Measurements of the aero-acoustic properties of the vocal folds and vocal tract during phonation into controlled acoustic loads

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The aeroacoustic properties of the vocal folds and tract are difficult to measure directly. Here, they were measured using broad- and narrow-band excitation at the mouth during phonation into various acoustic loads, including a non-resonant load provided by an acoustically infinite waveguide with cross section comparable with that of the tract. The tract is treated as a duct terminated by the larynx. Mechanical properties of the walls and terminations were determined using a microphone array (Dickens et al. 2007). The vocal fold response was monitored with an electroglottograph and wall motion was measured electromechanically. The impedance spectra show negative resistance bands at frequencies near those of phonation, consistent with regeneration at the folds. The walls give inertances consistent with thicknesses of order 1 cm and compliances consistent with distributed stiffnesses of about 100 kN/m³ (Hanna et al. 2012). The duct resonant properties are consistent with losses several times higher than the viscothermal losses at smooth rigid walls. Dickens, P., Smith, J., Wolfe, J., (2007) JASA, 121, 1471-1481. Hanna, N., Smith, J., Wolfe, J., (2012) Proceedings of the Australian Acoustical Society Conference.
INTRODUCTION

The aero-acoustic properties of the vocal folds and tract are difficult to measure directly. Here, they were measured using broad- and narrow-band excitation at the mouth during phonation into various acoustic loads, including a non-resonant load provided by an acoustically infinite waveguide with cross section comparable with that of the tract. The tract is treated as a duct terminated by the larynx. Mechanical properties of the walls and terminations were determined using a three microphone head (Dickens et al. 2007).

The vocal fold response was monitored with an electroglottograph and wall motion was measured electromechanically. The impedance spectra show negative resistance bands at frequencies near those of phonation, consistent with regeneration at the folds. The measurements indicate that the walls have inertances consistent with thicknesses of order 1 cm and compliances consistent with distributed stiffnesses of about 100 kN/m³ (Hanna et al. 2012). The duct resonant properties are consistent with losses several times higher than the viscothermal losses at smooth rigid walls.

METHOD

Vocal Tract Properties: Three Microphone, Three Calibration Broadband Measurements

Acoustic impedance measurements were made at the lips using a three-microphone array calibrated with three non-resonant loads (Dickens et al. 2007). Seven male subjects made an air-tight seal with their lips around the measurement head, and were asked to either produce the long vowel sound in the word “heard” [əː], or the same vocal gesture without phonation with an open or closed glottis. Simultaneous measurements of the frequency, bandwidth and magnitude of the vocal tract resonances were made with a frequency resolution of ~2.7 Hz from 14 to 4200 Hz. A typical single cycle of the measurement lasting 370 ms is shown in Figure 1. The average of similar cycles during the same vocal gesture was used to determine the bandwidths of the resonances.

Vocal Tract Properties: Non-Rigid Behaviour

Low frequency broadband measurements were also made for each subject. However, to improve signal:noise ratio, narrower frequency bands were used (10-50 Hz at ~0.3 Hz resolution and 14-400 Hz at ~0.7 Hz resolution). In addition, a small magnet was attached to the cheek and/or neck of four of the subjects. This allowed us to measure tissue velocity by recording the Faraday EMF in a coil of wire at a fixed distance from the magnet.

For semi-quantitative analysis of the tissue motion, Figure 2b shows simple physical and electrical models of the vocal tract behaviour that are appropriate at very low frequencies, at which the tract can be approximated as a compact object (i.e. the dimensions are much less than the wavelength of sound so the pressure is approximately uniform). Electrical analogues such as these have been proposed previously (e.g. Fant 1972, Ishizaka et al. 1975), however we know of no measurements of the frequencies and bandwidths of the LC resonances.

Vocal Fold Properties: Three Microphone Three Calibration Narrow Band Measurements

In addition to the broadband impedance measurements during phonation, the motion of the vocal folds was probed using narrow band excitation around the frequency of phonation, while subjects phonated in the upper and lower ranges of their normal voice (Mechanism 1). A quasi-infinite pipe (length ~200 m) behind the measurement head provided a purely resistive acoustic load on the vocal folds. The vocal fold behaviour was monitored with an electroglottograph.

RESULTS

The broadband impedance spectrum in Figure 1 shows that all but the lowest two impedance extrema of the vocal tract are qualitatively similar to those of a rigid, closed cylinder of comparable dimensions. However, the Q factors of the vocal tract correspond to losses several times larger than those of a rigid cylinder with purely visco-thermal losses, in line with previously reported data on a single subject (Hanna et al. 2012).
FIGURE 1. The dark curve shows a typical impedance spectrum obtained with the glottis closed for a single subject. Several cycles of such measurements are made lasting 370 ms each. The average of similar cycles during the same vocal gesture is then used for analysis. The pale line shows the calculated impedance spectrum of a rigid duct of similar dimensions (Fletcher & Rossing 1991).

At frequencies below several hundred hertz the vocal tract impedance deviates from that of a rigid tube. A low frequency broadband impedance curve is shown in Figure 2a. This non-rigid behaviour at low frequencies can be simply modelled as the compliance of the air in the tract in series with the inertance and compliance of the vocal tract walls, as shown by the equivalent circuits in Figure 2b. The measured frequencies give inertances consistent with a wall thickness of order 1 cm and compliances consistent with a distributed stiffness of about 100 kN/m³ (Hanna et al. 2012).

FIGURE 2. (a) Low frequency behaviour of the vocal tract. (b) Physical and electrical analogues. At ~200 Hz the volume of air in the vocal tract acts approximately as a compact acoustical element, here a spring of constant $k$ (compliance $C$) in parallel with the mass, $m$ (inertance $L$) of the vocal tract walls, this gives rise to a resonance with the observed impedance maximum. At lower frequencies $k$ is an open circuit, and a series resonance between the mass of the vocal tract walls and their own spring $k_t$ (compliance $C_t$) gives rise to an impedance minimum at ~20 Hz. Mechanical losses that lead to the finite $Q$ of the resonances are approximated as a resistance $R$.

The non-rigid behaviour of the vocal tract was also observed in the motion of the magnet placed on the cheek and/or neck of four of the subjects. Peaks in the mechanical admittance were measured corresponding to a large amplitude vibration of the cheeks, as shown in Figure 3, and to a lesser extent of the neck, similar to the pattern measured by Fant et al. (1976).
FIGURE 3. The EMF induced in a fixed coil of wire by a magnet placed on the subject's cheek during phonation. The tract was excited by broadband sound between 10 and 50 Hz. The peak in the mechanical admittance (large amplitude vibration) corresponds to the frequency (~20 Hz) of the first impedance minimum of the vocal tract.

The frequency of phonation, $f_0$ and its harmonics appear in the impedance spectra as additional signals with a phase uncorrelated with the synthesised sine waves of the probe signal (Figure 4). Bands of negative resistance appear close to these frequencies, consistent with regeneration at the folds.

FIGURE 4. The mean impedance spectrum magnitude and phase of several cycles during phonation clearly show the fundamental frequency $f_0$ and harmonics of the voice. The smooth pale line shows a measurement during exhalation, i.e. with the glottis open but no phonation.

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REFERENCES