ACOUSTIC TRANSMISSION-LINE ANALYSIS OF FORMANTS IN HYPERBARIC HELIUM SPEECH

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ABSTRACT

Acoustic transmission-line vocal tract models are used to study formant frequencies, bandwidths and amplitudes of hyperbaric heliox speech versus those of speech in air at 1 ATA. The models account for energy losses due to glottal impedance, lip/nostrils radiation, wall vibration, viscous friction and thermal conduction. New wall impedance values are presented, matching measurements of the closed tract resonance. On basis of a uniform tube model, an extended version of the classic Fant-Lindquist formula [1] describing formant frequency shift is developed, and formulas for bandwidth and amplitude shifts are given. A multitube vocal tract model is applied for analysis of the effects of nonuniform vocal tract cross-sectional area on the formant shift.

INTRODUCTION

The speech of divers breathing a hyperbaric heliox gas mixture at large depths is known to be nearly unintelligible. Although the intelligibility is raised by speech correction through helium speech unscramblers, the quality of the corrected speech is not sufficient for safe and efficient operation. The intelligibility decreases rapidly when moving towards greater depths, even with the most advanced of todays unscramblers. This might be a reflection of the fact that the knowledge of diver's speech distortion is far from sufficient, based upon simplified acoustic models of the speech production system. The purpose of this work is to achieve extended knowledge of the distortion through enhanced speech production models.

Assuming that speech can be considered stationary over the time interval considered, also neglecting nonlinear interaction, the speech spectrum S(f) (measured by a microphone) can be described by a linear source-filter model:

$$S(f) = G(f)\, V(f)\, L(f)\, M(f) \qquad (1)$$

where G(f) is the source (excitation) signal spectrum. V(f) is the vocal tract transfer function, L(f) is the radiation characteristic and M(f) is the combined mask/microphone response. All of these terms may contribute to the total speech distortion under hyperbaric heliox conditions. In this paper, however, we will concentrate on V(f), discussing distortion due to changing formant structure as depth and gas mixture are changed.

V(f), defined as the ratio of volume velocity through lips (nostrils in case of nasals) to volume velocity through glottis U_m/U_g (U_n/U_g), determines the formant(vocal tract resonance) structure of speech. Based upon a uniform acoustic single-tube model of the vocal tract, assuming lumped elements and neglecting glottal, radiation, viscous and thermal losses, Fant and Lindquist [1] derived their classical formula describing the nonlinear shift of formant frequencies from air at 1 ATA to hyperbaric heliox conditions. In a distribued elements representation, Richards and Schafer [2] have extended the uniform tube model to account for the loss terms lacking in the Fant-Lindquist model. Shifts of formant frequencies, bandwidths and amplitudes were all discussed.

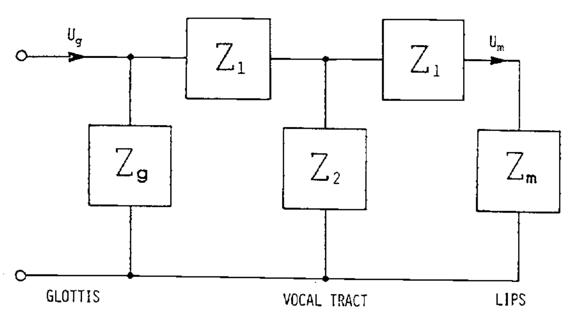
The first part of the present work is based upon Richards and Schafers uniform tube model. However, an extended mathematical discussion is performed, leading to explicite expressions and shift formulas for formant frequencies, bandwidths and amplitudes. In addition, new wall impedance data are derived and applied, providing more realistic bandwidths of lower first formants. In the second part of the work, a multitube vocal tract model is applied for analysis of the influence of nonuniform vocal tract geometry on the formant shift. With this model simulations of V(f) for 5 vowels and 2 nasal consonants were performed in air at 1 ATA as well as hyperbaric heliox conditions.

ACOUSTIC SINGLE-TUBE VOCAL TRACT MODEL

Transmission-Line Description

As a first approximation for studying vocal tract sound transmission, we neglected the effects of nonuniform vocal tract geometry. The vocal tract was modelled as a single, uniform (cylindrical), lossy tube of lengt l = 17.5 cm. and radius r = 1,26 cm., enabling derivation of explicite formant parameter formulas.

The acoustic transmission-line analog of the uniform tract model is shown in Fig. 1. Here $Z_g = R_g + i\,\omega\, L_g$ and $Z_m = R_m + i\,\omega\, L_m$



$$\frac{U_m}{U_g} = \left[\frac{Z_m}{Z_2} + \frac{Z_m Z_1}{Z_g Z_2} + \frac{Z_m}{Z_g} + \frac{Z_1}{Z_2} + \frac{Z_1^2}{Z_g Z_2} + 2\,\frac{Z_1}{Z_g} + 1\right]^{-1}$$

Fig. 1 Transmission-line analog of the uniform single-tube vocal tract model

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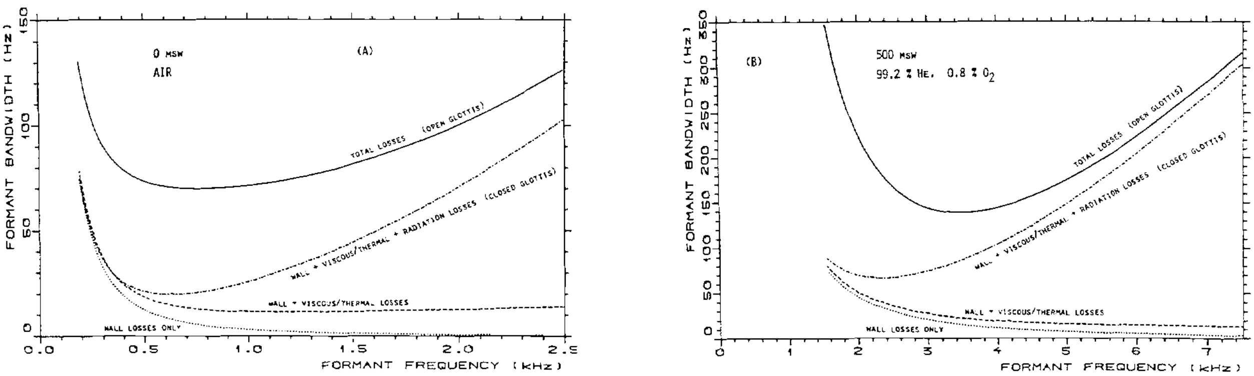

Fig. 2 Relative contributions to formant bandwidth B_n from the 5 energy loss terms, for (a) air/1 ATA, (b) heliox/48.4 ATA

are the glottal and lip radiation impedances, respectively. Z_1 and Z_2 are defined by $Z_1 = Z_0 \tanh(\gamma l/2)$, $Z_2 = Z_0/\sinh(\gamma l)$, where $Z_0 = (Z_a/Y_a)^{1/2}$ is the characteristic impedance and $\gamma = (Z_aY_a)^{1/2}$ is the (complex) sound propagation constant [3]. The acoustic impedance $Z_a = R_a + i\omega L_a$ is determined by viscosity and mass inertance of the gas. The admittance $Y_a = G_a + G_w + i(\omega C_a - 1/\omega L_w)$ is determined by thermal conductivity, gas compressibility, wall viscosity and wall mass vibration. For the glottal impedance, Flanagan's equivalent small-signal model [3] was used. The viscous/thermal loss terms were also taken from [3]. For the lip radiation impedance, the piston-in-sphere and piston-in-infinite-baffle models were both used. What wall impedance (wall viscosity and mass vibration) concerns, the values given by [3] (used by [2]) did not perform sufficiently well, giving rise to extremely large bandwidths of formants in the vicinity of the closed tract resonance. Wall impedance values providing more realistic results therefore had to be determined. This point is discussed in a separate section below.

It should be noted that in the present transmission-line representation there is no assumption of lumped elements. This would have constricted the validity range of the analysis.

Formant Analysis

The vocal tract transfer function V(f) of the uniform, single tube was derived from the conditions of continuity of pressure and volume velocity for vocal tract sound transmission. The complex poles of V(f) were then found, from which the formant frequencies and bandwidths were readily determinded. The details will not be given here. Under the assumptions $|Z_m/Z_0 + Z_0/Z_g| \ll 1$, $|Z_m/Z_g| \ll 1$, $R_a \ll \omega L_a$, $G_a + G_w \ll \omega C_a - 1/\omega L_w$ and $4(F_w/F_{n0})^2 k_g/k_m (1 - k_gk_m) \ll 1$, it is shown in [4] that the formant frequencies F_n, bandwidths B_n and amplitudes A_n are given by the formulas

$$F_n = \frac{\sqrt{F_{n0}^2 k_m^2 + F_w^2[1 - (k_gk_m)^2]}}{1 - k_gk_m} \quad (2)$$

$$B_n = \frac{k_m [B_v + B_h + B_g + B_m + B_w]}{1 - k_gk_m} \quad (3)$$

$$A_n = c/\pi l B_n \qquad , n = 1,2,\ldots \quad (4)$$

Here c is the speed of sound, $F_{n0} = (2n-1)c/4l$ is the nth formant frequency of the lossless uniform tube, $F_w = 1/2\pi(C_aL_w)^{1/2}$ is the closed tract resonance frequency, $k_m = (1+L_m/lL_a)^{-1}$ is a lip radiation correction factor (approximately equal to unity) and $k_g = L_g/C_a l|Z_g|^2$ is a glottal correction factor (nearly equal to zero except for lower frequencies in hyperbaric heliox gas). The bandwidth contributions are all frequency dependent, given as $B_v = R_a/2\pi L_a$, $B_h = G_a/2\pi C_a$, $B_w = G_w/2\pi C_a$, $B_m = R_m/\pi l L_a$ and $B_g = k_gR_g/\pi l L_g$.

The main contributions to the formant frequencies are seen to descend from the lossless formant frequencies and the vibrating cavity walls. The lip radiation and glottal impedances contribute through small correction terms only. Thermal and viscous losses do not influence at all. For the formant bandwidths, however, all losses contribute to the total damping. The relative contribution to the total bandwidth from each loss term is shown as function of formant frequency in Fig. 2 for air at 1 ATA and heliox at 500 msw. Lower formant damping is dominated by wall vibration and glottal losses, whereas upper-frequency formants are largely damped by lip radiation losses. Note that when each loss term is considered isolated, eqs. (2) and (3) reduce perfectly to the formulas given by Flanagan [3].

Formant Shift

Under the additional assumption that $k_gk_m \ll 1$ (valid for $f \gg F_w$) we are now able to obtain expressions relating formant frequencies, bandwidths and amplitudes in hyperbaric heliox (index "he") to the corresponding formant parameters in air at 1 ATA (index "a"):

$$\frac{F_{he}}{F_a} = \frac{c_{he}}{c_a}\left[1 + \left(\frac{\rho_{he}}{\rho_a} - 1\right)\left(\frac{F_{wa}}{F_a}\right)^2 + \left[1 + \left(\frac{\rho_{he}}{2\rho_a} - 1\right)\left(\frac{F_{wa}}{F_a}\right)^2\right] 2k_{ghe}k_{ma}\right]^{1/2} \quad (5)$$

$$\frac{B_{he}}{B_a} = \frac{[B_v + B_h + B_g + B_m + B_w]_{he}}{(1 - k_{ghe}k_{ma})\,[B_v + B_h + B_g + B_m + B_w]_a} \quad (6)$$

$$\frac{A_{he}}{A_a} = \frac{c_{he}}{c_a}\,\frac{B_a}{B_{he}} \quad (7)$$

where ρ is the density of the gas, proportional to pressure. We notice that for $|Z_g| = \infty$ we have $k_{ghe}k_{ma} = 0$, and the formant frequency shift formula, eq. (5), reduces to the classic Fant-Lindquist formula, originally derived under assumption of no glottal, lip radiation nor viscous/thermal losses [1]. Here it is shown to correspond to the closed-glottis case, with some restrictions on Z_m and z_w. In general, however, the glottal/lip radiation correction term, though small, should be included.

The curves of Fig. 5 gives the shifts of formant frequencies and bandwidths from air at 1 ATA to heliox at 500 msw as predicted by eqs. (5) and (6). We notice several interesting features:

- In the low-frequency region the formant frequency shift is dominated by pressure and wall effects. The shift of sound velocity dominates in the mid-and-upper-frequency range. The glottal and lip radiation losses imply a slight modification of the Fant-Lindquist formula at low frequencies only.
- In the upper frequency range the formant bandwidth shift is dominated by the glottal and lip radiation losses. Towards lower frequencies wall losses become more influent, while

glottal losses dominate the shift at the extreme low-frequency formants.

At low frequencies escpecially, the formant bandwidth shift is appreciably less than the formant frequency shift, indicating that the shift of formant bandwidths should not be corrected for by applying the Fant-Lindquist formula, as is done in advanced current unscramblers.

Neither the formant frequency nor bandwidth shift predicted by eqs. (5) and (6) agree with the results of Richards and Schafer [2]. For low-frequency formants the wall impedance values used in their analysis (given by [3]) implies serious overstating of the frequency and especially the bandwidth shift. Furthermore, in [4] it is shown that their formant bandwidth expression is equivalent to

$$B_n = \frac{k_m\left[B_h + B_g + B_w + (1 - (F_w/F_n)^2)(B_v + B_m)\right]}{1 - k_g k_m - (F_w/F_n)^2}, \qquad (8)$$

$n = 1,2,...$

implying nonrealistic large bandwidths as well as additional overstating of bandwidth shift for formants is the vicinity of the closed tract resonance frequency. The requirements of consistence with the assumptions already made in the derivation of eq. (8) implies that eq. (3) is the correct formant bandwidth expression.

Validity Range

It can be shown [4] that the approximations leading to eqs (2) - (7) are valid in the formant frequency range

$$F_w \ll F_n \ll \frac{3cr_m}{32\,r^2}, \quad n = 1,2,... \qquad (9)$$

where r_m is the lip opening radius. The lower limit constricting the validity range is a result of restrictions laid upon the glottal and wall impedances, while the upper limit arises because of restrictions laid upon the lip radiation impedance. Therefore, for typical tube parameters, the formulas are valid for 190 Hz << F_n << 2650 Hz in air at 1 ATA. For heliox at 500 msw, however, the validity range is constricted to 1550 Hz << F_n << 7500 Hz. From these considerations, we realize that there is need for a theory valid in a wide frequency range which is not constricted at large depths. This is solved by introducing the multitube vocal tract model, discussed below.

Wall Impedance

The specific wall impedance, defined as $z_w = r_w + i\omega l_w$, is essential for the present analysis, and the values for z_w given by [3] produce unrealistic large bandwidths for formants in the

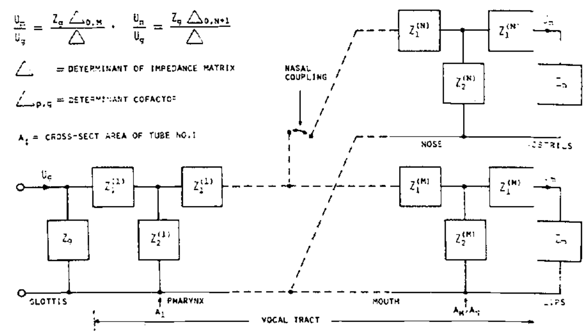

Fig. 3 Transmission-line analog of the multitube vocal tract model (after Flanagan [3])

lower frequency range [4]. A comment on the values used here should therefore be given. In order to obtain realistic estimates of z_w, it was matched to measurements of the resonance frequency and bandwidth of the closed vocal tract in air at 1 ATA. Eqs. (2) - (7) were derived under approximations not valid in the closed-glottis case and could not be used for this purpose. As a better approach, we assumed lumped elements representation, valid for $\gamma l \ll 1$. Under the additional assumptions of no viscous nor thermal losses, closed glottis ($|Z_g| \to \infty$) and lips closed (L_m/lL_a, $\omega L_m/R_m \to \infty$), the specific wall resistance and inductance were found to be

$$r_w = 2\pi l_w B_w(F_w) \qquad (10)$$

$$l_w = c^2/2\pi^2 r\left[F_w^2 + B_w^2(F_w)\right] \qquad (11)$$

where F_w and $B_w(F_w)$ are the closed tract resonance frequency and bandwidth, respectively. By matching this to F_w = 190 Hz and B_w = 75 Hz [5], we obtained r_w = 6500 kg/m^{2}s and l_w = 13.8 kg/m^2. These are the values used in all caluclations of this work. Note that the wall impedance is not uniformly distributed over the vocal tract and the values derived are valid only on an average basis.

ACOUSTIC MULTITUBE VOCAL TRACT MODEL

Transmission-Line Description

As a more realistic approximation of the vocal tract, a multitube model of the tract was developed and implemented. The purpose of this analysis was to obtain a model which, first, is valid in a wide frequency range also at large depths (to test the reliability of the uniform tube formulas, eqs. (2) - (7)) and second, enables investigation of the influence of nonuniform cross-sectio-

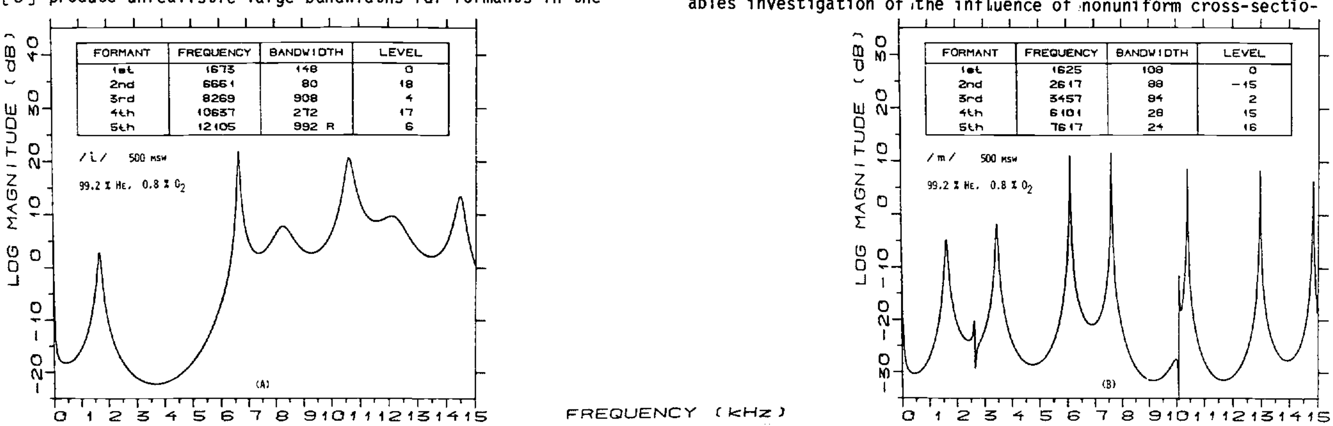

Fig. 4 Vocal tract transfer function V(f) for the vowel /i/ and nasal /m/ simulated for heliox gas and a pressure of 48.4 ATA

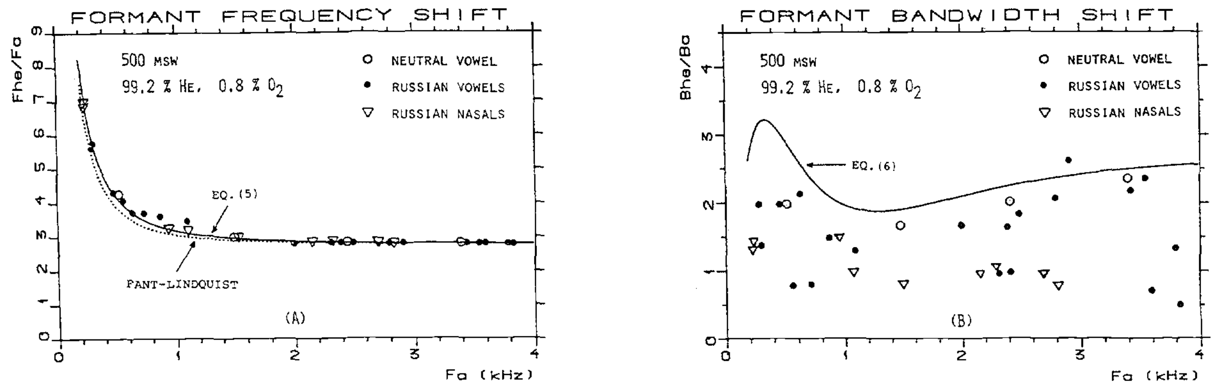

Fig. 5 Ratio of formant frequencies (a) and bandwidths (b) in heliox at 48.4 ATA to air at 1 ATA as function of F_a. Curves are uniform tube model predictions, markers are multitube model simulations

nal area on the formant shift.

The acoustic transmission-line analog of the multitube tract model is shown in Fig. 3. The pharynx, mouth and nose are all approximated by a number of cascaded, lossy, cylindrical tubes of arbitrary radii and lengths, all accounting for wall, viscous and thermal losses. Each tube is represented in the transmission-line as an equivalent distributed T-section. The network is terminated by impedances due to glottis and radiation from lips and nostrils. Network theory was applied to transform the conditions of continuity in pressure and volume velocity into matrix representation, suitable for computer simulation. The resulting transmission equations are given in Fig. 3. The general outline of the model is sketched in [3]. The recursion schemes for solving the impedance determinats involved, however, are derived in [4], and all the impedances involved are represented as distributed elements. The simulation system provides a flexible instrument where the model parameters (gas, glottal, lips, nostrils, wall and tube parameters) can be varied independently of each other. For vowel simulations, no nasal coupling was assumed. For simulation of nasals, the main transmission path is the pharyngcal/nasal cavities, with the mouth acting as a parallelling side-branch resonator, introducing antiresonances (zeros) in the frequency spectrum.

In this model there is implicite an assumption of plane wave propagation, valid for $f < c/2d$, where d is the largest cross-sectional dimension of the vocal tract. The simulations are therefore valid in the approximate range 0 - 7 kHz in air and 0 - 20 kHz in pure helium gas.

Simulation Results

Using cross-sectional vocal tract area data given by Fant [6], the formant structures V(f) of 5 non-nasalized Russian vowels (/a/, /o/, /u/, /i/, /e/) and 2 Russian nasal consonants (/m/, /n/) were simulated for various breathing gas mixtures and pressures corresponding to depths 0 - 500 msw. 34 - 40 tubes were used for modelling the vowels, 59 tubes were used for the nasals. Each tube was 0.5 cm long. In order to evaluate the reliability of eqs. (2) - (7), V(f) for the single, uniform tube of length 17.5 cm (the "neutral vowel") was also simulated. Formants were extracted from the computed data by a peak-picking routine. This provided data for shift in formant parameters for each individual phoneme. Details are given in [4].

Fig. 4 gives the transfer function V(f) for /i/ and /m/, simulated for conditions corresponding to 500 msw. In Fig. 5 the formant shift data obtained from the simulations of the uniform tube, the 5 vowels and the 2 nasals are plotted together with the predicted results of eqs. (5) and (6). We conclude with the following:

- The formant shift formulas, eqs. (5) and (6), are valid in a wider frequency range than their derivation procedure suggests.
- The extended Fant-Lindquist formula, eq. (5), describes the formant frequency shift independent of vocal tract geometry.
- The shift of formant bandwidth depends on articulation, i.e. vocal tract geometry. The "neutral vowel" has a bandwidth shift satisfactorily described by eq. (6), while nonuniform cross-sectional vocal tract area seems to decrease the mean formant bandwidth shift.
- Except for the lower frequency range, the mean bandwidth shift of nasals seems to be in the lower edge of the mean bandwidth shift of vowels.

CONCLUSIONS

Our analysis provides new insight into the shift of formant frequencies, bandwidths and amplitudes from air at 1 ATA to hyperbaric heliox conditions. For both uniform and nonuniform vocal tract geometry, the formant frequency shift is well described by the extended Fant-Lindquist formula, eq. (5). For nonuniform vocal tract (as is the realistic configuration for speech) our simulations indicate that the mean formant bandwidth shift is less than predicted by the uniform tube vocal tract model. For both uniform and nonuniform vocal tract the bandwidth shift is less than the formant shift, at low frequencies (in the range of the first formant) the difference is large. The shift of formant amplitudes is inversely proportional to the formant bandwidth shift.

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