinity for the flow along the mid line. The radius is given by $r = r_o\, d/x$, where x is the distance from the mid line and $d = W/2$ is the half-width of the glottis. With these simplifying assumptions about the flow pattern, which may be valid for a glottal width up to about two times $r_o$, the pressure difference between the mid line of the flow and the surface of the vocal folds can be estimated.

The centrifugal force per unit volume is given by $\rho V^2/r$ for radius r, and this can be integrated to give the pressure difference $P_c$ due to curvature of the lines, see Fig. 3:

$$P_c = \int_0^d \frac{\rho V^2}{r}\, dx.$$

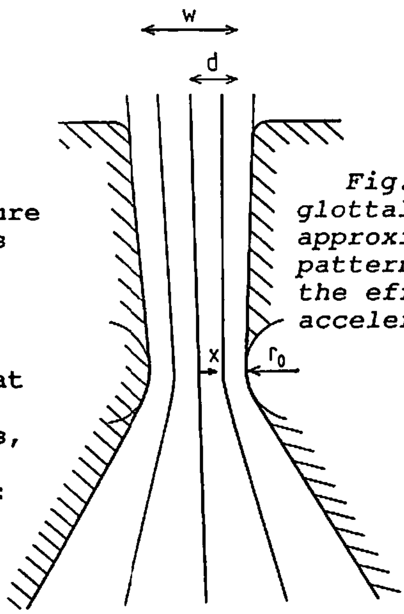


*Fig. 3. A hypothetical glottal shape with approximation of the flow pattern for estimation of the effect of convective acceleration.*

Neglecting friction and recovery terms the pressure drop P across the glottis can be written

$$P = k\, \rho V^2/2$$

where k is a constant that is close to unity. Combining these equations, we can express $P_c$ as a function of P as follows:

$$P_c = \frac{W}{2kr_o} P.$$

It thus seems that the convective acceleration can cause pressure differences of the same order of magnitude as the pressure drop across the glottis.

This finding has several implications. First, the original assumption of an even distribution of velocity across the glottal width appears to be invalid, but is unimportant for our approximate calculation. The velocity must be lowest at the mid line and increase towards the surfaces of the vocal folds. This is quite contrary to common explanation of the entry loss coefficient as caused by a contraction of the flow to the center line. The higher pressure in the middle of the flow is also a prerequisite for the flow to be able to follow the expansion of the glottal duct.

We can also argue that the flow pattern will be relatively independent of the pressure across the glottis as long as friction losses can be neglected. The velocity profile will instead vary with glottal width and vocal fold shape. In model experiments (Sherer et al, 1983, Binh et al, 1983) it has also been found that the pressure measured at glottal entry increases with glottal width in a way similar to that expected from the above calculation.

Another inference is that the entry loss coefficient has probably been overestimated in many model experiments. This is because it is common to associate the entry loss coefficient with the pressure drop from the tracheal part of the model to the pressure measured at glottal entry. This in turn may have led to an over-estimation of the pressure recovery above the glottis, which may explain the high recovery term in the formula of van den Berg et al. In the models of Fig. 1, the exit recovery was too low to be measured, except for the diverging glottis with an oscillating jet. According to the turbulent formula by Ishizaka and Matsudaira the pressure recovery should amount to 5%. In the present experiment, the exit recovery was measured as the difference between the pressure versus flow with and without the vocal tract tube. Usually the pressure recovery is measured as the difference between the pressure at glottis exit and the pressure somewhere above the glottis, which gives a different definition of the recovery term.

## COMPUTATIONAL FLOW MODELS

The discussion above reveals our lack of knowledge about fundamental mechanisms in laryngeal aerodynamics and it shows the need for better tools in modelling voice generation. We have here demonstrated how simplified vocal fold shapes and geometrical design of flow lines can be used. A perhaps more promising approach may be the use of cellular automata to model the air flow (Frisch et al, 1986). We have made a preliminary attempt to do so by using a two-dimensional triangular lattice gas model with hexagonal symmetry. This model is discrete in space and time. The "Boolean molecules" move from one node in the lattice to the next for each unit of time. The "molecules" collide under certain rules, so designed that particle number and momentum are conserved. By averaging the velocities of many particles in a given region we obtain a continuum description in terms of an averaged flow velocity as function of time.

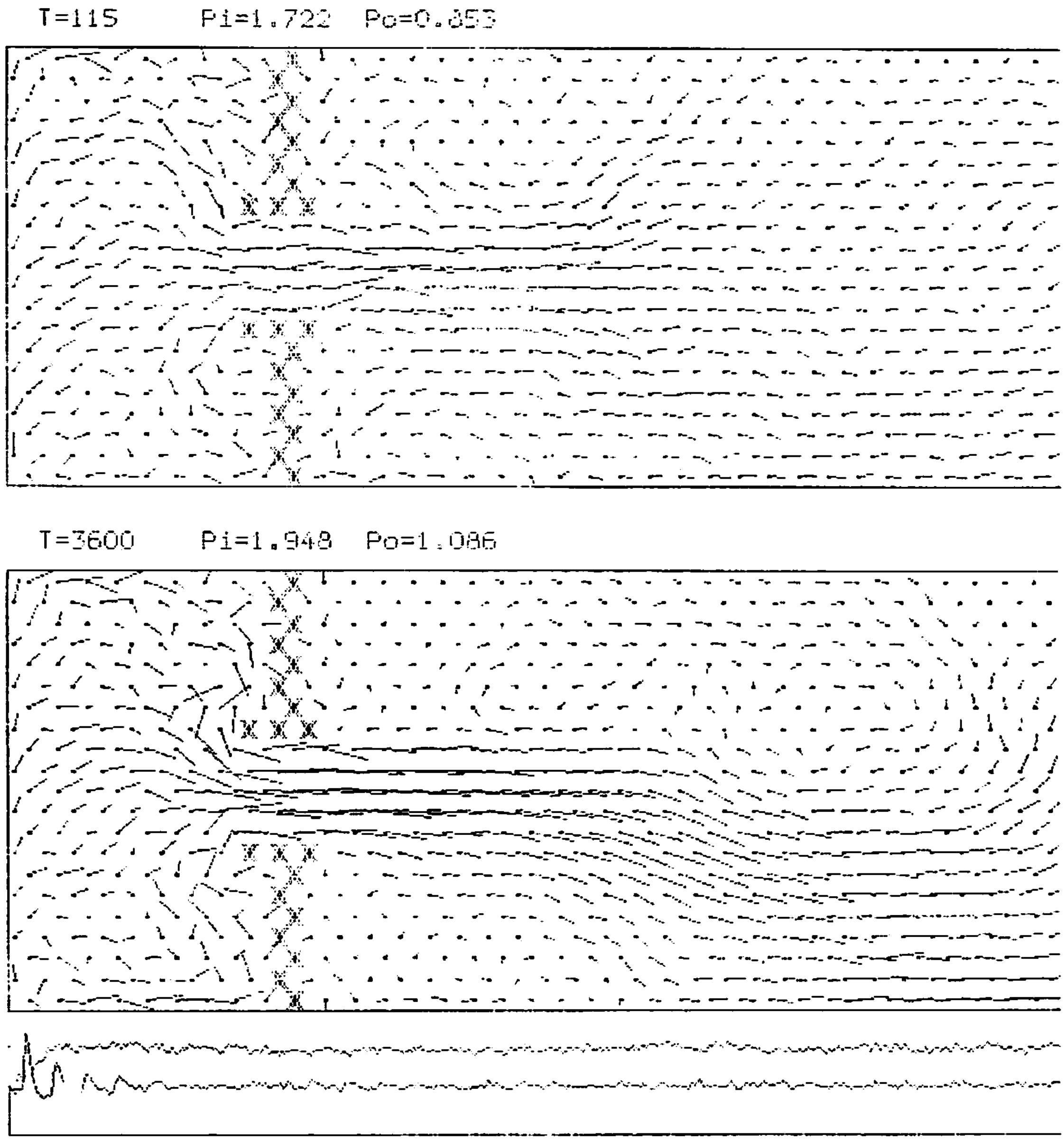


*Fig. 4. Flow patterns in a two dimensional lattice-gas model of a constriction at different instances in time after the flow has been applied to the left. The curves at the bottom show the pressure at the entry (upper curve) and at the exit (lower curve) as function of time.*

An example of modelling the flow through a constriction in a tube is shown in Fig. 4. The flow is applied from the left at time T=0 and the figure shows, from top to bottom, the flow patterns at sample times 115 and 3600. The direction of the flow is indicated by the lines extending from each point and the average velocity is represented by the length of the lines. In this case the scale of the lattice is large in order to minimize memory requirement and computing time. This results in an unrealistically high viscosity, because this is a function of molecule mean free path and thus the lattice mesh size.

Boundary conditions are usually easy to implement in lattice gas models. At the hard walls of the model we assume that the "molecules" behave as if they collide with a "molecule" moving in opposite direction. At entry the flow is applied by randomly introducing a certain number of "molecules" per sample time and at exit the mean pressure over time is kept constant by removing sufficient number of "molecules". At time T=0 the "molecules" have random directions and zero mean velocity.

The example shown in Fig. 4 is quite intriguing, but there are many uncertainties on the implementation of the model. Although simple at the cellular level, the system is very complex on the macroscopic level and the theoretical connection between these two levels are not yet fully worked out. There is at present a great interest in this new field of lattice gas modelling and the theories will probably be worked out in the next few years.

In another computational experiment we have divided the fluid into 'macro-molecules', parcels with equal contents of matter that still are small compared to the fixed structures bounding the flow, but very large compared to real molecules. In the computer each parcel is represented by a record of its position coordinates, its velocity components in the coordinate directions, its pressure, and finally a list of pointers to which molecules are its closest neighbours. These macro-molecules are left to interact and produce a time history of the flow. The difference from the hexagonanal lattice model is now, that movements and forces are considered as continuous. Fig. 5 shows two-dimensional pressure distributions obtained from this by averaging data from molecules passing areas in a stationary grid.

## DYNAMIC ASPECTS

We must justify the relevance of using results from static models when we want to study the vibrating vocal folds, which is a dynamic system. It is of considerable importance to be able to calculate volume velocity flow under dynamic conditions if we want to understand the mechanism of voice production. In vivo measurements (Kitzing & Löfqvist, 1975) as well as theoretical calculations (Fant, 1982) have shown that the pressure variation over the glottis during a vibratory cycle can reach the same order

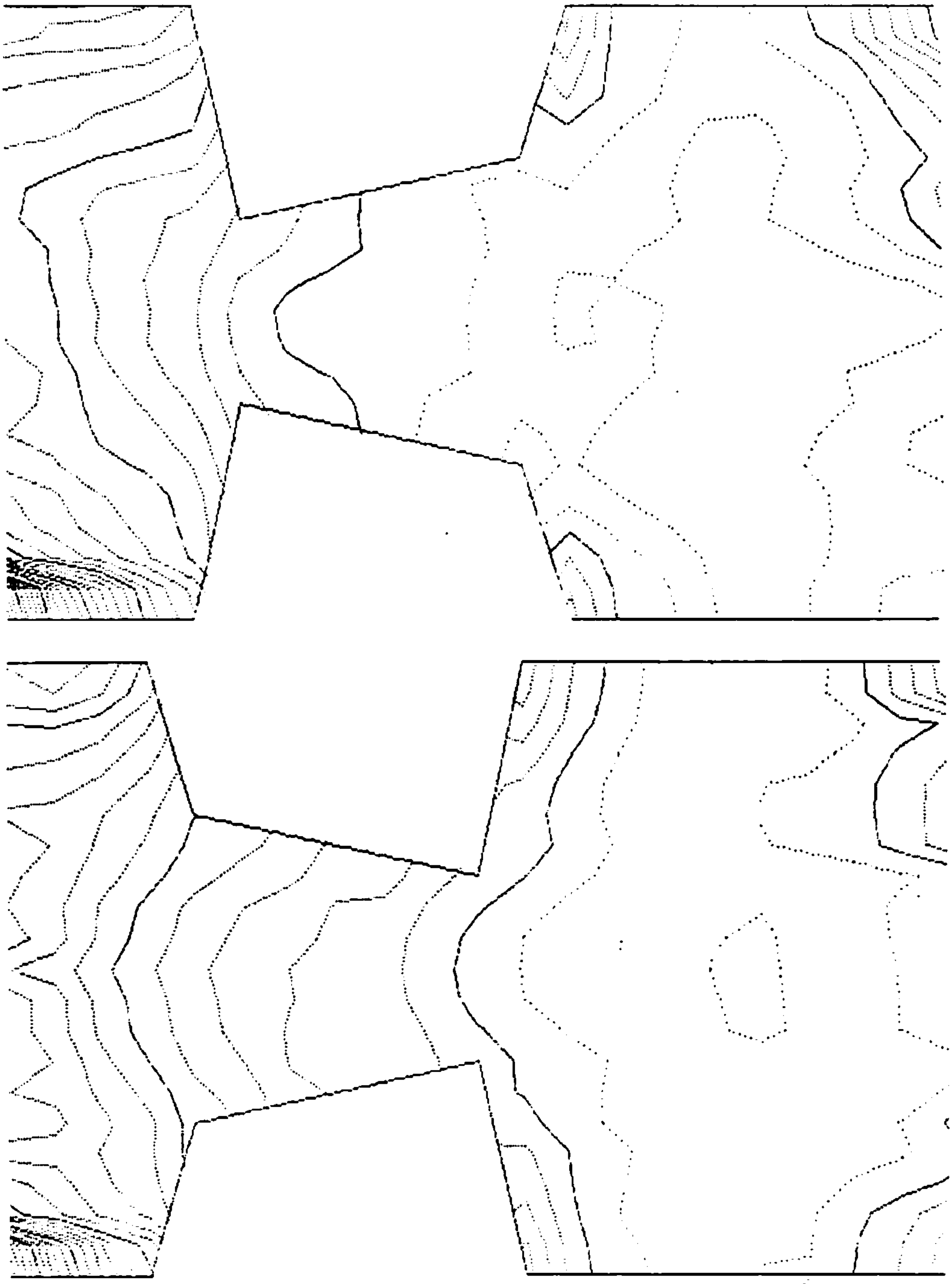

*Fig. 5 Contours of equal pressure obtained from a computer simulation of two-dimensional flow from left to right in a divergent and a convergent passage.*

of magnitude as the subglottic pressure. These pressure variations are caused by the sub- and supra-glottal resonances, especially the resonance of the first formant. The question is then if we can use the flow resistance of our static models as the instantaneous value in a dynamic simulation. A comprehensive answer to this question has not been given but we can point at some facts to consider.

First, we can estimate the air displaced by the moving folds. If we assume a chest voice at 100 Hz with a triangular area function, a peak area of 0.4 $cm^2$, opening and closing phases of equal length of 2.5 ms and a thickness of the folds of 2 mm, all quite realistic values, the displacement flow will be about 32 $cm^2/s$. At the same time the peak flow may be of the order of 600 $cm^2/s$. For higher fundamental frequencies the velocity of area change is proportional to the frequency but both the peak area and the glottal thickness will be smaller. The displacement flow should consequently not change much with the fundamental frequency. The displacement flow is, therefore, rather small compared to the total flow except in the beginning of the opening phase and close to the closure.

Second, the particle velocity of the air in the glottis has to be high so that the pressure drop across the glottis is approximately constant during the passage. Neglecting any entry coefficient the particle velocity is approximately:

$$V = 1.28 * 10^3 \sqrt{P}$$

V particle velocity in cm/s
P pressure drop in cm water

At a subglottic pressure of 9 cm water the particle velocity will then be 38 mm/ms in the narrowest part of the glottis. The flow in the glottal duct is mainly determined by the part that has a width of less than two times the minimum area. We can, therefore, assume that the mean particle velocity is 0.8 times the above value and the effective glottal length to 5 mm including the extension of the laminar jet at glottal exit. It then takes the air particle 0.2 ms to pass the glottis. From measurements of the pressure drop over the glottis during phonation (Kitzing and Lövqvist, 1975) we can estimate the maximum speed of pressure change to be about the subglottic pressure per ms. In the present example the pressure may change about 20% during the time it takes an air particle to pass through the glottis. This seems to be a reasonably slow change in the pressure so that the flow pattern will be the same in the dynamic case as in the static case for the same pressure drop.

CONCLUSIONS

Present aerodynamic theories of the larynx are based on one-dimensional flow theories and empirical data. Using the formula by Ishizaka & Matsudaira the pressure drop across the glottis can be calculated with an accuracy which in most cases is within 20%. However, the one-dimensional flow theory is not adequate when modeling vocal fold vibrations. Here a new approach using the two dimensional flow theory is needed.

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