EFFECTS OF ACOUSTIC INTERACTION BETWEEN THE SUBGLOTTIC AND SUPRAGLOTTIC CAVITIES OF THE HUMAN PHONATORY SYSTEM

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ABSTRACT

The purpose of this work, is to describe the effects of the coupling of the subglottic and supra glottic cavities of the human phonatory apparatus. For this, we will determine and use the transfer function of the vocal tract evaluated owing to an exploration of the human phonatory system using an external excitation using a pseudo-random sequence; this method was developed by Djeradi et. al. 1991. This evaluation will be carried out on the basis of the following three conditions of the glottis: open glottis, closed glottis and variable glottis. One of the advantages of this method will be used, indeed, it is possible, at the time of the same expiry phase that corresponding to a sustained articulatory configuration, to record the signal of the sound itself and the useful signal for the measurement of the transfer function. The comparison of the various spectral data thus obtained highlights the subglottic effects of coupling on the one hand and shows that the conditions at the glottis have an influence on the resonances of the supraglottic cavities on the other hand. This enabled us highlight an increase in the value of the resonance frequencies, of the band-widths and a modification of the deviation between the resonances of the vocal tract. We have also noted the appearance of additional resonances peaks that can correspond to subglottic cavities During the second phase, we reproduced these effects by simulations on geometrical configurations obtained by the X- rays method performed on the same person and for the same configurations.

SOMMAIRE

Dans ce travail, nous allons décrire les effets de couplage des parties subglottiques et supra glottiques de l'appareil phonatoire humain. Pour cela, nous allons déterminer et exploiter la fonction de transfert du conduit vocal évaluée grâce à une exploration du système phonatoire humain à l'aide d'une excitation extérieure par une séquence pseudo aléatoire, cette méthode a été développée par Djeradi & al en 1991. Cette évaluation sera faite pour les 3 conditions de la glotte : glotte ouverte, glotte fermée et glotte variable. Nous allons utiliser l'un des avantages de cette méthode, en effet, il est possible, lors de la même phase d'expiration correspondant à une configuration articulatoire soutenue, d'enregistrer le signal du son lui-même et le signal utile pour la mesure de la fonction de transfert. La comparaison des différentes données spectrales ainsi obtenues permet la mise en évidence des effets de couplage subglottiques d'une part et montre que les conditions à la glotte ont une influence sur les résonances des cavités supraglottiques d'autre part. C'est ainsi que nous avons pu mettre en évidence un accroissement de valeur des fréquences de résonance, des bandes passantes et une modification de l'écart entre les résonances du conduit vocal. Nous avons également noté l'apparition de pics de résonances supplémentaires pouvant correspondre à des formants subglottiques. Dans une seconde phase, nous avons reproduit ces effets par des simulations sur des configurations géométriques obtenues par la méthode des rayons X sur le même sujet et pour les mêmes configurations.

1. INTRODUCTION

The production of fricative makes use of two actions: (1) opening/closing of the glottis and (2) execution of the constriction. When performing measurements in phonation, these two actions are executed simultaneously. In this case, the vocal tract has a glottic average opening which depends on the frequency of the oscillations of the vocal cords. This phenomenon intervenes in the measurement of the transfer functions of the vocal tract in the form of a coupling of the subglottic parts and supraglottic parts. The coupling effect also depends on the duration of the measurement because it is difficult to maintain a configuration of the duct sufficiently stable to take measurement, the appearance of the effects is better when the time of measurement is short.

The current study has attempted to evaluate the effects of coupling of the subglottic parts on the transfer function of the vocal tract. For this purpose, the human phonatory system will be explored by using a pseudo-random sequence for the three following conditions of the glottis: open glottis, closed glottis and variable opening area to the glottis.

The results of an experimental and theoretical analysis of the effects of subglottic coupling on the transfer function of the vocal cavities will be presented. The method developed by Djeradi et al. (1991) at the ICP of Grenoble will be used. The above method is based on the transcutaneous excitation of the vocal tract, at the level of the glottis, using an exciter delivering a pseudo-random sequence. The FFT of the inter correlation of this signal with the signal that is collected at the lips provides the acoustic transfer function of the vocal tract.

The analysis will focus on five Arabic back fricatives/ χ, ɣ, ʕ, ħ, h /. The first three fricatives are voiced and the two last ones are silent. The area functions were determined from the X-ray data of a male. The corresponding transfer functions were calculated for glottis conditions (open and closed). To obtain the right correspondence between the subglottic resonance frequencies that are measured and/or simulated, it was necessary to adapt the geometric parameters of the phonatory system.

Theoretically, the human speech production system can be represented by the following general diagram:

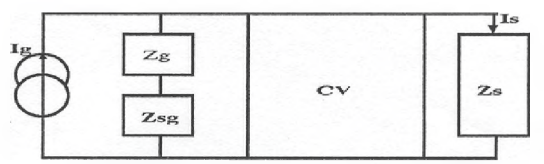

Figure 1. Equivalent Diagram of the phonatory system

Ig : Capacité flow at the the glottis.
Zg : glottic impedance.
Zsg : subglottic impedance.
CV: quadripole representing the vocal tract.
Zs: output impedance (radiation at the lips).
Is: exit flow (measured at the lips).

The transfer function of this system is defined as the ratio of the flow at lips and the flow at the glottis:

$$\text{FTR} = \| Is / Ig \|$$

FTR depends on the input impedance of the quadrupole represented by the vocal tract, as well as on two variables Z_s and Z_{sg}. When the glottis is open Z_g becomes small (short circuit) and the transfer function mainly depends on the Z_{sg} impedance. The acoustic features of subglottal cavities, represented here by Z_{sg}, will thus be visible on the response curve of the system. On the other hand, when the glottis is closed Z_g becomes infinite (open circuit) and the Z_{sg} impedance is thus negligible compared to Z_g, and the transfer function will be representative of supraglottic cavities only.

In the case of the voiced speech (phonation) the glottis area varies with the vibration of vocal cords, and one estimates then an average glottis opening area whose equivalent area is equal to the average of the glottis area taken over several times of the phonation. Consequently Z_g will also be a function of time and will have an average value for which the effects of Z_{sg} would appear more or less important on the transfer function. These different situations will be examined in this study.

The geometry of the supraglottic cavities changes depending on parameters such as - the articulatory opposition (uvular vs. pharyngeal), and the voiced vs. unvoiced opposition. The spectral impact of the subglottic cavity changes will be evaluated. The analysis includes 640 spectra out of which 320 corresponding to phonation: 160 for the open glottis condition and 160 to closed glottis condition.

It is possible to consider the phases of opening or of closing of the glottis separately but the phenomenon of production as a whole would not be very different.

2. EXPERIMENT AND ANALYSIS

2.1 The operating procedure

The first difficulty of this study is the lack of the mastering of the control of the glottic state. It is not easy to keep the glottis open (or closed) and to maintain, at the same time, its articulatory configuration constant in the fricative mode It is also not easy to reproduce, in a stable manner, these gestures from one experiment to another. One thus needed a long phase of training before being able to control the glottic contraction.

To carry out our experiment the following experimental set-up ,given in Figure 2, was designed.

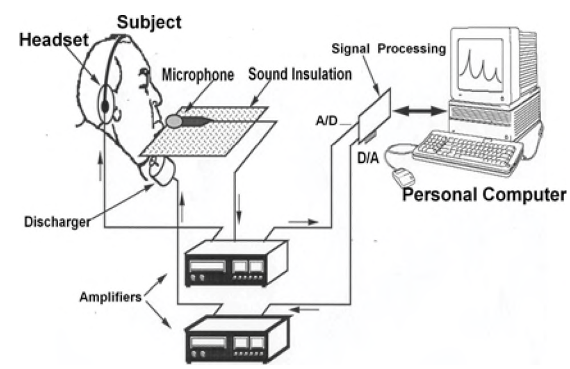

Figure 2 Diagram of the experimental set-up.
[Djeradi et. al. 1991]

The following process was followed to measure the transfer function transfer of the vocal tract with a closed glottis: the subject is placed in a soundproof room, it starts by positioning the source of pseudo-random excitation , by placing the "vibrator" on the skin of its neck, near its glottis, and for that, he excites his vocal tract using a white noise and the return helmet will enable him to appreciate the acoustic effect relating to the position in space of this source, he will then maintain the position of the "vibrator" and will search for the correct position of its articulators, by producing the sound to be analyzed. Once this is reached, he will then stop completely his breathing while maintaining its configuration constant and it is at this instant that one takes measurement. The determination of the transfer function for the open glottis is carried out in the same way as that for the closed glottis except that it is pro necessary to breathe continuously during measurement and try, by the feeling which is vided by the passing air on the articulations, to obtain a more precise control (of the gesture) of constriction without however pronouncing the sound. One should take care so as the glottis remains constantly open and the geometrical configuration remains steady throughout all the measurements.

The measurement protocol is shown in Figure 3.

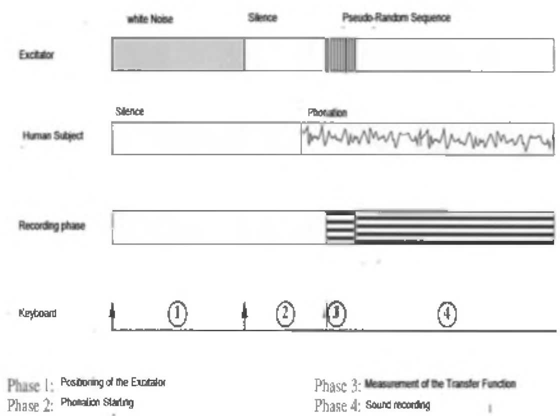

Figure 3. Diagram of the protocol of the measurement of the transfer function.

The theoretical principle is shown schematically in Figure 4.

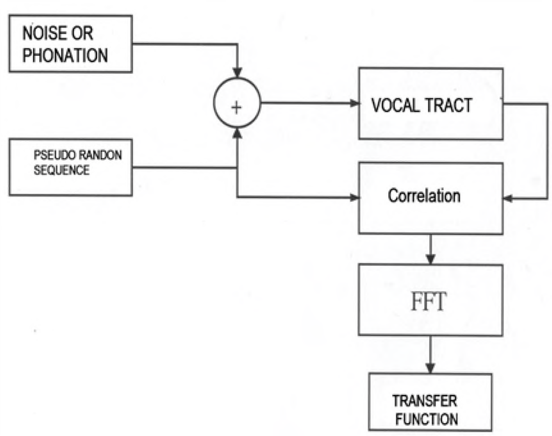

Figure 4. Theoretical principle of the method.

2.2 The effects of subglottic coupling

The results of the experiments are shown in Figures 5, 6 and 7 and in Tables 1 and 2. It must be noted that the functions thus measured are rather complex. In spite of this apparent complexity, a great number of spectral peaks and valleys are seen to be present at constant values.

In addition the curves obtained with open glottis are close to the curves obtained in phonation. We clearly observe the appearance of the additional spectral peaks on the response curves for open glottis and which did not exist on the curves obtained with closed glottis; these peaks have lower amplitude.

In addition the anti-resonance that is visible on the "uvular" curves with the open glottis and in phonation at 2500 Hz, disappears on the curves with closed glottis. The presence of additional peaks is followed by a quasi-systematic reduction in the amplitude of the main resonances (if we compare these with that of measured resonances with closed glottis). On the curves of Figure 5, we see clearly that the instantaneous frequency deviation between Fp3 and Fp4 resonances tends to increase with the opening of the glottis.

We also clearly see as the fricative having the same articulatory location, present nearly identical resonance frequencies, whether it is for the two uvular ones than for the two pharyngeal ones. Consequently we deduce from it that the geometrical shapes are close. The weakness of the values of the standard deviations (of the values of the frequencies of the raised formants on the curves [Thesis A.Djeradi 92]) testifies the stability of the corpus (Tables 1 and 2).

In addition, we notice an increasing trend in the first two frequencies and of the fourth resonance frequency, and a decreasing trend of the third resonance frequency of resonance when one changes from the "uvular" contraction to the "pharyngeal" contraction

The passage from a pharyngeal constriction to a laryngeal constriction involves a decrease of the first resonance and an increase of all the others.

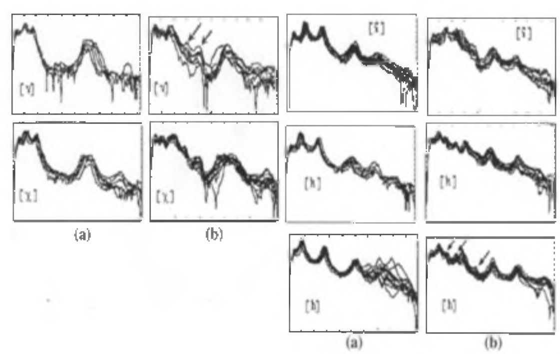

Figure 5. Transfer functions measured for the five fricatives (a) closed glottis, (b) open glottis

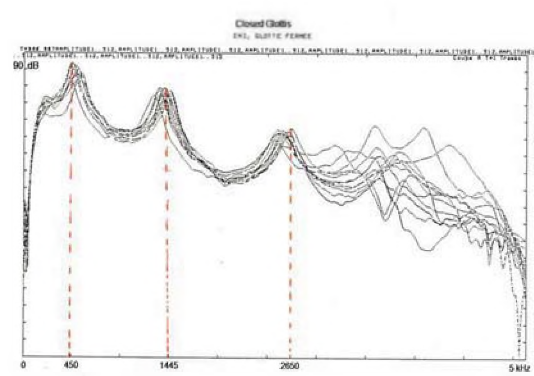

Figure 6. Average frequencies and standard deviations of the measured peaks of resonance with open glottis

The retreat of the location of constriction from the uvular zone up to the area of the high pharynx causes a decrease of the back cavity, and an increase of the corresponding frequencies, probably Fp1, Fp2 and Fp4. In contrast, the volume of the front cavity increases and probably involves a fall of the frequency of corresponding resonance Fp3. We have recorded the peaks of the resonance frequencies on the transfer functions in the case of the open glottis. We find the same tendencies in the evolution of the frequencies with the retreat of the location of the constriction.

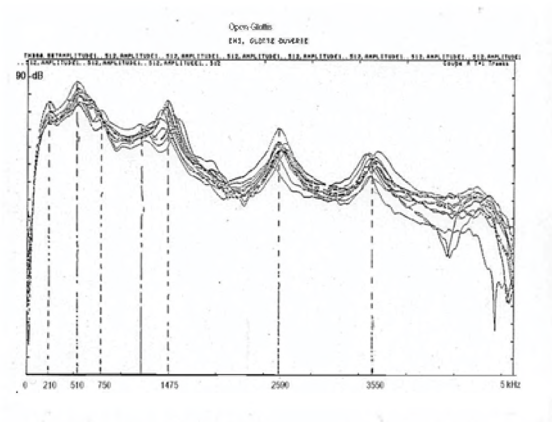

Figure 7. Transfer function measured for the fricative [h] with open glottis.

Table 1. Average frequencies and standard deviations of the measured peaks of resonance with closed glottis.

	/χ/	/ʁ/	/ʕ/	/ħ/	/h/
Fp1	230	220	220	230	220
écart-type	20	20	20	20	20
Fp2	510	520	690	660	540
écart-type	40	20	29	30	20
Fp3	920	870	1370	1290	1440
écart-type	35	30	50	30	25
Fp4	2830	2820	2600	2550	2640
écart-type	90	50	50	40	30
Fp5	3150	3200	3540	3470	3750
écart-type	60	100	40	50	30

The comparison of two types of curves clearly shows the presence of three to four additional spectral peaks. These peaks are at frequencies of 430, 1000, 1400 and 2000 Hz for "uvular". In the case of pharyngeal, also called "vertical", these peaks are visible at the frequencies of 430, 750, 1200 and 2000 Hz. We therefore note that only two common frequencies, 430 and 2000 Hz, are found in both the cases.

It can be concluded that the other frequencies depend on the supraglottic cavities: indeed when these frequencies are close (750 and 1200 Hz for the "verticals" and 1000 and 1400 Hz for the horizontal ones), only one peak appears in the spectrum close to that of supraglottic resonance but with a larger band-width. If this idea of superposition to the other missing frequencies, in one or the other of these two classes of consonants, can be generalized, one can conclude that the subject presents six resonance frequencies of the subglottic cavities - 430, 750, 1000, 1200, 1400, 2000 Hz.

Table 2. Average frequencies and standard deviations of the measured peaks of resonance with open glottis.

	/χ/	/ʁ/	/ʕ/	/ħ/	/h/
Fp1	220	230	230	220	230
écart-type	20	20	20	20	20
Fp2	430	430	430	430	430
écart-type	25	25	20	20	22
Fp3	540	550	580	550	530
écart-type	28	28	14	14	14
Fp4	790	770	760	740	740
écart-type	20	42	15	30	30
Fp5	1000	1010	1030	1025	1020
écart-type	40	45	18	13	10
Fp6	1250	1240	1230	1210	1200
écart-type	25	72	60	22	50
Fp7	1450	1440	1490	1470	1470
écart-type	25	20	30	35	35
Fp8	1970	1990	2010	2030	2030
écart-type	60	40	79	72	30
Fp9	2790	2820	2590	2590	2580
écart-type	60	40	79	72	30
Fp10	3270	3290	3460	3520	3500
écart-type	60	70	35	30	30

2.3 Conclusion

The effects of coupling of the subglottic parts appear on the transfer function of the vocal tract by the presence of additional peaks. These peaks are located for the speaker at frequencies of 400, 700, 1000, 1200, 1400 and 2000 Hz. The modification of the shape of the vocal tract acts slightly on these frequencies. In addition, the amplitude of the peaks resulting from the coupling of the subglottic and the supraglottic parts is low compared to the amplitude of the main peaks emanating from the supraglottic cavities.

3. SIMULATION OF THE SUBGLOTTIC EFFECTS

3.1 Modeling 3D vocal tract

For the 3D modeling of the vocal tract we used the data taken from X-ray images. [Djeradi et. al. 1991]. The modeling of the mechanisms of the production of fricative requires a precise knowledge of the dimensions of the vocal tract. The choice of the X-rays based method for obtaining the sagittal cuts is interesting for on the one hand the subject of study is the constant fricatives, whereas one tries to obtain a good quality of the image without too much exposing of the subject to strong amounts of X-rays. This is accomplished by considering the semi-capital profile of the voiced fricative and that of non voiced fricative are very close (Bothorel et al., 1986).

The emission source of the X-rays is located at five or six metres from the subject to be bombarded and the photosensitive plate intended to receive the projection of the head of the speaker, is placed at 5 cm from the X-ray. We can thus neglect the distortion which results from this projection. To obtain a good contrast of the soft parts of the head (language, lips.), we will use adequate aluminum filters. The image obtained is projection on a plane parallel to the sagittal plane of all the head.

The experiment consists at asking the subject to maintain the pronounced fricative for the longest time possible in order to obtain stable sounds from one experiment to the next.

As of the stabilization of the sound, we make a quasi simultaneous acquisition of the image to x-rays, sound and photography of the lips.

In addition plaster moldings of the hard parts of the vocal tract enabled us to better specify dimensions of this area.

3.1.1. Acquisition of the contours

This phase can be done only manually, because it is impossible to determine the sagittal profiles of the vocal tract by an automatic treatment of the image. Indeed, the x-ray reading is not always easy. It was often necessary to consult specialists; however no unanimous decision was possible. The profiles were traced manually on transparent nylon sheets. .

We note that the contour at the lips can be easily read for all the configurations. The layout of the hard part of the palate is adjusted owing to the cutting of this zone obtained by plaster molding. On the other hand, at the velum, interpretation remains very delicate because of the side returns of the velum which are apparent. The back wall of the naso pharynx and the glottis can easily be located for all the configurations. At the level of the tongue, we made the decision to follow the furrow and not the higher edges.

We have noted some osseous marks with an aim of standardizing the scales of measurement of the various geometric elements of the vocal tract for the entire configurations.

3.1.2 Digitalization of the contours

In this phase we used a system of image processing developed by the laboratory of image and pattern recognition of the INPG (S. Olympieff). The interest of this system compared to traditional measurements is in addition the automation of the measurement, the high degree of accuracy in the detection of the contours; we thus obtain a better estimate length of the vocal tract and surface at the lips. This system provides for each contour, coordinates X, Y of all the pixels (these pixels are contiguous and are ordered in the direction of the displacement).

3.1.3 The measurement grid

The use of a grid to determine the sagittal function is now general (Heinz & Stevens 1965 and reconsidered again by Maeda 1979). The discretization of the vocal tract is not uniform since the grid is made up of three different parts. Between the glottis and the bottom of the pharynx, this grid consists of parallel straight lines; from the bottom of the pharynx to the oral cavity, we use a system of radii of a portion of a circle whose middle is the concordant point of the various straight portions. This grid thus divides the vocal tract into a certain number of sectors, and each section of the sagittal profile corresponds then to the zone of the vocal tract comprised between the two straight lines which define the sector.

Fixed reference marks are selected with respect to the anatomical invariants that are linked to the cranium and to the spinal column of the subject. The vertical axis of the system is selected to be parallel to the wall of the bottom of the pharynx. approximates the contour of the velum.

Our reference marks (the incisor and the hard part of the palate) helped us to define the same framing that is used as a scale for all the contours.

3.1.4 Determination of the sagittal functions

We thus manage to delimit the various sections by closed contours for which we calculate the centre of gravity and surface in pixels. The median line of the vocal tract consists of segments joining these centres of gravity. The length of each section is then obtained by measuring on this median line, the length of the segment joining the two lines of the grid delimiting this section. The sagittal distance is finally calculated as being the sectional surface divided by its length, we thus obtain the sagittal functions represented in Figure 8.

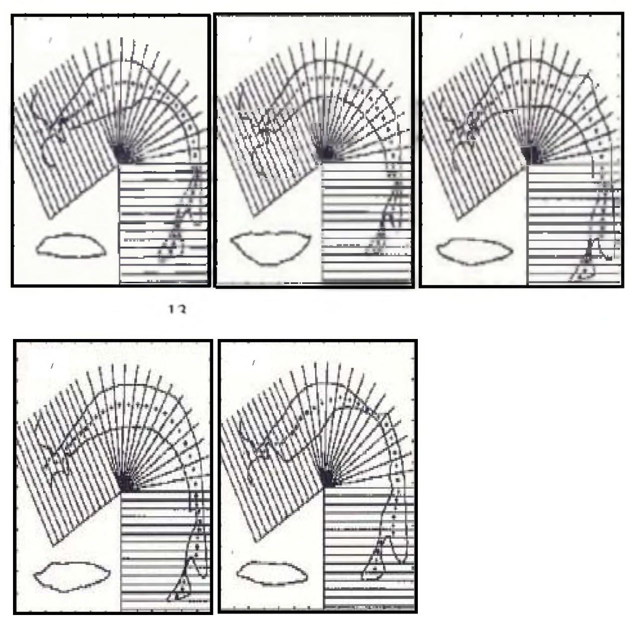

Figure 8 Sagittal slices of the five back Arabic fricatives with scale of measure; the median line of the vocal tract is the center is the center of the circle represented by the dotted line. The lip opening is represented on the bottom left of each slice.

3.1.5 Determination of the area functions

The passage from the sagittal function to the area function is carried out by the traditional method suggested by Heinz and Stevens [1965]. The principle consists in applying the following relation between the area A and the sagittal distance D (i.e. the height of a section): $A = ad^{b}$ where **a** and **b** are the coefficients which depend on the area of the vocal tract.

The initial area functions of the five fricatives are obtained by the application of the coefficients determined by Perrier et. al. on the French vowels. Then using the sensitivity functions such as are defined by Fant and Pauli (1974) or Mrayati and Carré (1976) and of the pressure distributions and the flow in the vocal tract, we have adjusted the initial transfer functions in order to obtain a good superposition of the measured transfer functions with those obtained by simulation.

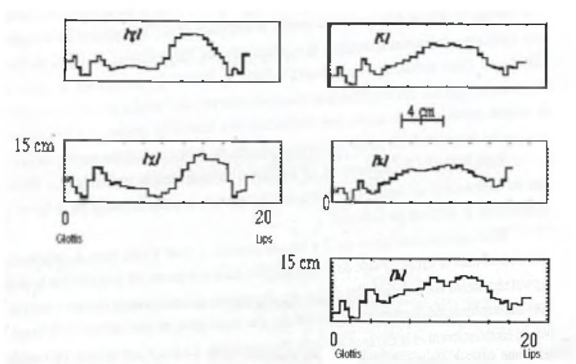

Figure 9 The Sagittal functions of the 5 back fricative of Arabic.

3.2 The simulation model of the subglottic effects

To simulate the effects of coupling of the subglottic parts on the supraglottic parts, we represented the vocal tract by its area function and the subglottic parts by a cell of Foster with 3 resonances (600, 1000, 2000Hz equivalent to those measured at the time of the experimental phase).

The complete model, whose general diagram was given in Figure 1, also allows tointegrate the various losses: heat losses, viscosity losses and those due to the impedance of the walls. On the other hand, in the case of the opened glottis, we cannot take into account the resistance to constriction. The area to the glottis is the variable parameter, on which the effects of coupling given in the experimental phase are determined. The values of the glottic area, approximately, - 0.05, 0.25, 0.35, 0.5 and 0.7cm^2 - describe a sufficient interval for the production of the analyzed consonants.

3.3 Results

It is clearly shown on the simulation curves of Figures 10 and 11, that the subglottic effects appear much better when the glottis is open. The spectral peaks correspond in a general to those of the cell of Foster when the area of the glottis ranges between 0.25 and 0.35 cm^2. In fact this opening varies also with the shape of the subglottic parts.

Thus in the case of the pharyngeal, the glottic area is closer to 0.35 cm^2, the obtained frequencies are 550, 1010 and 2050 Hz. In the last case, we have noted the systematic presence of a peak which was not present for the subglottic parts or for the supraglottic part. The frequency is, on average, equal to 1700Hz. It can also be noted that the band-width increases when the frequency of a subglottic part is close to that of a supraglottic part.

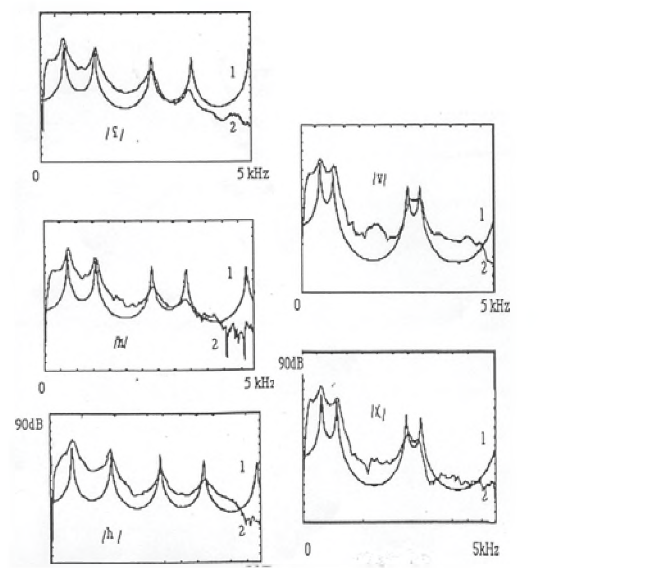

Figure 10 Superimposition of the transfer functions, (1) functions simulated (2) measured functions with closed glottis.

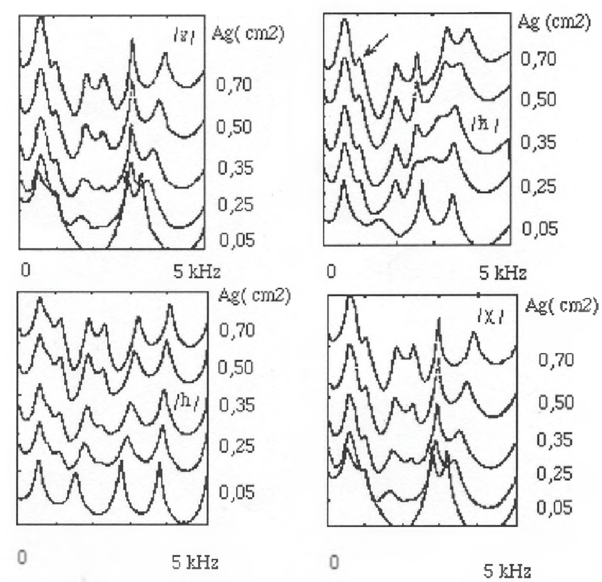

Figure 11 Transfer functions simulated of the back fricatives of the Arabic

In addition, the presence of the effects of coupling involves a difference in the behaviour of the supraglottic cavities. Indeed, the resonance frequencies of the vocal tract have increased.

4. CONCLUSION

A methodology was developed to evaluate the acoustic characteristics of the human phonatory system. The best data on the transfer functions and the area functions in the case of the back fricative of Arabic was thus obtained. The acoustic contributions of the subglottic system in the production of the back fricative consonants were also highlighted. Additional spectral peaks were observed clearly on the transfer function of the vocal tract with the open glottis.

The systematic analysis of these effects on each acoustic configuration made it possible to better specify the acoustic relations between the subglottic and supraglottic parts.

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