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Acoustical–Mechanical Modelling of Voice Tract

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Modelling voice tract using an acoustical–mechanical analogy is shown in this article. The process of modelling voice tract is often reduced to one-dimensional acoustical model, i.e. planar waveguide model. With this acoustical-mechanical model, computer programs are utilized to analyze and synthesize the voice tract. Hence, it is possible to calculate models which describe the voice tract with satisfactory quality and detail level and these models can be used in practice and applied to particular cases. In this article the process of producing a voice tract model is presented. The process includes the usage of three different computer programs, each of them dedicated to one segment of modelling. Recordings for three speakers were made and the analysis of voice parameters was performed. After the analysis is completed, a two-dimensional model of the voice tract was made, which resulted in a mechanical model consisting of specific number of tubes. Finally, the evaluation procedure for the model is done by applying a software developed specifically for this purpose, in order to determine whether the resulting model truly represents the voice tract of each speaker.

Key words: Acoustical-mechanical analogies, Vocal tract, Vocal cords, Mechanical oscillator, Modulation, Planar waveguide model, Simulation

Akustičko–mehanički model govornog trakta. Ovaj članak daje primjer izrade modela govornog trakta zasnovanog na akustičko-mehaničkim analogijama, za tri govornika, pomoću računalno zasnovanog sustava. Definiranje modela govornog trakta često se svodi na jednodimenzionalni akustički model, planarni valovodni model. Kad je napravljen akustičko-mehanički model, u analizu i sintezu uvode se računala i računalni programi. Pomoću njih se dobivaju modeli i izračuni koji sa zadovoljavajućom kvalitetom i preciznošću opisuju govorni trakt, pa takve modele možemo koristiti u praksi i primjenjivati na konkretne slučajeve. U članku su za dobivanje modela govornog trakta korištene tri različite programske podrške, svaka u svom segmentu izrade modela. Snimljena su tri govornika i napravljena je analiza glasa. Nakon toga je, opet koristeći računalo, izmodeliran dvodimenzionalni model govornog trakta, koji kao rezultat daje mehanički model s određenim brojem cjevčica. Na kraju je napravljena provjera tog modela sa programskom podrškom koja je napisana za tu svrhu, kako bi se utvrdilo da dobiveni model zaista predstavlja govorni trakt pojedinog govornika.

Ključne riječi: akustičko-mehaničke analogije, govorni trakt, glasiljke, mehanički oscilator, modulacija, planarni valovodni model, simulacija

1 INTRODUCTION

The process of developing the voice tract model will be presented in this article. The production of voice tract models is not new to modern era. Already in the late 18th and early 19th century initial attempts were made to develop a model of voice tract, so called "Speaking machine" with the help of tubes (see Fig. 1). In the first half of the 20th century, the first voice tract model with a filter that performs the basic principles of the nowadays models was developed. Today, the development of a voice tract model is often done applying a one-dimensional acoustical–planar waveguide model, and during its analysis and development, computer programs are used.

In order to describe the formation and propagation of sound in the voice tract, application of laws of physics is inevitable. It is therefore necessary to understand the physical phenomena associated with sound propagation in a limited–closed space. It is possible to set up a set of partial differential equations, which describe the motion of air in the voice tract, according to sound propagation principles. Several approaches can be applied in order to analyze and synthesise sound wave propagation through the speech tract. A set of data necessary to construct an electrical model is very complex, which is the reason that this approach is still far from realization. Reliability of this method is limited by uncertain assumptions of environment – human and surrounding space, such as the impedance of the walls, the precise form of voice tract, and radiation impedance on the lips. The main difficulty is the complexity of the aerodynamic equations which should describe the voice tract as a three-dimensional and time-variable environment. Therefore, the model of voice tract is often defined as one-dimensional acoustic model, the planar waveguide model. An acoustical– mechanical-electrical analogy is usually used to develop such a model, because the acoustic resonant systems behave/react similar in physical environment and differential equations have formally the same appearance as in the mechanical and electrical circuits. In this article an example of voice tract model is given, obtained using a PC-based analysis system. With the help of such a system mechanical models are described using polynomials of n-degree, which enable the computation, analysis and modelling of the voice tract.

2 ACOUSTO - MECHANICAL MODELLING OF VOICE TRACT

We have applied several approaches to the analysis and synthesis of sound wave propagation through the voice tract, with variable levels of accuracy and modelling possibilities. The most accurate approach to describe the voice tract would be to solve the wave equation in three-dimensional space with a finite number of network elements. Since such an approach includes non-repairable effects such as losses and noise generation due to turbulence and swirl, it has not been implemented yet.

The source of the human voice are the lungs, which by pushing air through the voice system - vocal cord and tissue structure, produce a series of pulses with wide frequency range. The mechanism of establishing and maintaining vibrations involves a complex human anatomy, muscle control, nonlinear flow of air due to interaction of pressure in the oral tract with a stream of air through vocal cord and changes in the cross section and position of the voice tract. In order to prepare the model for simulation, the considered voice system is associated with supraglottal and subglottal system.

The analysis and mechanical modelling of speech tract are given below, based on the patterns of three young and adult speakers with healthy larynx who pronounce the vowel "a". The recording was performed by article's authors and it was conducted with the same professional recording equipment for all three speakers, in the anechoic chamber, under fully controlled acoustical conditions.

First step in the analysis process of the recorded patterns was the acoustical analysis of speech, for which the program textitSpeech Analyzer [17] was used. This program is based on the fast Fourier transform, which is an efficient algorithm to decompose sound into a spectrum of its frequency components. In Fig. 2 the spectrum of vowel "a" of Speaker 1 is shown, with its first, second and third formant. This example shows that the first and second formants are clearly pronounced, while the third formant is almost negligible.

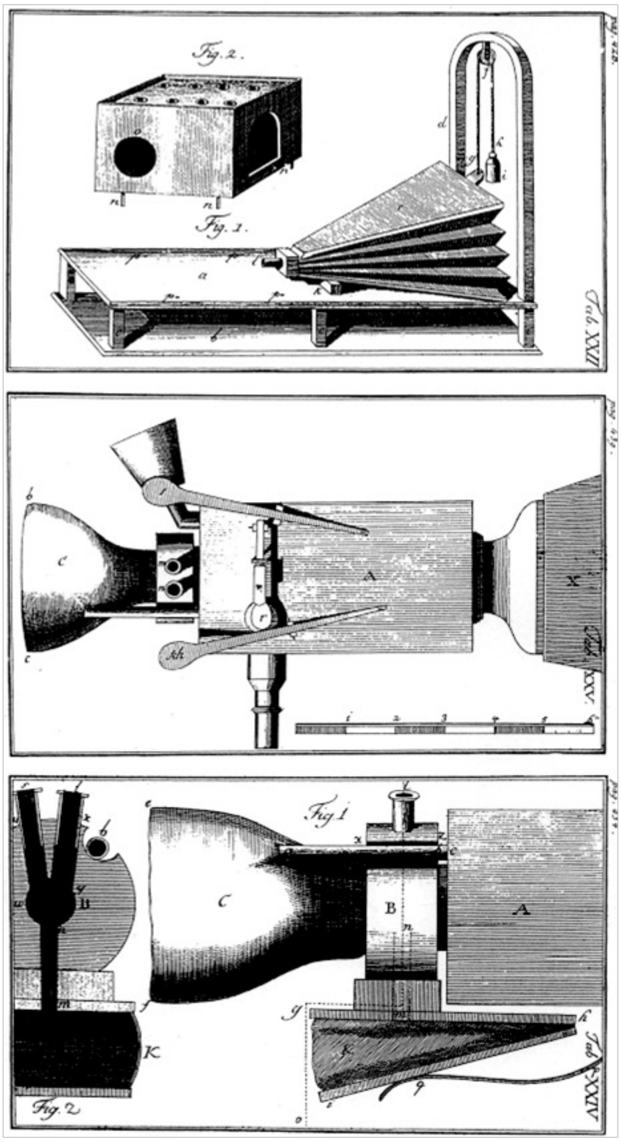

Fig. 1. Drawings of the first mechanical model of speech tract, 18th century [18]

To create a mechanical waveguide model of a voice tract, a program Articulatory speech synthesizer is used. This is an interactive multimedia software tool used to demonstrate the mechanism of speech production. It is based on a geometric description of the vocal tract based on a set of articulatory parameters and a mechanism to control

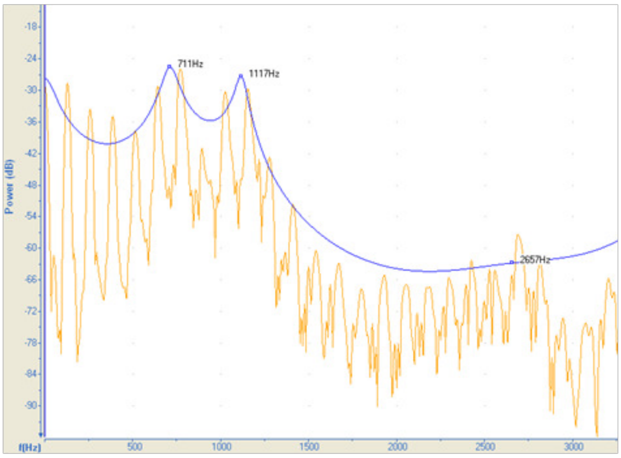

Fig. 2. The spectrum of vowel "a" of Speaker 1, with the formants, obtained with [17]

the parameters during an utterance [14]. In Fig. 3 the two-dimensional view of the voice tract model is shown, and in Fig. 4 the spectrum with the formants, obtained with this model, is presented. The good correlation is achieved between here obtained formant frequencies to those of the recorded voice of the Speaker 1 in Fig. 2. (and analyzed with *Speech analyzer*).

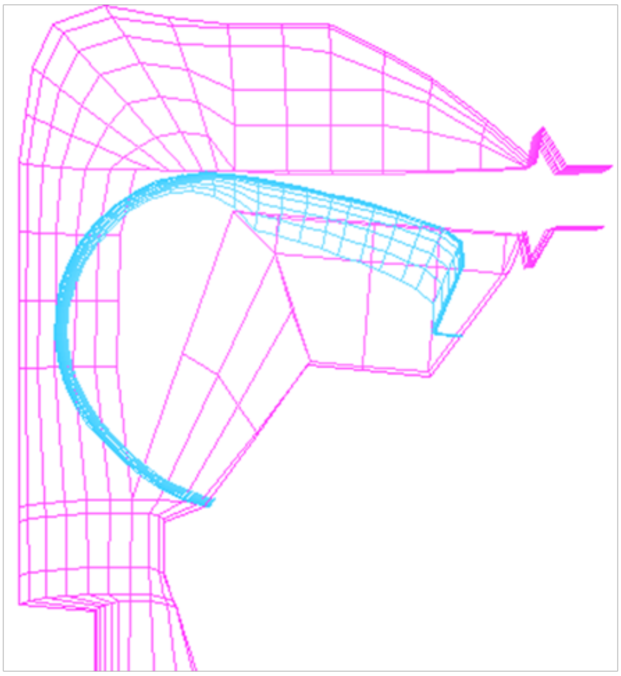

Fig. 3. Two-dimensional view of the voice tract model of Speaker 1

In Fig. 5 the two-dimensional waveguide model consisting of 32 tubes is shown, obtained from the mechanical model for Speaker 1 (Fig. 3) and the layout of formants for this model. The layout is obtained using VTAR - *Vocal Tract Acoustic Response* [15]. VTAR is Matlab-based computer program for vocal tract acoustic response calculation based on frequency-domain formulation. In Fig. 6 a three-dimensional view of the speech tract mechanical model for Speaker 1 is shown and its dimensions are given in Table 1. The considered model consists of 32 tubes arranged side by side in the same plane.

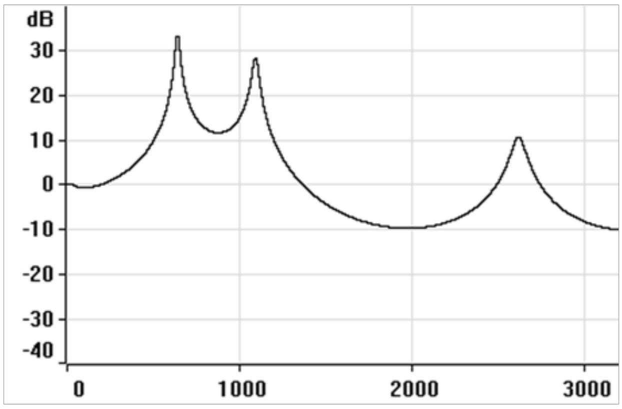

Fig. 4. The spectrum of vowel"a" of Speaker 1 obtained with a model from Fig. 3.

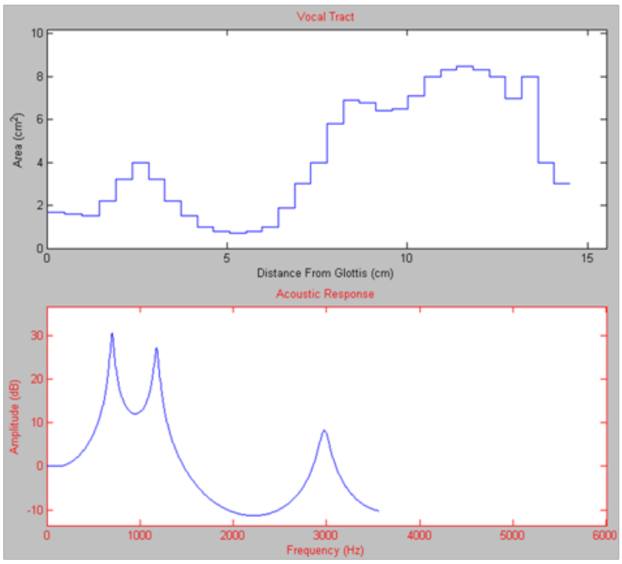

Fig. 5. Formant frequencies view for two-dimensional waveguide model made of 32 tubes for the Speaker 1

Vocal tract is modelled as concatenation of various

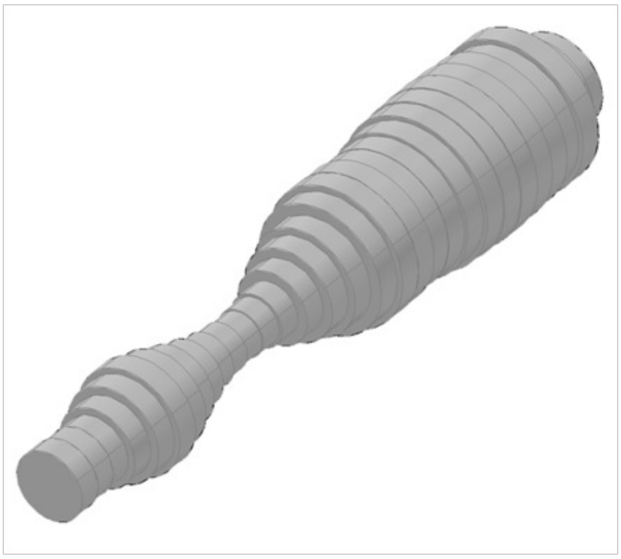

Fig. 6. Three-dimensional view of the voice tract waveguide model for Speaker 1

Table 1. Dimensions of 32 tubes for Speaker 1; length of each tube is 0,49 cm.

Tube No.	1	2	3	4	5	6	7	8
Area [cm2]	1,70	1,60	1,50	2,20	3,20	4,00	3,20	2,20
Tube No.	9	10	11	12	13	14	15	16
Area [cm2]	1,00	0,80	0,70	0,80	1,00	1,90	3,00	4,00
Tube No.	17	18	19	20	21	22	23	24
Area [cm2]	5,80	6,90	6,80	6,40	6,50	7,10	8,00	8,30
Tube No.	25	26	27	28	29	30	31	32
Area [cm2]	8,50	8,30	8,00	7,00	8,00	4,00	3,00	8,50

modules (such as single tube, branching, and lateral channels). For each module the input and output pressure and volume velocities are interrelated as defined in a transfer matrix. The coefficients of the matrices are calculated by the transmission-line model and the chain matrix approach, including losses due to flow viscosity, heat conduction, and vocal tract wall vibration. Since significant accuracy of format frequencies is achieved, this way of modelling and calculation could be used in practice.

In Fig. 7 the curves that approximate the series of waveguide tubes representing mechanical voice tract model are shown. These curves are defined by polynomials of the fifth, tenth and fifteenth degree. For the calculation of the polynomial a computer program Graph [16] was used. The functions that best describe the construction of the tubes are:

$$\begin{aligned} A(l) &= 0,00034l^5 - 0,016l^4 + 0,26l^3 \\ &- 1,63l^2 + 3,58l + 0,36 \end{aligned}, \tag{1}$$

$$R = 0,9,$$

$$\begin{aligned} A(l) &= -7,48 \cdot 10^{-8} l^{10} + 6,65 \cdot 10^{-6} l^9 - 2,56 \cdot 10^{-4} l^8 \\ &+ 4,94 \cdot 10^{-3} l^7 - 0,06l^6 + 0,4l^5 - 1,54l^4 + 2,79l^3 \\ &- 1,38l^2 - 0,43l + 1,79, \end{aligned} \tag{2}$$

$$R = 0,95,$$

$$\begin{aligned} A(l) &= 2,04 \cdot 10^{-11} l^{15} - 1,99 \cdot 10^{14} - 8,57 \cdot 10^{-8} l^{13} \\ &- 2,17 \cdot 10^{-6} l^{12} - 3,70 \cdot 10^{-5} l^{11} - 4,63 \cdot 10^{-4} l^{10} \\ &+ 4,7 \cdot 10^3 l^9 - 0,04l^8 + 0.3l^7 - 1,68l^6 + 6,82l^5 \\ &- 18,24l^4 + 28,96l^3 - 22,8l^2 + 6,32l + 1,65 \end{aligned}, \tag{3}$$

$$R = 0,96.$$

Polynomial approximation of the vocal tract function allows precise definition and calculation of vocal tract model's section of any length. Calculation shows the complexity of the expression and corresponding correlation coefficient R. The correlation coefficient R is good enough for the approximation with polynomial of tenth degree. In this example it is equal 0.95, leading to the conclusion that the dependence of the surface of voice tract cross section as a function of the distance from vocal cords does not have to be calculated with greater precision in practice. Very small gain in the correlation is obtained by increasing the polynomial degree.

The analysis of the stationary model of the vocal tract is the basis for the future development of a time-varying model which should be applied for synthesis of natural high fidelity speech signal. Also, the analysis of the stationary model with minimal satisfactory accuracy (correlation) is the basis for the future development of an automated process which identifies and verifies a speaker

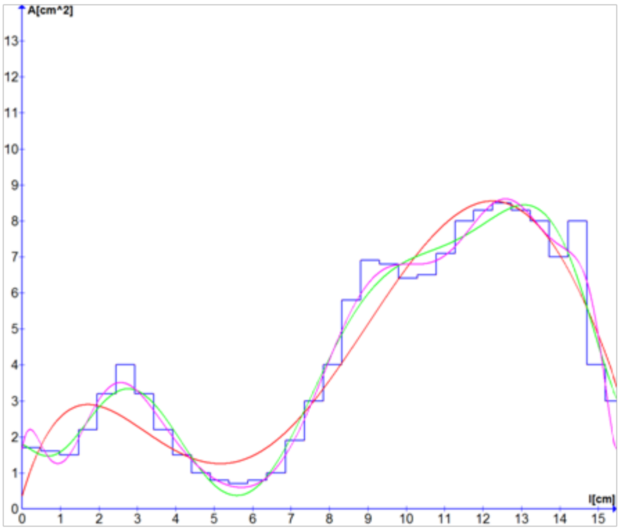

Fig. 7. Cross section area of voice tract, depending on the distance from vocal cords for Speaker 1

with a high degree of accuracy. The predicted and possible application of this research are: conversion of text to speech; interactive voice machines; interactive access to web based multimedia applications; authorized control in robotics (voice authentication and access management); detection of malformations of the vocal tract for the medical purposes and voice synthesis for people with damaged vocal tract.

In Fig. 8 the spectrum with formats of vowel "a" for Speaker 2 is shown. The difference between the formant frequencies of Speaker 1 can be noticed especially in the second and third formant, which points to the difference in voices of those two speakers.

In Fig. 9 the two-dimensional view of the model of voice tract of Speaker 2 is shown, and in the Fig. 10 the spectrum with formants for this model is shown. Matching between the formants' frequencies and formants' frequencies derived from recorded voice is significant.

In Fig. 11 the waveguide model for Speaker 2, consisting of 32 tubes, and acoustic response of this model is shown. The difference in the mechanical model, especially its middle section, in relation to the Speaker 1 can be seen. Matching of the formats' frequencies layout with those of the recorded voice is in satisfactory boundaries. In Fig. 12 the curves defined by polynomials of the fifth, tenth and fifteenth degree that best approximate mechanical waveguide model which is made of 32 tubes of equal length are shown. Polynomials are:

$$\begin{aligned}A(l) &= 7,98\cdot 10^{-5}l^5 - 3,6\cdot 10^{-3}l^4 + 0,06l^3\\ &- 0,35l^2 + 0,4l^3 - 0,35l^2 + 0,79l + 0,4\end{aligned}, \quad (4)$$

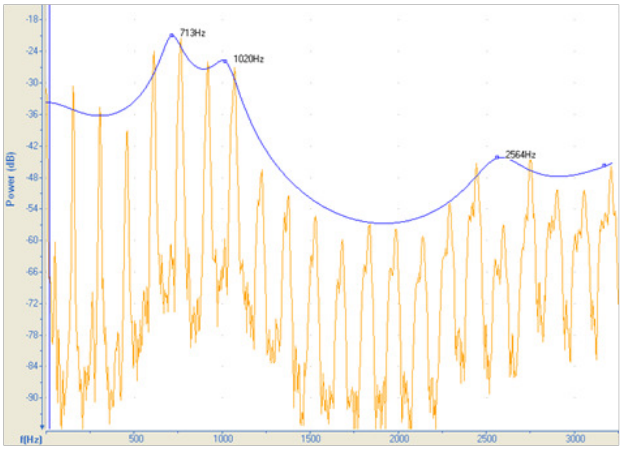

Fig. 8. The spectrum of vowel "a" of Speaker 2, with the formants

$$R = 0,85,$$

$$\begin{aligned}A(l) &= -2,14\cdot 10^{-8}l^{10} + 1,93\cdot 10^{-6}l^9 - 7,32\cdot 10^{-5}l^8\\ &+ 1,51\cdot 10^{-3}l^7 - 0,02l^6 + 0,14^5 - 0,61l^4 + 1,51l^3\\ &- 2l^2 + 1,35l + 0,41\end{aligned}, \quad (5)$$

$$R = 0,94,$$

$$\begin{aligned}A(l) &= 6,48\cdot 10^{-12}l^{15} - 6,38\cdot 10^{-10}l^{14} - 2,67\cdot 10^{-8}l^{13}\\ &+ 6,01\cdot 10^{-7}l^{12} - 7,06\cdot 10^{-6}l^{11} + 1,43\cdot 10^5 l^{10}\\ &8,84\cdot 10^4 l^9 - 0,02l^8 + 0,14l^7 - 0,8l^6 + 3l^5\\ &- 7,26l^4 + 10,78l^3 - 8,75l^2 + 3,24l + 0,39\end{aligned}, \quad (6)$$

$$R = 0,95.$$

The value of correlation coefficient R = 0.94 is obtained with the tenth degree polynomial approximations and as such is at satisfactory level, hence can be used in further computing.

In Fig. 13 the spectrum of vowel "a", with a prominent first three formants for the Speaker 3 is shown. The difference in the positioning of the first formant relative to the first two examples can be seen.

In the Fig. 14 the two-dimensional view of the voice tract model made for Speaker 3 is shown, and Fig. 15 shows the spectrum with formants, obtained by this model. The layout of formants' frequencies coincides well with

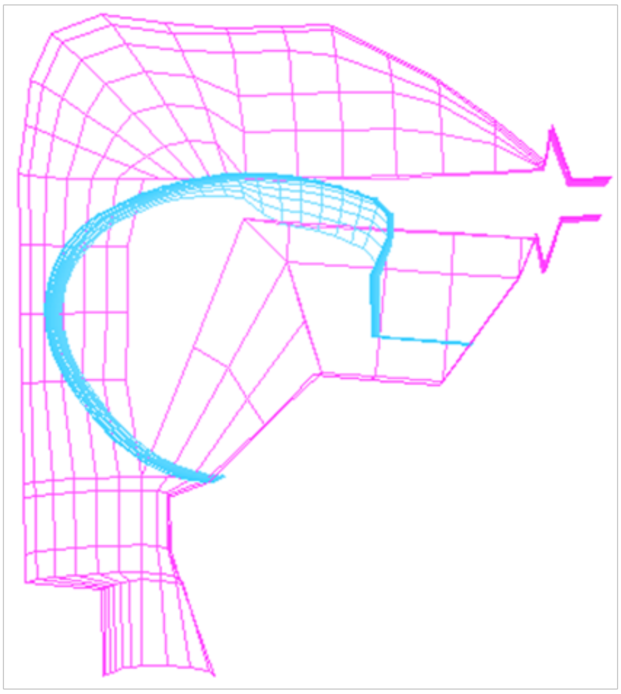

Fig. 9. Two-dimensional view of the voice tract model of Speaker 2

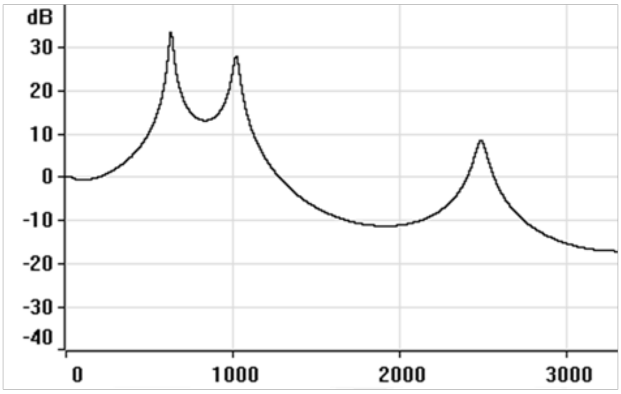

Fig. 10. The spectrum of vowel "a" of Speaker 2

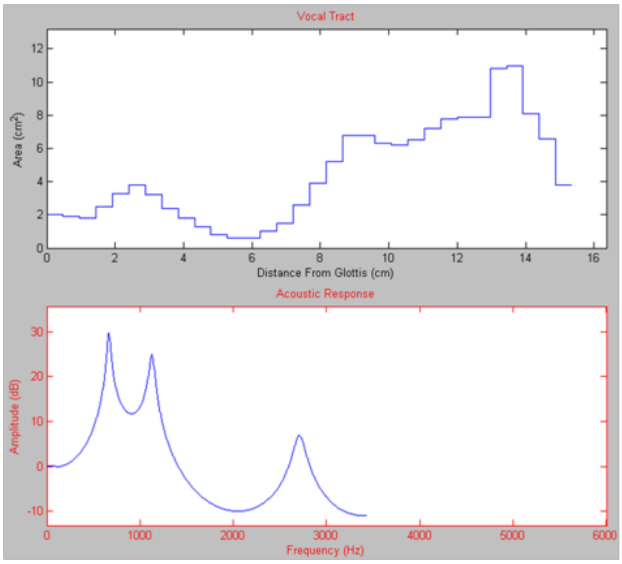

Fig. 11. Formant frequencies view for one-dimensional waveguide model made of 32 tubes for the Speaker 2

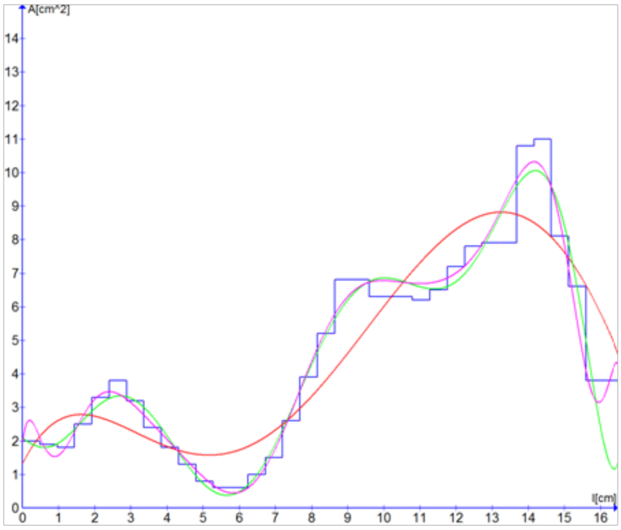

Fig. 12. Cross section area of voice tract, depending on the distance from vocal cords for Speaker 2

those obtained from the analysis of the recorded voice of the Speaker 3.

In Fig. 16 the one-dimensional waveguide model made of 32 tubes and taken from a model derived from *Articulatory speech synthesizer* program is shown. Formants' layout resulting from computation is well matched with the layout resulting from the voice of the Speaker 3 which is recorded and analyzed.

In Fig. 17 the curves are shown, which are defined by polynomials of the fifth, tenth and fifteenth degree that best approximate mechanical waveguide model made of 32 tubes of equal length. Polynomials are as follows:

$$\begin{aligned} A(l) = 1,59 \cdot 10^{-4} l^5 + 5,65 \cdot 10^{-4} l^4 \\ + 0,07 l^3 - 0,81 l^2 + 2,47 l + 0,62 \end{aligned}, \tag{7}$$

$$R = 0,9,$$

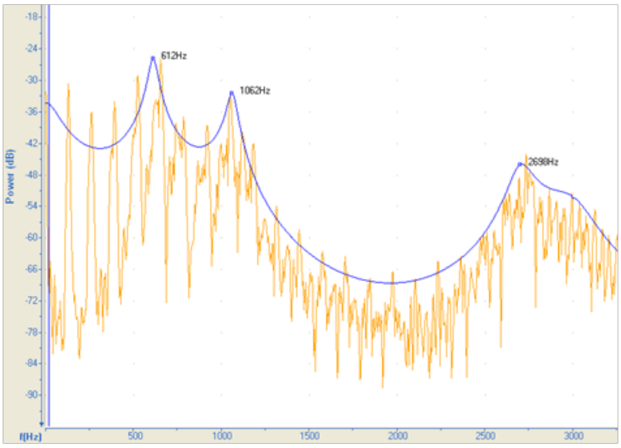

Fig. 13. The spectrum of vowel "a" of Speaker 3, with the formants

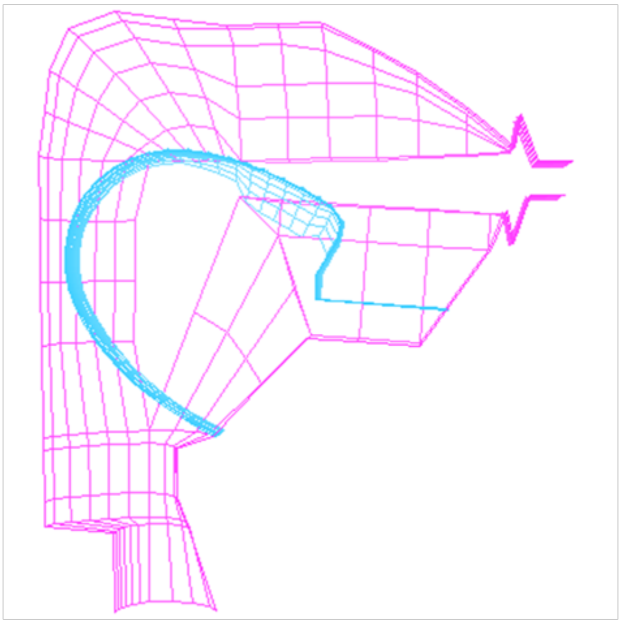

Fig. 14. Two-dimensional view of the voice tract model of Speaker 3

$$A(l) = 4,13 \cdot 10^{-8} l^{10} - 1,63 \cdot 10^{-6} l^{9} - 1,71 \cdot 10^{-5} l^{8} + 1,43 \cdot 10^{-3} l^{7} - 0,03 l^{6} + 0,25 l^{5} - 1,19 l^{4} + 2,64 l^{3}, - 1,95 l^{2} + 0,09 l + 1,74 \quad (8)$$

$$R = 0,96,$$

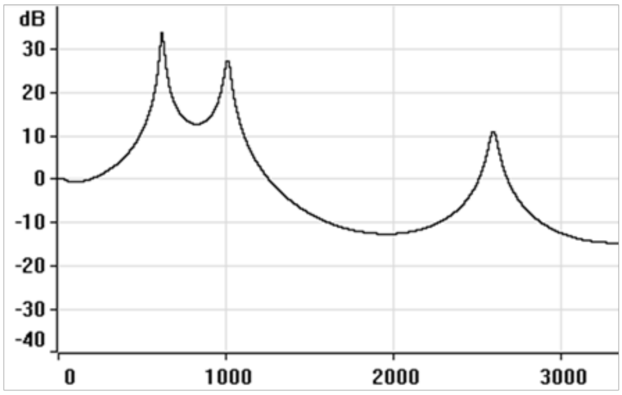

Fig. 15. The spectrum of vowel "a" of Speaker 3

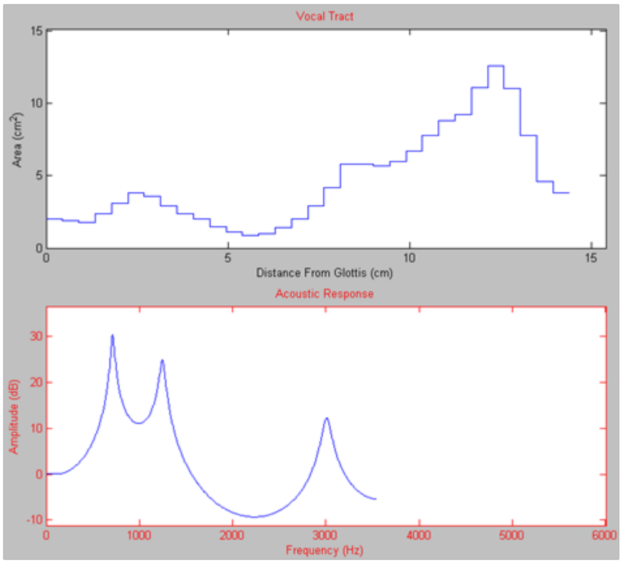

Fig. 16. Formant frequencies view for one-dimensional waveguide model made of 32 tubes for the Speaker 3

$$A(l) = 7,96 \cdot 10^{-12} l^{15} - 8,98 \cdot 10^{-10} l^{14} + 4,54 \cdot 10^{-8} l^{13} - 1,36 \cdot 10^{-6} l^{12} + 2,75 \cdot 10^{-5} l^{11} + 4 \cdot 10^{-4} l^{10} + 4,3 \cdot 10^{-3} l^{9} - 0,04 l^{8} + 0,25 l^{7} - 1,31 l^{6} + 5,02 l^{5} - 13,11 l^{4} + 20,93 l^{3} - 16,75 l^{2} + 4,68 l + 1,66, \quad (9)$$

$$R = 0,96.$$

The correlation coefficient R = 0.96 is obtained with the tenth degree polynomial, so as such can be applied in practice.

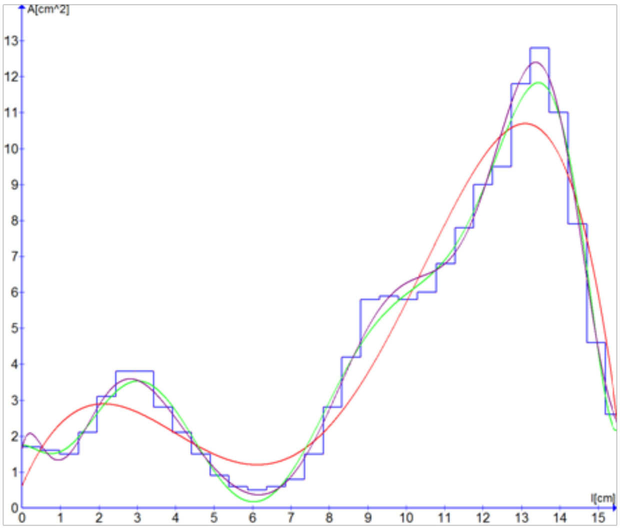

Fig. 17. Cross section area of voice tract, depending on the distance from vocal cords for Speaker 3

3 CONSLUSION

The process of defining voice tract models is extremely complex, so development of such models is focused on simplified forms which provide results of acceptable quality level. In this article three different software packages were used for obtaining a vocal tract model, each in its own segment of the modeling. First the spectrum analysis of recorded three speakers was made. In second the mechanical model was developed, from which a two-dimensional waveguide model was established, consisting of a finite number of tubes. The obtained stepwise profile was then approximated with a polynomial of tenth degree. Data obtained from the developed acoustical – mechanical voice tract model are of satisfactory accuracy and detail level, so such voice tract models can be used in practice and applied to real life cases.

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Siniša Fajt was born on 1963 in Zagreb. He graduated from the Faculty of Electrical Engineering in Zagreb in 1989 with B.Sc.E.E. degree, branch Radiocommunications and Professional electronics. In 1994 he received M.Sc.E.E. degree from the Faculty of Electrical Engineering in Zagreb. In 2000 he obtained Ph.D. degree from the Faculty of Electrical Engineering and Computing in Zagreb. Starting with 1990 he worked in RIZ-INFOTEHNA Company in Service department, as chief engineer for organization and monitoring service network of audio and video techniques. In 1992 he joined the Department of Electroacoustics of Faculty of Electrical Engineering in Zagreb where he worked as scientific assistant - junior researcher. In 1997 he gained assistant position at the Department of Electroacoustics of Faculty of Electrical Engineering and Computing in Zagreb. In 2000 he became senior assistant. In 2003 he gained position of assistant professor at the Department of Electroacoustics of Faculty of Electrical Engineering and Computing in Zagreb, in 2008 he gained position of associate professor, and in 2013 he gained the same position. He took part in several projects of acoustics and electroacoustics. In 1994 he was awarded Silver medal "Josip Lončar" for his Master's thesis. Siniša Fajt was honoured by the Homeland War Memorial Medal for the participation in homeland war from 1991 on, as well as by Medal for Operation Storm for his contribution in the military-police action "Storm".

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