MEASUREMENTS ON THE EFFECTS OF GLOTTAL OPENING AND FLOW ON THE GLOTTAL IMPEDANCE

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ABSTRACT

A new method to measure the acoustical impedance of an artificial glottal orifice is presented. The plate with the orifice is mounted to one end of a tube resonator with the other end being open. The impedance of the orifice seen from the tract can be solved from the resonance frequencies and bandwidths. The frequency characteristic of the orifice is easily otained under different DC-flow conditions. The results show that under turbulent flow the effective glottal inductance is clearly only a fraction of its flowless value. The measured glottal resistance is close to the theoretical value given by Flanagan's two-mass model.

INTRODUCTION

The acoustical impedance properties of the glottal orifice are an important part of the modelling and simulation of speech acoustics. In voiced sounds this impedance forms a time varying load for the vocal tract. Thus the transfer function of the tract is also varying according to the changes in the glottal impedance over the pitch period.

In the 50's the glottis was treated as a current source generating pulses into the vocal tract and the inner impedance of the generator was thought as "probably having the form of a large resistance and an inductance in series" [1]. In the early models the glottal impedance was just a large resistance. The effects of the reactive part were included in the generator pulse shape.

In recent analysis of speech acoustics the input impedance of the vocal tract at the glottis, the time varying infinite glottal impedance, and the input impedance of the subglottal system are considered [2-4]. In this approach the acoustical *interactive* nature of the source-filter system is also modelled. The successful use of these models depends strongly on the precision of the parts: how close one can describe the true acoustical phenomena in the source-tract system.

The glottal impedance is an important part of the models. The glottal impedance data is still taken from the acoustic research done in the 50's. Van den Berg et al. [5] made measurements on the DC resistance of the glottis with human larynx and with a mechanical model. These results are commonly used for the resistive part of the glottal impedance. The inductance of a short tube section neglecting the end corrections is mainly used for the glottal inductance [6-7].

The behavior of alternating sound waves superimposed on some DC flow in an orifice is a complex phenomenon. The particle velocity in the glottis is typically high enough to make the flow turbulent. This introduces more nonlinearities into the system. Moreover, some jet formations will appear in the vocal tract, and the sound waves in the tract have to propagate through this turbulent medium. This makes the problem extremely hard to handle analytically [8-9].

This paper describes a new method to measure the *total* frequency dependent orifice impedance as seen from the tract. The impedance measurement is made *indirectly* by monitoring the resonances of a tube mounted tightly to a plate with an orifice. Some measurement results are presented and discussed.

METHOD

A plate with a glottal opening is mounted tightly between two hardwalled aluminium tubes. The subglottal tube is acoustically damped with a soft wedge (see Fig. 1). This tube is connected to an air pressure source via an air flow meter. The supraglottal tube opens to free space. This tube is chosen to be one metre long so as to achieve dense resonances in the frequency area of interest. These resonances can be analyzed by mounting a microphone (B & K 4134) close to the glottal end of the tube. This must be done with care to avoid any possible leak of air through the mounting hole. The acoustical energy needed for the measurement of the tube resonances is fed from a loudspeaker system outside of the tube.

In our measurements the frequencies of sinewaves were monitored with a high quality counter. When using pseudorandom sequences the resonance parameters were estimated with an HP 3561A analyzer. All measurements were carried out in an anechoic chamber at the Acoustics Laboratory of the Helsinki University of Technology.

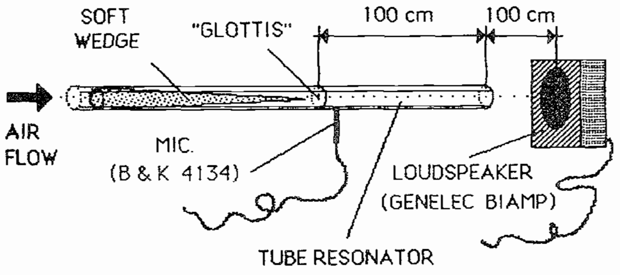

FIG. 1. Arrangement for the measurements.

The basic idea of this arrangement is first to analyze the losses of the tube itself when the glottis is completely closed. This is achieved by measuring the tube's resonance frequencies and bandwidths. When this information is compared with the resonances of an idealized lossless tube with the same dimensions it is possible to determine a loss impedance for the system. Now all of the acoustical losses of different types (like viscose, thermal, yielding wall and radiation) are lumped to one single loss impedance.

In the second phase the plate at the glottal end is changed to produce an artificial glottis. Now the loss factors of the resonator are increased. The glottal impedance seen from the tract can be calculated by measuring the tube resonances under this condition and by using the earlier knowledge about the losses under closed glottis condition. The procedure can be repeated for different glottal openings and flows to determine how these parameters affect the impedance.

THEORETICAL CONSIDERATIONS

In the following section the theory of transmission line is applied to solve for the loss impedance of the tube. Both closed and open glottis situations are considered.

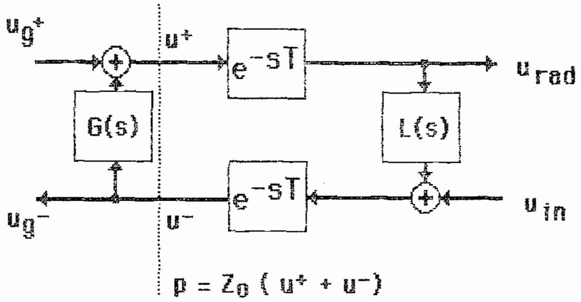

FIG. 2. The tube resonator as a transmission line.

Fig. 2 illusrates the analytical way the problem is handled. A volume velocity wave (u_{in}) of sinusoidal or pseudorandom sequence produced by the loudspeaker flows into the tube through its open end. After a delay of e^{-sT}, where T equals l/c of a loseless tube (l = tube length, c = sound velocity), the wavefront reaches the glottal end of the tube (u-). There the wave or some part of it reflects back (u+) appearing after the same delay at the open end. Here one part is radiated out (u_{rad}) and one part reflected back and summed with the incoming signal.

In the case of the closed glottis the reflection coefficient G(s) is assumed to be 1. All possible losses are now included in the reflection coefficient L(s) at the other end of the tube. The pressure registered by the microphone at the glottal end is related to the sum of the volume velocities u+ and u-:

$$p = Z_0 (u^+ + u^-) , \qquad (1)$$

where $Z_0 = \rho c/A$ is the characteristic impedance of the tube. Based on the structure of Fig. 2 we can solve for the transfer function:

$$\frac{p}{u_{in} Z_0 e^{-sT}} = \frac{1 + G(s)}{1 + G(s) \cdot L(s) \cdot e^{-2sT}} = H(s) \qquad (2)$$

The resonance frequencies and bandwidths are used to solve for the amplitude and phase functions of the unknown G(s) and L(s) , which first are written in the form:

$$G(s) = e^{-\partial_G(w)} \cdot e^{j\mathbf{f}_G(w)} \qquad (3)$$

$$L(s) = e^{-\partial_L(w)} \cdot e^{j\mathbf{f}_L(w)}$$

The attenuation factor (∂) and the phase factor ($\mathbf{f}$) are now separated. In the closed glottis case Eq. (2) gets the form:

$$H(s) = 2 / \{ 1 + e^{-\partial_L(w)} \cdot e^{j\mathbf{f}_L(w)} \cdot e^{-2s\mathbf{T}} \} \qquad (4)$$

The poles $s_n = \beta_n + jw_n$ of H(s) are located at the frequencies w_n, where:

$$w_n 2\,\mathbf{T} - \mathbf{f}_L(w_n) = (2n-1) \cdot \pi \ , \quad n=1,2,..,N \qquad (5)$$

and the attenuation function must satisfy :

$$\boldsymbol{\beta}_n 2\,\mathbf{T} = \partial_L(w_n), \qquad (6)$$

where $\boldsymbol{\beta}_n = -\pi\,\mathbf{B}_n$, and $\mathbf{B}_n$ is the 3dB bandwidth of the n-th resonance. Thus the amplitude and phase functions for the reflection coefficient L(s) at the resonance frequences of the tube are:

$$\partial_L(w_n) = -2\,\pi\,\mathbf{B}_n\,\mathbf{T} \qquad (7)$$

$$\mathbf{f}_L(w_n) = w_n 2\,\mathbf{T} - (2n-1) \cdot \pi$$

Now, it is easy to solve for the corresponding functions of G(s):

$$\partial_G(w'_n) = 2\,\pi\,\mathbf{B}'_n\,\mathbf{T} - \partial_L(w'_n)$$

$$\mathbf{f}_G(w'_n) = w'_n 2\,\mathbf{T} - (2n-1) \cdot \pi - \mathbf{f}_L(w'_n), \qquad (8)$$

where w′ and B′ denote the new resonance frequencies and bandwidths corresponding to the open glottis case. Because the function L(s) is determined only at the closed glottis resonances (w_n) the values at w'_n must be estimated by interpolation.

RESULTS AND CONCLUSIONS

All the measured glottal openings were 4 mm in depth. The opening had a rectangular form with an average height of 18 mm. The width of the opening varied from 0.45 mm to 1.95 mm. One diverging profile was also studied having a width from 0.5 mm to 2.0 mm. An effective width of 1 mm was used for this orifice when solving for the theoretical value of its inductance, and a width of 0.5 mm for the calculation of its resistance.

The results obtained from the measurements are compared to the following theoretical model commonly used:

$$Rg = Z0 + 12*V*0.4/(H*W^3) + Ro*U*(0.69-Ar*(1-Ar))/Ag^2$$

$$Lg = Ro*(0.4+dd+dm)/Ag \qquad (9)$$

$$dd = 0.48*SQRT(Ag)$$

$$dm = \pi*SQRT(2*V/(Ro*w))/(W+H),$$

where Z0=6.89 g/(s*cm^4) is the characteristic impedance of the 2.77 cm diameter tube, V= air viscosity, Ro= air density, H= opening heigth, W= opening width, Ag= opening area, Ar= Ag/At, where At = tube cross-sectional area, U= volume velocity, w= angular frequency. The end correction term (dd) and the term (dm) due to the viscosity are taken from ref. [8]. The term Z0 is added to the resistance to include the effect of the subglottal tube on the measured impedance. The equation for the resistance is taken from ref. [7] and gives a better match to the results than the formula given by van den Berg [5].

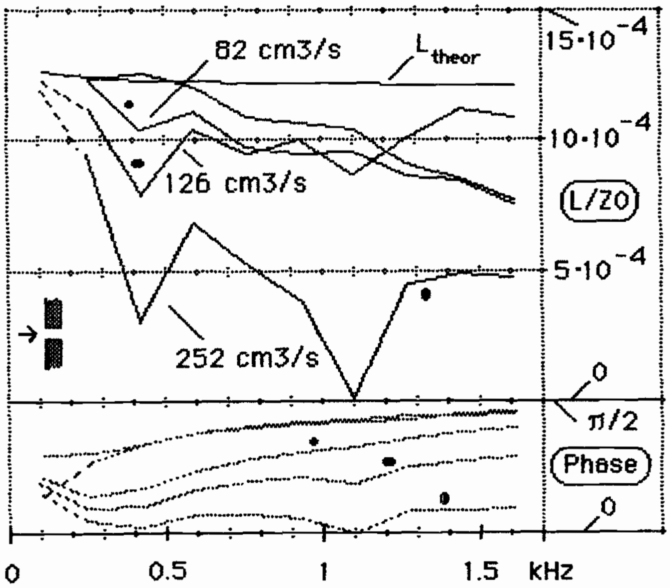

FIG. 3. Normalized inductance of the uniform opening under different flow conditions. The dimensions of the opening: depth d=4 mm, height h=18.2 mm width w=0.45 mm

In the first phase the flowless impedance of the different orifices are calculated from the data and compared to the values given by the model (9). The results match fairly well for all orifices only if both correction terms (dd, dm) are included in the inductance.

In the second phase impedances under different DC-flow conditions are obtained. The resistive part of the orifice impedance follows the model well except for having a tendency to diminish at higher frequencies.

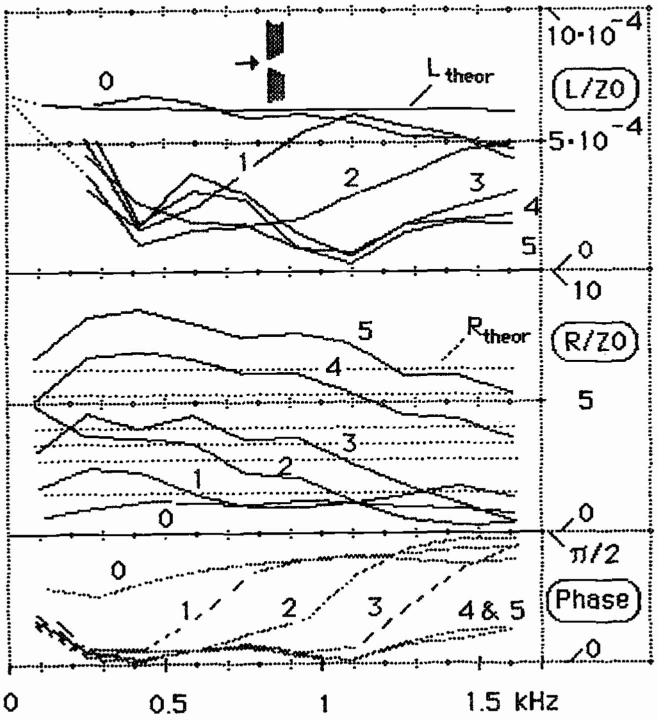

FIG. 4. Normalized inductance and resistance of the diverging opening: d=4 mm, h=17.9 mm, w_1=0.5 mm, w_2=2 mm. Flow/ cm^3/s: 0) 0 1) 82.3 2) 126 3) 168 4) 252 5) 315.

The most notable difference between the model and the results appear in the behavior of the inductance. This is illustrated by figures 3 and 4. The effective average inductance obtained by the method goes down with increasing flow. When a higher DC-flow is passed through the orifice the effective inductance is a fraction of its flowless value.

The novel measuring method introduced above has produced a new view on the complexity of glottal orifice air dynamics and acoustics. Our results show that the average glottal inductance is smaller than was previously known especially at frequencies above 0.5 kHz. Based on the comparison of different flow and orifice profile conditions the decrease in the inductance seems to be related to the turbulence in and after the orifice.

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