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ANALYSIS OF INFLUENCE OF VOCAL FOLD –VOCAL TRACT MODELS CONNECTION BY USING FEM

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Abstract: *The Source-filter theory does not take into account many important circumstances for generating of vowels, e.g. the effects of source on filter. One of these effects is investigated in this paper, specifically changing of the glottal gap. Modal analyses were performed using 2-D models comprising a part of trachea, the glottal gap and straightened simplified vocal tracts for various vowels. Based on the modal analyses, classification of each cavity mode (vocal tract/trachea modes) for various glottal gaps was recognized. The glottal gap size ranged between 0 to 10 mm. The results show that some of the first ten natural frequencies of the model are significantly dependent on the glottal gap and the other natural frequencies are almost independent. From the glottal gap size of 5 mm towards lower values, an abrupt change in acoustic pressure occurs in the glottal gap zone. At higher pressure this change is not apparent at all.*

Keywords: ***Artificial vocal chords, vocal tract, trachea, modal analysis, vowel production.***

1. Introduction

The paper deals with an investigation of the glottal gap effect on modal characteristics of respiratory and vocal tracts air cavities. The respiratory tract is represented by a 2-D model of the trachea. The vocal tract is represented by a 2-D model based on simplified models of vocal tracts for each vowel (Arai et al., 2009).

Universally accepted and respected Source-Filter theory (Fant, 1970; Mišun, 2010) in its simple form, i.e. linearity and independence of the sources on the filter and vice versa, does not take into account many important circumstances which occur during generation of vowels (Rothenberg 1980). Besides the other omitted circumstances, it is also the effect of the source on the filter when glottal gap changes (g). This effect is investigated in this paper. Characteristics of artificial source-voices are investigated in (Mišun et al., 2010). First ten natural frequencies of models with various glottal gap settings are evaluated. Vocal tract and trachea are divided by the laryngeal part represented in the model by a gap of a certain size. Extreme cases of this size can either divide the model into two separate cavities ($g = 0$) or the models are linked together into single cavity without any obstruction ($g = g_{max}$).

2. Material and Methods

For computational modeling, finite element method (FEM) – which is commonly used in similar biomechanical problems – was chosen. In our case, models linking together the vocal tract, vocal cords and trachea were modeled in 2-D by using ANSYS 12.0. The geometry was discretized using 2-D elements FLUID29 which allow modal analysis. As for material properties, typical characteristics of the air at temperature of 20 °C and at atmospheric pressure of 101.325 kPa were used; i.e. density = $1.2041 kg \cdot m^{-3}$, sonic velocity = $343\ m \cdot s^{-1}$. UNSYM method was used for eigenvalue and eigenvector extraction. This method allows using unsymmetrical mass matrix as well as stiffness matrix.

For the following analyses, only inside space of the airways consisting of air without structural tissues was considered. In APDL programming language, parametric models representing the trachea,

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artificial vocal cords and vocal tracts for each vowel were created. Trachea was of a constant size in all analyzed cases. Dimensions of straightened simplified vocal tract were taken from (Arai et al., 2009), dimensions and shape of the trachea were obtained from the respiratory tract anatomy literature. Distances between the vocal cords at their closest points in various cases ranged from 0 to 10 mm.

The significant boundary conditions in the investigated cases were impermeable wall around the flowing media (i.e. the condition of zero displacements) and also balancing of internal pressure with the outer one at the outflow of the vocal tract as well as at the trachea-lung junction (i.e. the condition of zero acoustic pressure).

The series of calculations for the investigated vowel follows. The glottal gap is changed gradually (g = [0 0.25 0.50 0.75 1.00 1.25 1.50 1.75 2.00 2.25 2.50 2.75 3.00 5.00 7.00 10.00] mm). All models are analyzed and the first 10 natural frequencies $F_1 - F_{10}$ of each model are stored.

3. Results

Results presented in this paper come from the model representing the Czech vowel A (i.e. [aː] according to International Phonetic Alphabet). The dependence of natural frequencies on the size of the glottal gap is shown in Fig. 1. It is evident that some natural frequencies are dependent significantly. On the other hand, the significance of other natural frequencies is barely noticeable. Specifically for the Czech vowel A, the second, the fourth and the eighth natural frequency is dependent very significantly. Frequency shift is the largest at the second natural frequency (336 Hz).

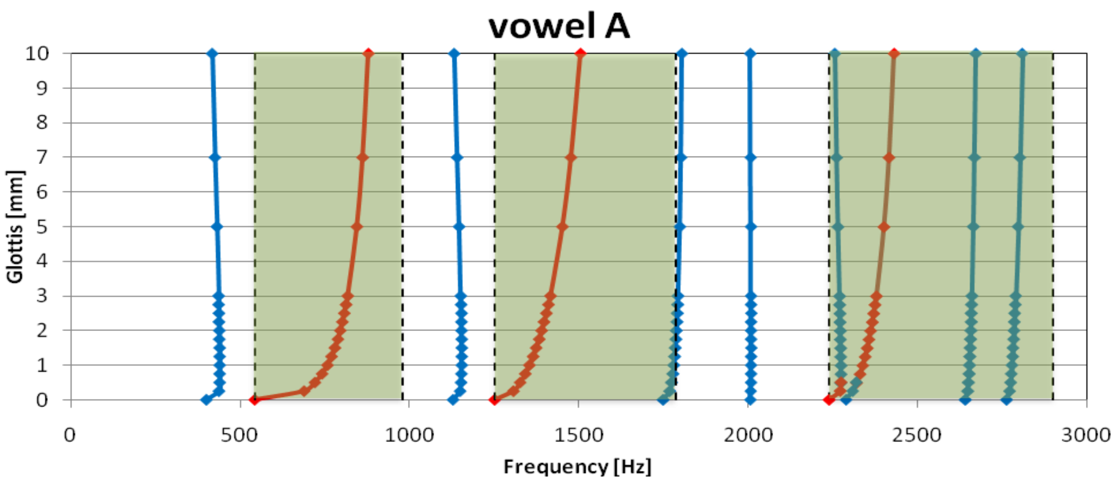

Fig. 1: The dependence of natural frequencies on the size of the glottal gap for Czech vowel A.

For the case the glottal gap is closed (g = 0) the model is divided into two separate cavities. From the analysis, one can decide which of the evaluated natural frequencies belongs to vocal tracts and which one belongs to the trachea. This differentiation is graphically illustrated in Fig. 1. Natural frequencies F2, F4 and F7 (in some cases also F8) denoted in red belong to the vocal tract. The other frequencies denoted in blue belong to natural frequencies of trachea. The green zone in Fig. 1 represents boundary between the two cases:

1. only the vocal tract without the trachea is analyzed;
2. the vocal tract is linked together with the trachea without any obstruction for the first three natural frequencies of the vocal tract.

The Fig. 1 also shows that some frequency values are independent of their size of the gap (almost vertical lines) and that some frequencies significantly decrease with closing the glottal gap. Uncertainty in the classification of frequencies F7 and F8 is because for the small gap these two frequencies approach each other to the minimum (approx. 30 Hz).

Fig. 2 shows the first 7 modal shapes of the model representing modes of the vocal tract and the trachea (for g = 0.25 mm). For this size of glottal gap, frequencies F2, F4 and F7 belong to the vocal tract modes. The other frequencies belong to the trachea.

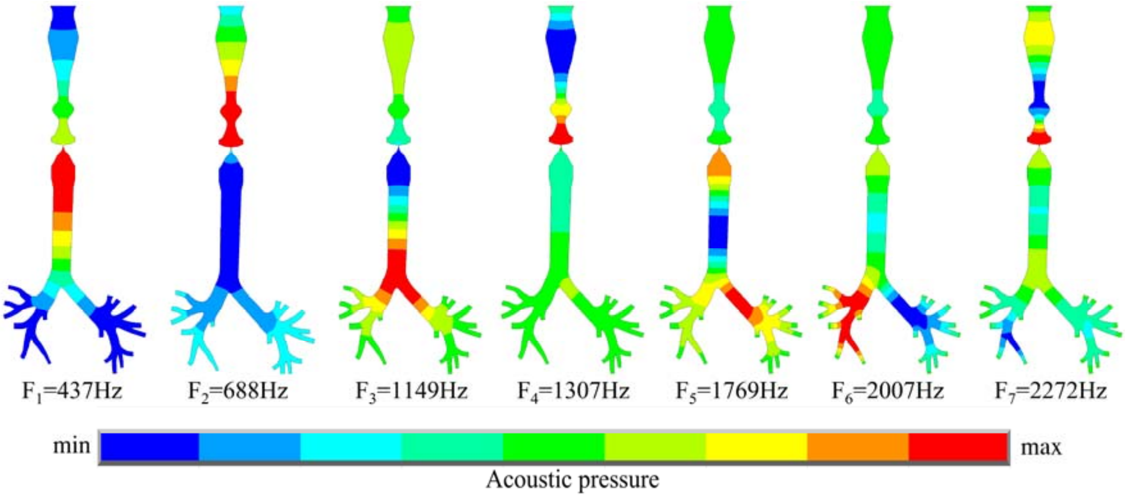

Fig. 2: Modal shapes of the first seven modes of model for Czech vowel A.

The lowest values of natural frequencies occur in the model which is divided by the vocal cord (g = 0) into two separate cavities. On the contrary, the highest values of natural frequencies occur in the model with the largest glottal gap (g = 10 mm). One can expect that even higher value of the natural frequency of the vocal tract can be obtained when the vocal tract is opened at both ends (the boundary condition p = 0). This case is plotted in Fig. 1 as the upper border in the colored zones.

Fig. 3a shows the abrupt change in acoustic pressure for the Czech vowel A (g = 0.25). This change occurs in the narrowest point of the model (glottal gap) – see yellow zone. The red zone corresponds to the vocal tract from the outflow of the vocal tract towards the vocal cords. The blue zone corresponds to the trachea from the vocal cords to its bifurcation. Fig. 3b shows the same situation for the 10 mm gap. It is seen that the whole system behaves as one continuous unit and that the change in acoustic pressure is not even noticeable. This pressure change starts from the glottal gap size of 5 mm towards lower values.

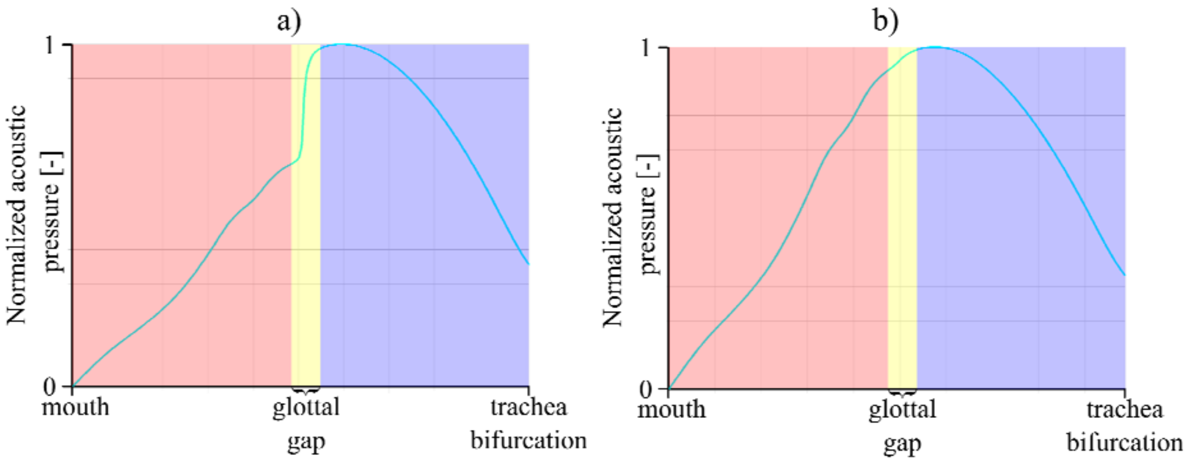

Fig. 3: The acoustic pressure distribution along the path (from mouth to trachea bifurcation) for Czech vowel A: a) glottal gap 0.25 mm b) glottal gap 10 mm.

The calculated values of the first three natural frequencies of the vocal tract (formants) for each vowel are compared in Tab. 1. The distribution of the formants associated with the ability to distinguish between various vowels from the calculated values corresponds with the values presented in (Mišun et al., 2010).

Tab. 1: The comparison of the first 3 natural frequencies, computed for glottal gap 0.25 mm.

Czech vowel	***F1***	***F2***	***F3***
A [a:]	*688*	*1307*	*2272*
E [ɛ:]	*582*	*1536*	*2245*
I [i:]	*378*	*1518*	*2385*
O [o:]	*652*	*1275*	*2221*

4. Conclusions

Similarly to removing the tonsils (Laukkanen et al., 2007), the size of the glottal gap has a significant effect on some natural frequencies of the vocal tract / trachea connection, especially on the natural frequencies of the vocal tract. Mainly these frequencies (formants), especially the first three of them, affect the quality and clarity of voiced vowels. It is quite difficult to determine exactly what boundary conditions must be prescribed for the correct modeling of whisper.

The changing glottal gap g has a significant effect on the modal properties of the vocal tract. The simplest approach of the generally accepted theory of generation of vowels, the Source-filter theory, does not take this into account. Although only the modal analysis of the interconnected models of the vocal tract and the trachea was performed in this paper, one can expect that this effect will be also taken into account when similar models are investigated in the time domain.

Further investigation should follow and the question why the natural frequencies are differently sensitive to the change of the glottal gap g should be answered.

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