COMPUTER MODELING OF THE VOCAL FOLDS FUNCTION BASED ON THE "BUBBLES" PRINCIPLE

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Abstract: There have been several modified versions of the vocal folds function described in literature. They share a common predominant view whose central idea is an expressive effect of Bernoulli´s underpressure produced within the space of the glottis at an increased speed of the airflow which passes between the vocal folds in motion. In the version of the vocal folds function an important role is played by the flowing air alone and its variable parameters (pressure, speed and mass). Due to the numerous weak points identified regarding these principles there has been a new principle defined and developed, preliminarily called the *„compressed air bubbles"*, in short *„bubbles"*. The contribution describes this new functional model of generating loud source voice. The plane finite-element model of the vocal folds function has been used for verification of the compressed air bubble principle. The basic parameters of the model are the characteristics of the subglottal pressure in relation to the glottis gap, and further the spectral and modal properties of the vocal folds model structure.

Introduction

Due to the numerous weak points found in the Bernoulli´s principles as defined by different authors in the literature there has been another principle defined and developed, preliminary called *„compressed air bubbles"*, in short *„bubbles"* – [1], [2], [5], [6], [7]. This principle of the substitute vocal folds function was patented by WIPO (World Intellectual Patent Organisation) in Geneva, name "Device for Stimulating the Voice Organs", number : PCT/CZ2004/000041.

Based on this principle, there have been several types of artificial vocal folds made – [3], [4]. The paper deals with the FE computer model of the vocal folds function based on the "bubble" principle.

Regarding the need to generate a loud voice and select a frequency of a specific height the following needs to be stated :

- the tone height can be influenced by the system parameters which man is able to influence by his will,
- man cannot affect e.g. the speed of airflow passing through the glottis, and so this speed cannot be the cause of the change to the tone height; consequently, the flowing air medium can have no influence on the vocal folds motion.

Materials and Methods

Based on the idea mentioned above there has been a principle defined and developed, initially called *„compressed air bubbles"*, in short *„bubbles"*.

The transport of the compressed air bubble (air column, small air volume) through the glottis from the subglottal to the supraglottal space is the fundamental idea of this principle – [1], [2], [7].

The air bubble with the highest subglottal pressure should be shifted as soon as possible to the upper part of the closed glottis. After the glottis opening the bubble expands from the highest subglottal air pressure so that the acoustic pressure amplitude to be source voice generated has the highest value in this case. This condition is very important for a higher intensity of voice generation.

According to this principle of the vocal folds function, the main forces acting on the vocal folds during phonation are as follows :

- the subglottal air pressure under the vocal folds and in the whole trachea; the overpressure acts on the relatively large inner subglottal surface, producing a considerable higher force opening the vocal folds,
- resilient forces of the vocal folds muscles which act against the opening of the vocal folds,
- forces of inertia of the vocal folds structure.

The forces of inertia of the air bubble cannot play a significant role with regard to the low value of air density, a small size of the moved bubble and also to small changes of the airflow speed.

The driving phenomenon for the vocal folds during phonation is the compressed air in the subglottal space (in trachea), which always reaches a higher resulting air pressure value here than within the supraglottal space, and is the function of the glottis opening m – Figure 1.

So that the basic characteristics of the vocal folds function is the relation of the subglottal air pressure and the opening between the vocal folds in the form defined by the ellipse $p_{SG}(m)$ – [6], [7].

The driving subglottal pressure $p_{SG}(m)$ is in the ellipse form – Figure 1. The subglottal pressure course has four traces (branches) a, b, c, d, and they are bordered by the letters: **O**, **A**, **C**, **E**.

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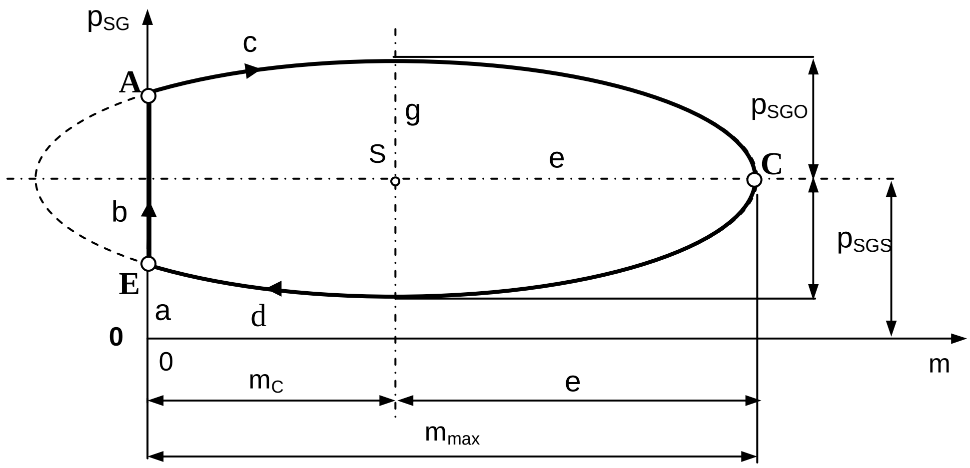

Figure 1: Characteristic of the subglottal pressure $p_{SG}(m)$ as a function of the glottis m

Description of an individual traces – Figure 1:

- Trace "a" is limited by the points **O – A**. This is a phonation phase, the vocal folds are in the contact. The glottis has value : m = 0. The subglottal pressure is increasing from the zero value up to p_{SGA}.
- Trace "c" is limited by the points **A – C.** This phase means the vocal folds opening : m > 0.
- Trace "d" is limited by the points **C – E.** This phase means the vocal folds closing : m > 0.
- Trace "b" is limited by the points **E – A.** In this phase vocal folds are closed : m = 0.

We define relations for the characteristics of the subglottal pressure $p_{SG}(m)$. The dependence of the subglottal pressure versus glottis value is in the ellipse form - [6], [7]

$$\frac{(m-m_C)^2}{e^2}+\frac{(p_{SG}-p_{SGS})^2}{g^2}=1 \qquad (1)$$

Maximum opening glottis value (C – parameter of the truncation of the left part of the ellipse, C = 0~1)

$$m_{max}=m_C+e=e(C+1) \qquad (2)$$

than

$$e=\frac{m_{max}}{1+C} \qquad (3)$$

and

$$g=p_{SG0}=0.6.p_{SGS} \qquad (4)$$

Subglottal pressure at points **E, A** :

$$p_{SGE}=p_{SGS}\left(1-0.6.\sqrt{1-C^2}\right) \qquad (5)$$

$$p_{SGA}=p_{SGS}\left(1+0.6.\sqrt{(1-C^2}\right) \qquad (6)$$

Subglottal pressure courses for the three traces : a, c, d

$$p_{SGa}=p_{SGb}=p_{SG}+\Delta p_{SG} \qquad (7)$$

$$p_{SGc}=p_{SGS}+p_{SGO}\cdot\sqrt{1-\frac{(m-m_C)^2}{e^2}} \qquad (8)$$

$$p_{SGd}=p_{SGS}-p_{SGO}\cdot\sqrt{1-\frac{(m-m_C)^2}{e^2}} \qquad (9)$$

We defined a model of the vocal folds function which is based on the air bubble principle. Firstly we introduce a plane FE model of the vocal folds, Figure 2. Vocal folds are modeled by the structural elements and the subglottal pressure is defined in all inner nodes of the vocal folds model. The subglottal pressure $p_{SG}(m)$ is changed due to the glottis value changes – Figure 1.

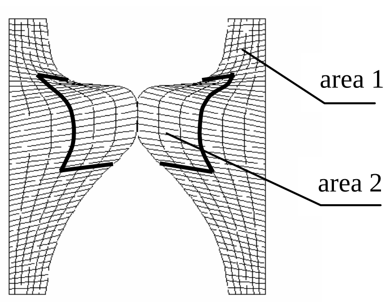

Figure 2: Finite element vocal folds model

Model parameters :

- number of elements 848
- number of nodes 2146
- type of elements – PLANE82
- contact elements on the inner surface of the vocal folds: TARGET169 a CONTACTS172

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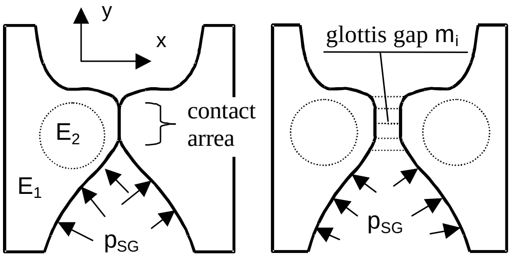
- Young's modulus of material, Figure 3:
  E_1 = 1,5E+06 Pa (area 1)
  E_2 = 3,0E+06 Pa (area 2).

Scheme of the vocal folds interaction and subglottal pressure is in Figure 3.



a) phonation phase b) opening phase

Figure 3: Scheme of the vocal folds model

Horizontal motion between nodal points i , j – Figure 3

$$m_{ij} = u_{xi} - u_{xj} \tag{10}$$

where u_{xi} , u_{xj} are horizontal deformations of the structure in nodes i , j.
Glottis value is than

$$m \rightarrow \min(m_{ij}) \tag{11}$$

The excitation force in the node n of the vocal folds model is the subglottal pressure in the form

$$F_n(t,m) \quad p_{SGk}(m) \tag{12}$$

where k = a, b, c, d (traces of the working ellipse).
The equation of the motion of the FE model in matrix form

$$\mathbf{M}\ddot{\mathbf{q}} + \mathbf{K}\mathbf{q} = \mathbf{F}(t,m) \tag{13}$$

where there are:
M, K – mass matrix, stiffness matrix of the vocal folds model structure,

$\mathbf{q} = \begin{bmatrix} \mathbf{x} \\ \mathbf{y} \end{bmatrix}$ - column vector of model motion coordinates.

After integration of eq.(13) we obtain coordinates and first derivations of the model motion: $\mathbf{q}(t)$, $\dot{\mathbf{q}}(t)$. The characteristic phases of the plane vocal folds model motion are presented in Figure 4.

The individual characteristic phases:

- fundamental phonation phase
- opening vocal folds in the lowest part
- opening in the upper part
- closing in the lowest part
- step by step closing from the lowest part up to the highest one
- fundamental phonation phase.

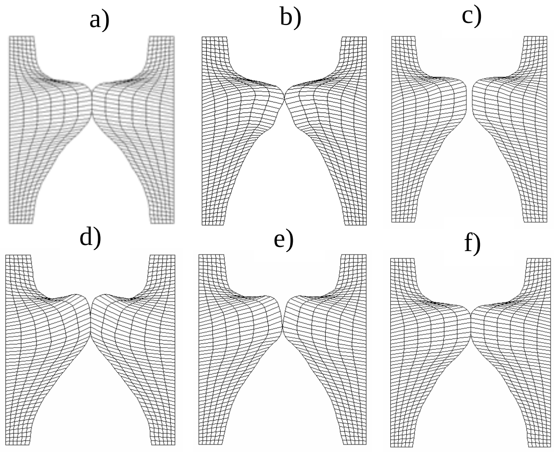


Figure 4: Characteristic phases of the phonation model

In Figure 5 to Figure 9 are presented subglottal pressures courses calculated for parameters: C, p_{SGS}.

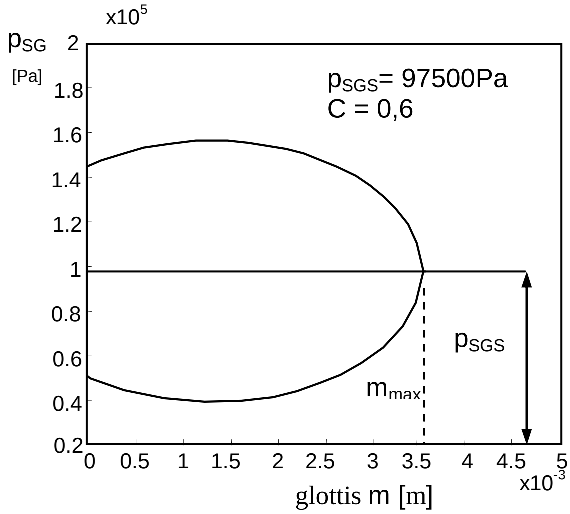


Figure 5: Characteristic $p_{SG}(m)$ for parameter C = 0.6

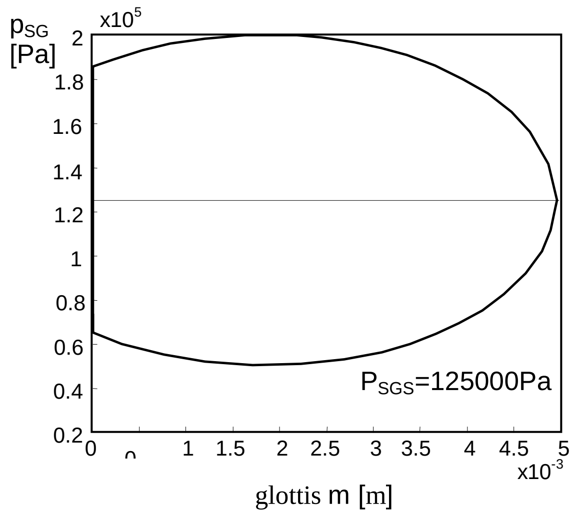


Figure 6: Characteristic $p_{SG}(m)$ for parameter C=0.6

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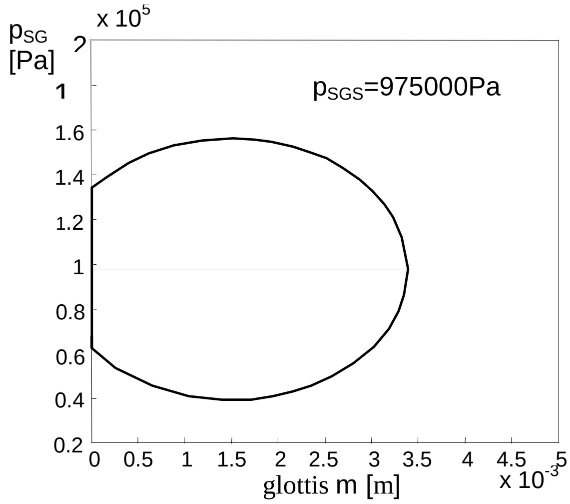

Figure 7: Characteristic $p_{SG}(m)$ for parameter C=0.8

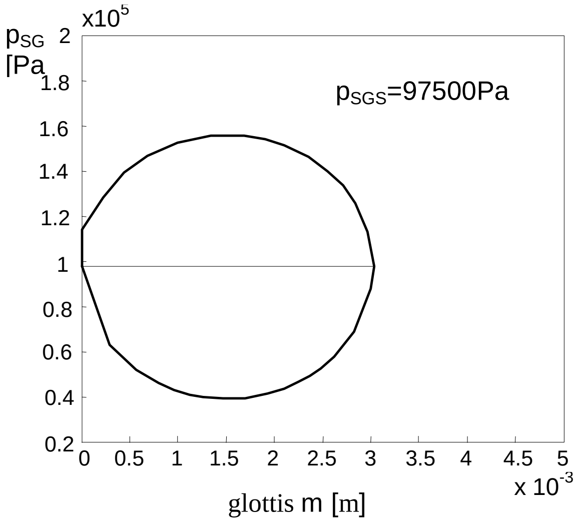

Figure 8: Characteristic $p_{SG}(m)$ for parameter C=1

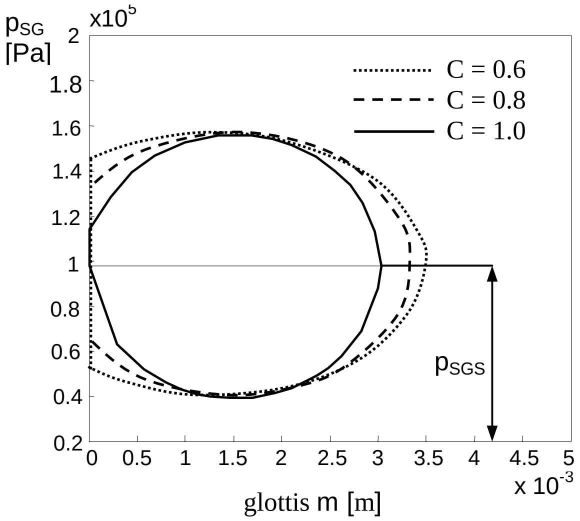

Figure 9: Characteristics $p_{SG}(m)$ for parameter subglottal pressure p_{SGS} = 97500Pa and various value C

Characteristics are calculated for various value of the mean value of subglottal pressure p_{SGS}. The source voice intensity change is coming due to the change of the mean value of the subglottal pressure in the trachea. The higher the mean value of the subglottal pressure the higher intensity of the source voice of the computer vocal folds model.

In Figure 10 and Figure 12 are presented characteristics $p_{SG}(m)$ each of them is for set values of the mean subglottal pressure p_{SGS} .

Discussion

The characteristics $p_{SG}(m)$ vary when the parameters of the model are changed. We followed the two parameters only that influence the phonation of the source voice of the vocal folds model.
We have showed influence two parameters:

- parameter C that characterises the time closing of the vocal folds during phonation,
- mean value of the subglottal pressure p_{SGS}= const. for individual characteristic $p_{SG}(m)$.

When we analyse characteristics in Figure 5 up to Figure 12 we can state as follows:

- An ellipse characterises the functionality of the subglottal pressure versus the glottis value: $p_{SG}(m)$.
- When the damping is not considered in finite element model then the main axis of the ellipse is in the horizontal position.
- The parameter C characterises the truncation of the left part of the ellipse $p_{SG}(m)$ and in consequence, the time of vocal folds closing during every phonation phase.
- The smaller the parameter C (time of vocal folds closing is longer) the higher the p_{SGA} – Figure 1 and also the higher vocal folds opening – Figure 9.
- The higher mean value of subglottal pressure p_{SGS} the larger the characteristic of $p_{SG}(m)$ and the higher the maximum of the subglottal pressure and the higher the maximum of vocal folds opening.– Figure 10, Figure 11 and Figure 12.
- The higher mean value of the subglottal pressure p_{SGS} the higher the intensity of the model source voice.
- So that the model presented respects the very important vocal folds properties – the change of the source voice intensity of the vocal folds.
- When the parameter C=1 the vocal folds are coming in the mutual contact only in one time moment – Figure 8.
- The higher mean value of subglottal pressure p_{SGS} the higher the maxima of $p_{SG}(m)$ – Figure 10, Figure 11 and Figure 12.
- When the subglottal pressure p_{SGS} is changed the minima of the $p_{SG}(m)$ vary a little only – Figure 10, Figure 11 and Figure 12.

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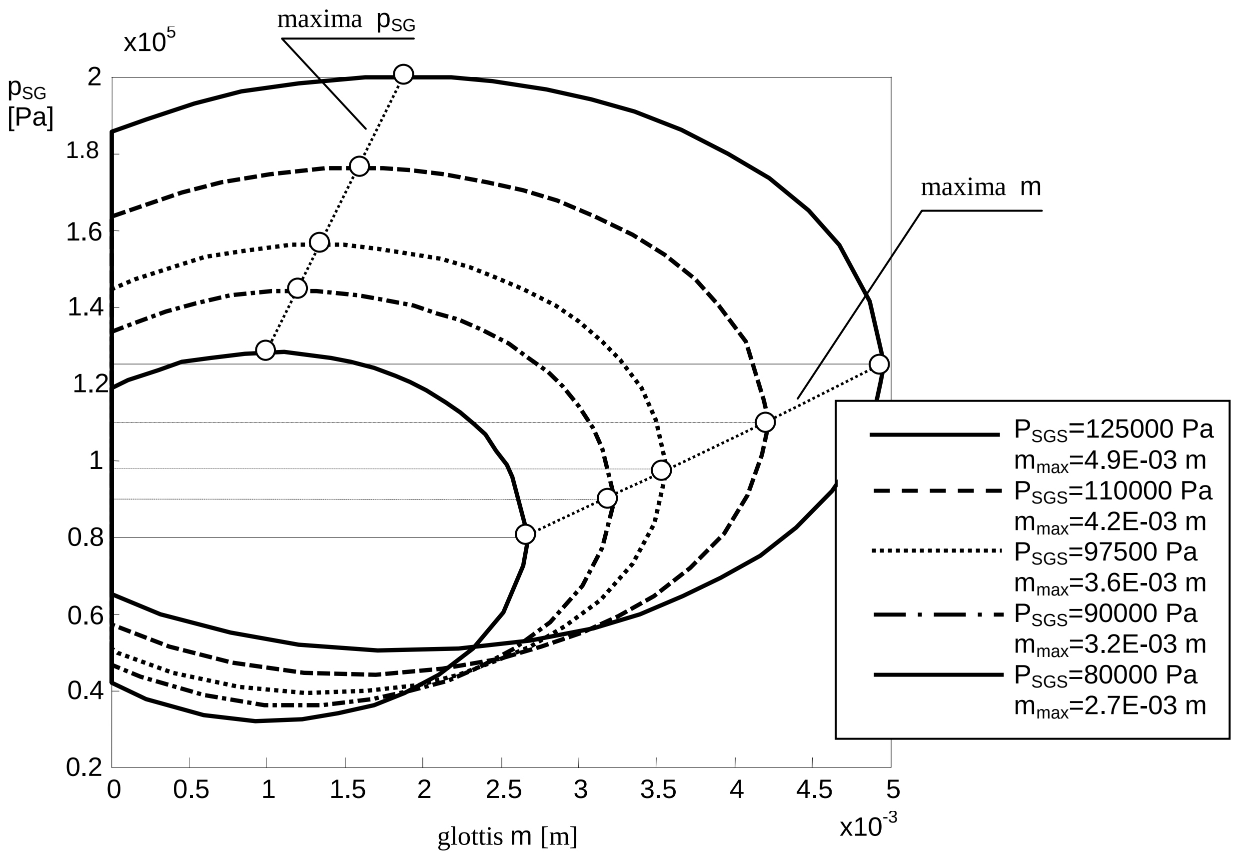

Figure 10: Set of characteristics $p_{SG}(m)$ for parameter C = 0.6 and altered value of p_{SGS}

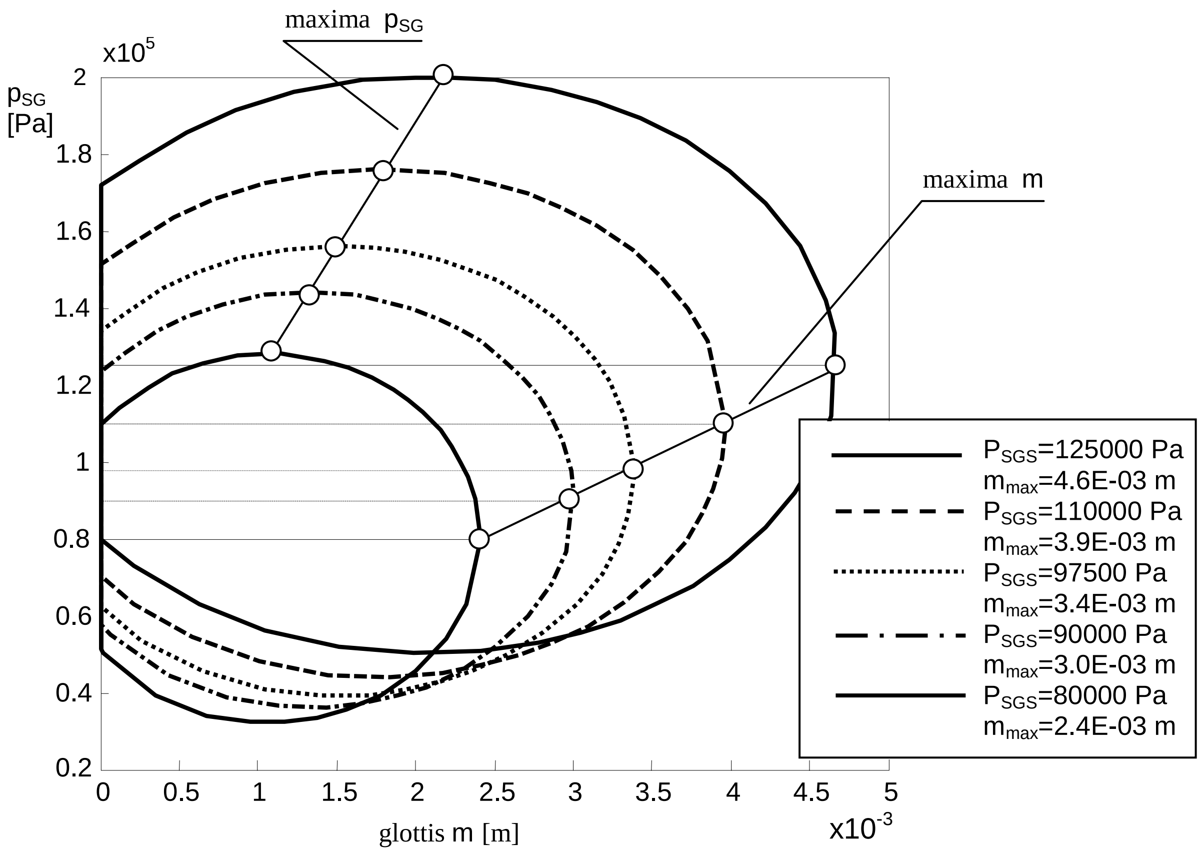

Figure 11: Set of characteristics $p_{SG}(m)$ for parameter C = 0.8 and altered value of p_{SGS}

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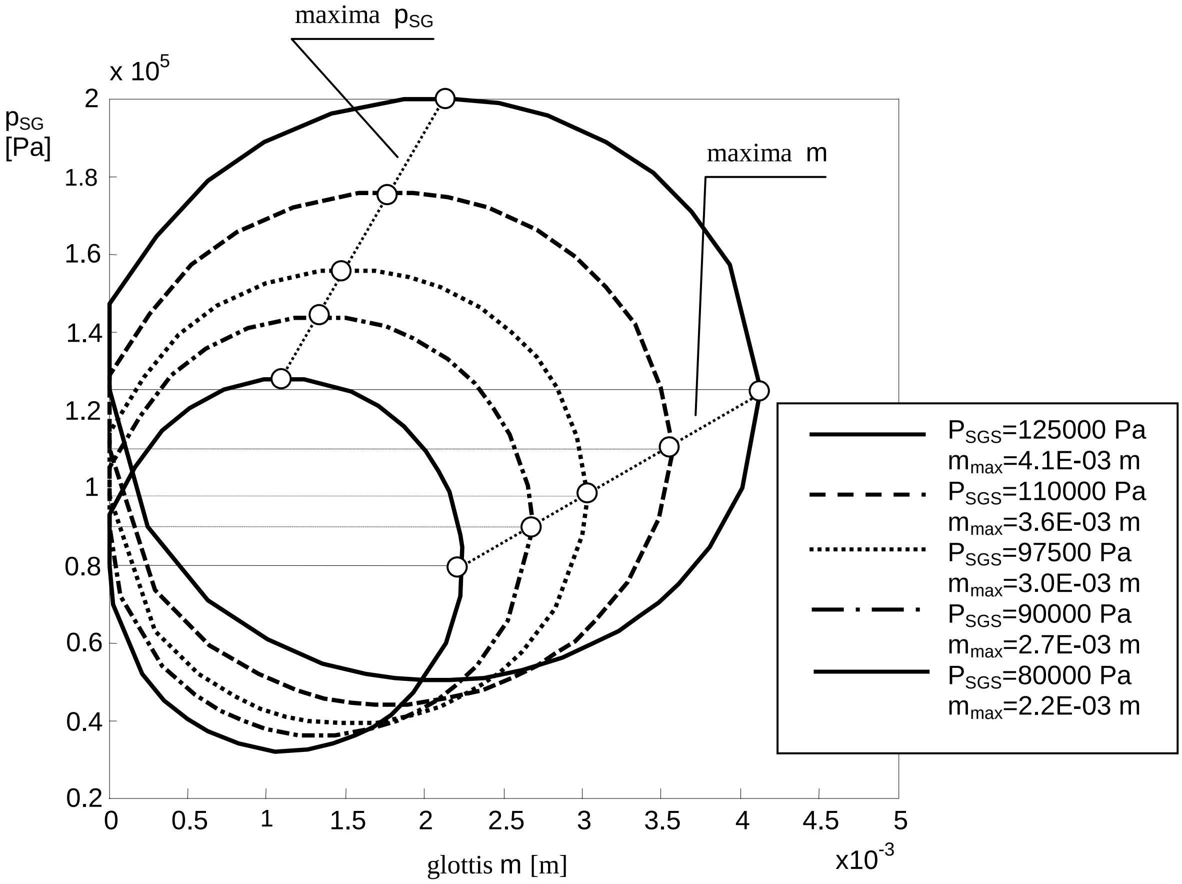

Figure 12: Set of characteristics $p_{SG}(m)$ for parameter $C = 1$ and altered value of p_{SGS}

Conclusion

The definition and creation of the FE vocal folds function model on the principle of compressed air bubble to be shifted from the subglottal area into supraglottal one and farther into the vocal tract seems to be viable and corresponding to the observations of the behaviours of real vocal folds during phonation.

The analysis described leads to the conclusion that if a speaking person wants to increase his/her voice intensity (i.e. speak more loudly), they must generate a higher value of the subglottal pressure by a consciously increased lung activity, which is then, while passing through the glottis, transformed into the higher source voice intensity.

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