MEASUREMENT OF THE GLOTTAL IMPEDANCE WITH A MECHANICAL MODEL

HANS WERNER STRUBE STEFAN RÖSLER

Drittes Physikalisches Institut, Universität Göttingen,
Bürgerstr. 42-44, D-3400 Göttingen, Fed. Rep. of Germany

ABSTRACT

The glottal impedance is measured at acoustic frequencies, using a mechanical model with adjustable slit width and air flow. The glottis is inserted in a measuring tube with subglottal absorber, supraglottally excited by periodic wideband pulses. The complex reflectance of the glottis as function of frequency is directly computed from the incident and reflected waves, which are separated by a two-microphone directional coupler. The measured curves are compared to theory and are expressed as functions of frequency, slit width, and air flow.

INTRODUCTION

The knowledge of the glottal impedance is essential for the understanding of the source-tract coupling, e.g., the variation of formant frequencies and damping during the glottal cycle, and of the oscillation mechanism itself. The resistive part of the impedance consists of a linear, viscous component R_V and a nonlinear, flow-dependent component R_k due to kinetic effects (turbulence, beam formation, etc.). These components were measured for DC flow by the pressure drop across a glottal model [1]. For nonstationary flow, the air mass causes an additional, reactive part of the impedance, so that the electrical analogue (pressure = voltage, volume velocity = current) is an RL series circuit. This form was also used in a simulated self-oscillating glottal model [2].

However, it can not be theoretically expected that the values for R measured at DC still hold at acoustic frequencies, since the viscous boundary layer and the turbulence formation are frequency-dependent. Further, the inductance should be somewhat larger because of the approximately radial flow close to the glottal slit and also slightly frequency-dependent (see below), and turbulence effects on the inductance are unknown. As the theoretical treatment of all these effects, including nonzero DC flow and turbulence, is highly difficult, an experimental determination of the impedance as function of frequency, air flow, and glottal slit width appears desirable. Such measurements have previously been performed by means of the resonances of a tube attached to a glottal model [3]. Our approach is more direct, immediately yielding the complex reflectance as function of frequency.

THEORY

The impedance measured by us is a differential (AC) impedance. As the acoustic amplitudes are small, all terms of the Navier-Stokes equations nonlinear in AC quantities are neglected. Especially, if the total kinetic part of the pressure drop is KU^2 (U = instantaneous total volume velocity), the kinetic part of the AC pressure drop is $2KU_{DC}U_{AC}$, so that $R_k = 2KU_{DC}$ (vanishing for no DC flow!). According to [1], $K = 0.44\rho/A^2$ (ρ, A see below). At higher frequencies possibly this might not hold.

The linear (viscosity and mass) parts of the impedance, Z_{Vi}, can be theoretically derived in good approximation. The glottis is assumed as a rectangular slit of length l, width w, area A = lw, and depth d. If $w \ll l$, and w and $d \ll$ wavelength, the impedance is

$$Z_{Vi} = (i\omega\rho d/A)g/(g - \tanh g), \qquad g = (w/2)\sqrt{i\omega\rho/\eta},$$

ρ = air density, η = dynamic viscosity. For $\omega \to 0$,

$$Z_{vi} = 12 d\eta l^2/A^3 + i\omega(6/5)\rho d/A,$$

which is the classic expression except for the factor 6/5 in the inductance. For $\omega \to \infty$, on the other hand, $Z_{vi} = i\omega\rho d/A$. Thus the inductance is also slightly frequency-dependent.

As the slit is contained in a partition across a tube, the impedance has to be supplemented by an end correction due to the approximately two-dimensional radial flow near the slit. This yields an additional inductance of roughly

$$L_{rad} \approx (\rho/l\alpha)\ln(D/w),$$

D = tube diameter perpendicular to the slit, α = sum of opening angles of sub- and supraglottal baffles. Also some additional damping will result which we will not derive.

METHOD OF MEASUREMENT

(The same principle, suggested by M.R. Schroeder, was used earlier at this Institute for measuring the lip radiation impedance with a model head [4].)

Apparatus

A fairly realistic larynx model was formed of metal (Fig. 1). The glottis itself is a slit between two adjustable parallel plates tightly inserted in the larynx model. The slit measures are: l = 18 mm, d = 3 mm, w = 0 to 3 mm. The larynx model is extended on both sides by thick-walled uniform brass tubes of 10 mm inner diameter. Subglottally, a funnel with sound absorbing material is attached through which a DC air flow can be supplied. Supraglottally, the tube ends at a pressure-chamber loudspeaker and an air outlet with a plastic hose filled with cotton wool (Fig. 2).

The loudspeaker emits periodic wide-band pulses (68–5000 Hz), chirp-like with Schroeder phases [5] for a low peak factor. They are generated by a TMS 32010 signal processing system and D/A converted at 20 kHz sampling rate, with 2048 samples/period to facilitate FFT processing. By two ¼" condenser microphones (Brüel & Kjaer 4136) coupled to the tube some 22.5 cm "above" the glottis, the incident and reflected waves can be separated computationally and thus the complex reflectance be determined. The microphones are screwed into the tube walls without grid caps and coupled through holes of 1 mm diameter. Disturbance by the additional volume was estimated to be completely negligible. The signals are low-pass filtered at 5 kHz with 96 dB/octave and digitized at 20 kHz rate by two A/D converters in the TMS 32010 system. Sampling is period-synchronous with the excitation pulses. The blocks of 2048 sample pairs are transferred to a large laboratory computer (Gould 32/9705), where 100 periods are averaged for noise reduction and the further evaluation is performed. Channel crosstalk is less than −80 dB.

Evaluation

Let b be the distance from the centre between the microphones to the reference plane in which the reflectance is to be measured, 2a the microphone distance (Fig. 3), R = R(ω) the reflectance, and k_i, k_r the complex propagation "constants" for the incident and reflected waves. If c is the sound velocity and v the DC-flow velocity,

$$k_i = (i\omega + q\sqrt{\omega})/(c-v), \quad k_r = (i\omega + q\sqrt{\omega})/(c+v),$$

where $q\sqrt{\omega}$ (small; $q \approx 0.8\ s^{-1/2}$) represents the combined viscous and heat-conduction losses. Then the microphone signals $F_1(\omega)$, $F_2(\omega)$ are proportional to $\exp(k_i(b\pm a)) + R\exp(-k_r(b\pm a))$, where +a and −a belong to F_1, F_2, respectively. Solving for R, we obtain

$$R = \exp((k_i+k_r)b)\cdot(F_2\exp(k_i a)-F_1\exp(-k_i a)) / (F_1\exp(k_r a)-F_2\exp(-k_r a)).$$

From R, the glottal impedance follows as

$$Z = Z_0(1+R)/(1-R) - Z_{SG},$$

where $Z_0 = \rho c/A_{tube}$ is the characteristic impedance of the tube and Z_{SG} the impedance of the subglottal system. The latter is measured before by replacing the larynx model with a uniform tube piece.

As the computation of R fails at the zeros of the denominator and becomes rather inexact at low frequencies, two different microphone distances 2a (24.6 and 120 mm) may be used.

Calibration

As the microphones and the connected amplifiers, filters and A/D converters are not identical for both channels and differences would cause detrimental errors, the channels must be calibrated relative to each other. For this purpose, the signals are recorded for each microphone screwed into the same fitting in the measuring tube. The complex

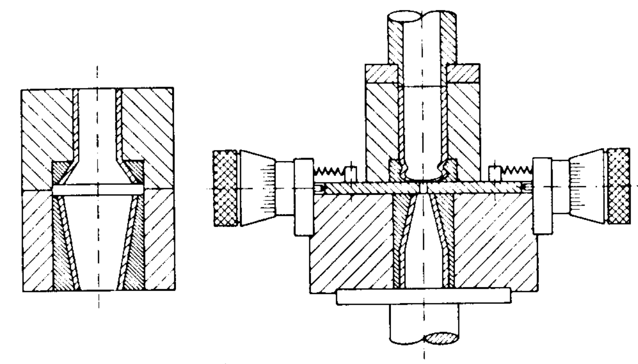

Fig. 1. Larynx model; two perpendicular sections.

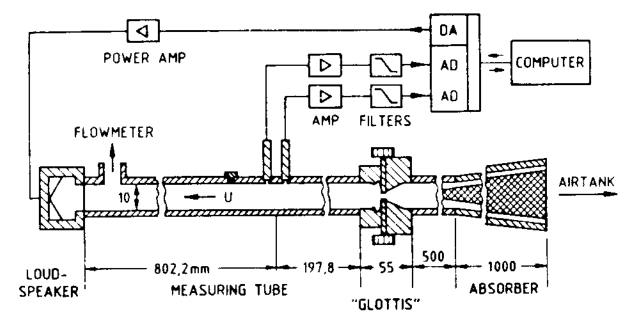

Fig. 2. Schematic of measuring apparatus.

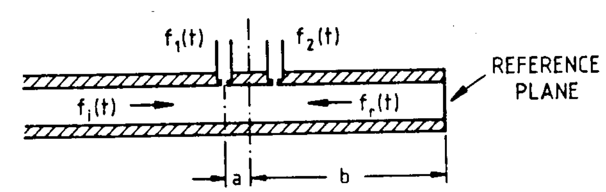

Fig. 3. Schematic of directional-coupler principle.

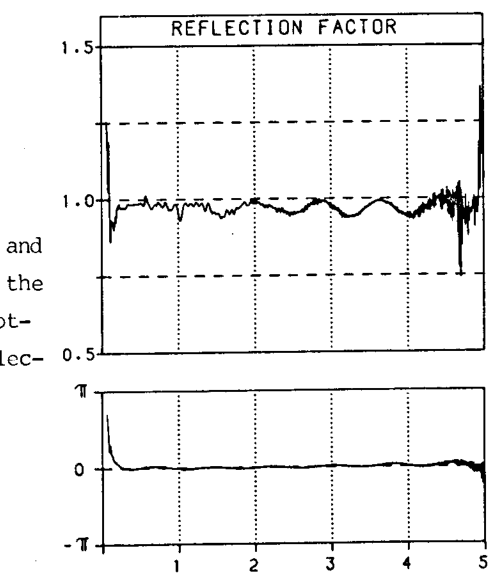

Fig. 4. Magnitude and phase of the closed-glottis reflectance.

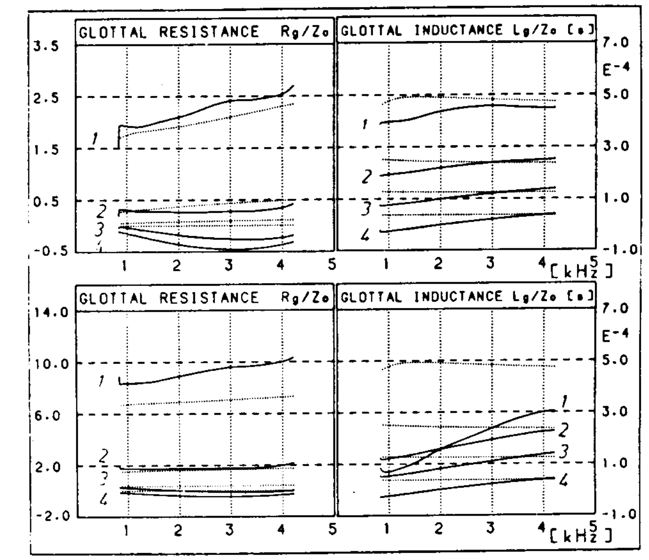

Fig. 5. Resistance and inductance for flows U = 0 (top) and 164 cm^3/s (bottom). Glottal width w = 0.2, 0.4, 0.8, 3.0 mm (1 to 4).

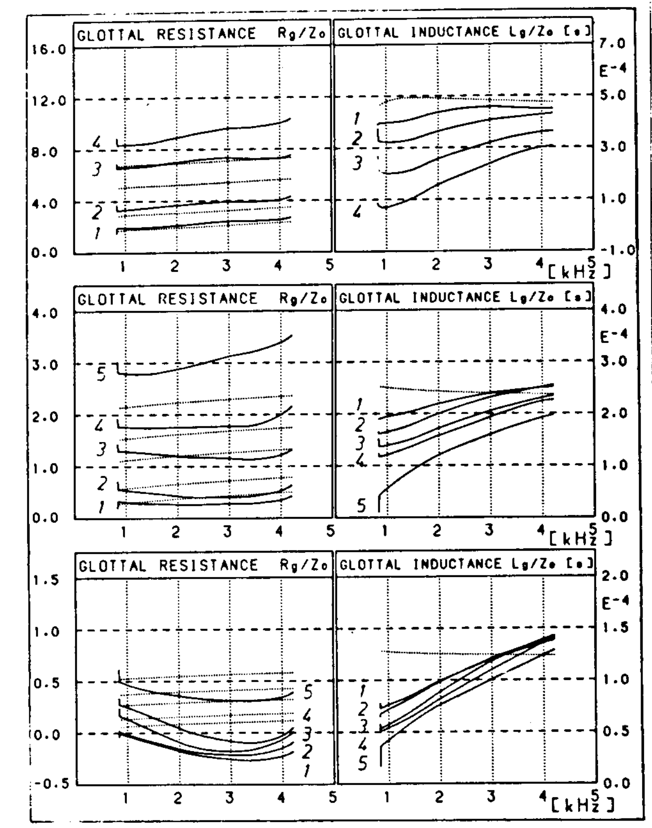

Fig. 6. Resistance and inductance for widths w = 0.2, 0.4 and 0.8 mm (top to bottom). Flow U = 0, 38, 109, 164, 245 cm^3/s (1 to 5).

quotients of the corresponding DFT values are taken as calibration factors for one microphone.

As a test, the result for completely closed glottis should yield $R(\omega) \equiv 1$, apart from some high-frequency deviations due to the nonuniformity of the tube close to the glottis. This allows to determine the exact reference distance b from the linear phase trend of R. Inexact assumptions of a and q will cause periodicities of R with frequency-period of c/2b; minimizing their amplitudes thus permits better adjustment of the a and q values.

RESULTS

All results shown here are preliminary and will hopefully have been improved at the time of the congress. So far, only one microphone distance 2a = 24.6 mm has been used.

Calibration

Fig. 4 displays magnitude and phase of the reflectance for closed glottis. The trends in the phase and the residual c/2b-periodicities show that we have not yet fully reached the required exactness; better calibration methods are under development. The average |R| cannot be raised above 0.98 ($q = 0.88\ s^{-\frac{1}{2}}$) without distorting the curves.

The subglottal impedance Z_{SG} was found very close to Z_0 except at the lowest frequencies.

Measurements

The periodicities are presently smoothed out by a triangular moving average of the reflectance of length c/b in frequency. Figs. 5 and 6 show the glottal impedance (with Z_{SG} subtracted out) for various openings w and flows U. The dashed curves are the theoretical ones,

$$R_g = \mathrm{Re}\, Z_{Vi} + R_k(U), \quad L_g = (\mathrm{Im}\, Z_{Vi})/\omega + L_{rad},$$

see THEORY. For U = 0, the agreement is fairly good, except for a too low (even partly negative) resistance at large glottal openings and a too low inductance at low frequencies. The reason for these (unphysical) deviations is presently not yet clear but probably related with the calibration problems. For nonzero flow, the inductance is considerably decreased at low frequencies and the resistance is increased, especially for narrow width w where the velocity U/lw in the glottis is large. A similar effect for the inductance was also found by Laine and Karjalainen [3] around 1 kHz.

Discussion

A direct comparison of our results with [3] is not yet possible since our frequency range lies above that (≲ 1.5 kHz) considered in [3]. For useful results in the low-frequency range, we shall apply the microphone distance 2a = 120 mm and a lower sampling frequency.

The results at higher frequencies show a very strong dependence on the choice of the reference plane (distance b). Actually, as the "exact position" of the glottal impedance is somewhat arbitrary, so is the impedance itself. We define b so as to yield no linear phase trend for closed glottis, and the closeness between theoretical and measured curves seems to justify this procedure.

The flow effects on the inductance are presently not yet expressed by a theoretical or empirical formula. The relevant parameter appears to be the velocity in the glottis, U/lw, rather than the flow U. The kinetic resistance R_k at large U should be somewhat higher than according to [1]. The frequency dependence of R_k seems to be small.

As for the effect of the glottal impedance on the vocal-tract acoustics, the subglottal impedance must not be subtracted out. If the actual Z_{SG} is close to ours (our tube has roughly the diameter of the trachea), the real part for not too small openings w is entirely dominated by Z_{SG}.

REFERENCES

[1] J. van den Berg, J.T. Zantema, P. Doornenbal, jr.; J. Acoust. Soc. Am. **29**, 626-631 (1957).

[2] J.L. Flanagan, L.L. Landgraf; IEEE Trans. Audio Electroacoust. **AU-16**, 57-64 (1968).

[3] U. Laine, M. Karjalainen; Proc. ICASSP 86, 1621-1624 (1986).

[4] J. Kretschmar; Fortschritte der Akustik - DAGA'75, 429-432 (Weinheim: Physik Verlag, 1975).

[5] M.R. Schroeder; IEEE Trans. Inform. Th. IT-16, 85-89 (1970).