COMPUTATIONAL MODEL OF VOICE PRODUCING ELEMENT IN TERMS OF VARYING INLET PRESSURE

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The computational model of the reed-based element is in scope of this article. This element is studied for its potential suitability to generate an artificial source voice. Compressed air is being used like a source of the energy to produce the voiced speech (similar to the healthy voiced speech). Two-way interaction of solid and fluid part of the computational model has been considered for the solution. Computation has been performed by the finite element method (Ansys) and results have been processed by the software MATLAB. Basic characteristics like a frequency spectrum and a fundamental frequency of generated source voice are evaluated. Relationship between deformation of the reed and the pressure in front of the reed is presented. This characteristic represents one of the basic phonation theories which are in our scope. This theory is based on the compressed air 'bubble'.

Keywords: *artificial vocal folds, vocal tract, FEM, structural-fluid interaction, reed-based element*

1. Introduction

Health human's voice is generated in the vocal folds. The vocal folds, with narrow glottis between them, are during the speech tightened. Vocal folds are vibrated by the pressure and the flow of the air. Consequently, the area above the vocal folds (supraglottic area) is excited by the regular changes of the compressed air. These pulses are in the vocal tract filtered and they are emitted into the surrounding space like a human's voice by passing the mouth.

After a total laryngectomy, in which a man loses a natural source of the voice – the vocal folds – various different methods of the voice rehabilitation exist (for instance a tracheo-esophageal voice, application of an electrolarynx or a pseudo-whisper). The voice prosthesis, which generates the source voice sounding like healthy vocal cords, is used less frequently [1].

We considered another principles of the source and subsequent voice generating while we were working on the prototypes of an artificial vocal folds [2], [3] and after more detailed research the reed-based voice producing element has been selected. Theory of the pressure-controlled reed-based element's behavior inside of the flowing air has been known for many years [4]. Similar problems have been explored in the field of musical instruments by Helmholtz. Four types of reed elements have been considered: (+,+); (+,−); (−,+); (−,−), where the first sign represent deformation response to the pressure's growth in front of the reed element. The second sign represent response to the overpressure behind the reed

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element. In other words, the positive sign represent grooving of the gap between the reed element and the stopper, the negative sign represents reduction of this gap. Health men's vocal folds are during common phonation represented by type (+,−). The computational and the experimental model represented in this article is similar to the type (−,+), i.e. after the subglottic's pressure growth the gap between the reed element and the stopper is reduced. Output characteristic, such as acoustic pressure behind the element, has been evaluated in dependence on the reed element's deformation and the pressure in front of it [5].

2. Material and methods

The created computational model includes two-way interaction between the fluid (air) and the solid phase (reed). Using this model, it is possible to analyze time behavior of the reed position, of acoustic pressures in air cavities and of acoustic pressures at the model outlet. The model is solved in time domain with time step $\Delta t = 1{\times}10^{-5}$ s. The driving force is pressure p_{SGS} at the model inlet which represents mean subglottal pressure generated in the lungs. For different calculation variants, p_{SGS} values are selected from the range of normal pressures in the lungs reported in [6]. No extreme pressure values reported in the literature are considered, e.g. for loud singing – the reed-element is not suitable in such cases.

The computational model was created parametrically in Ansys parametric design language (APDL, see Figure 1). The model was created by using approx. 26 000 finite elements representing mainly the air. The fluid-solid interaction is based on the reed surface loading by pressure obtained from CFD calculation. Reverse solid-fluid interaction is based on the fact that the deformed reed changes the shape of the cavity with the flowing fluid.

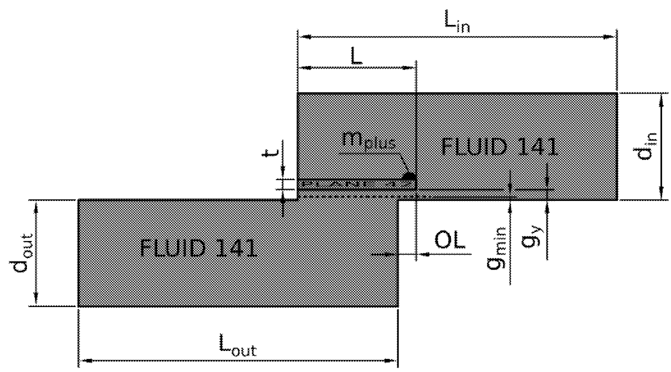

Fig.1: Parametric model with changeable parameters and corresponding finite element types

Using the geometry parameters, the two-dimensional computational model is set to match the already produced experimental model. This is done because of the future easier comparison of the calculation with experimental results. The geometry is discretized by a finite element mesh as follows. The fluid area consists of FLUID141 elements, the solid phase area consists of PLANE42 elements and the reed is appropriately covered with CONTACT175 contact elements and TARGET169 target elements.

Models of boundary conditions and loads (Fig. 2) are again set to match the experimental model as much as possible. The reed is fixed on the one side and the remaining surface, which interacts with the air, is loaded by the pressure calculated at each time step. Zero velocity is specified at all hard (impenetrable) walls of the air model. The inlet pressure p_{SGS} is prescribed at the model inlet and zero pressure is prescribed at the outlet into the atmosphere. Under the reed is also created a stopper with which the reed comes into the contact during the solution.

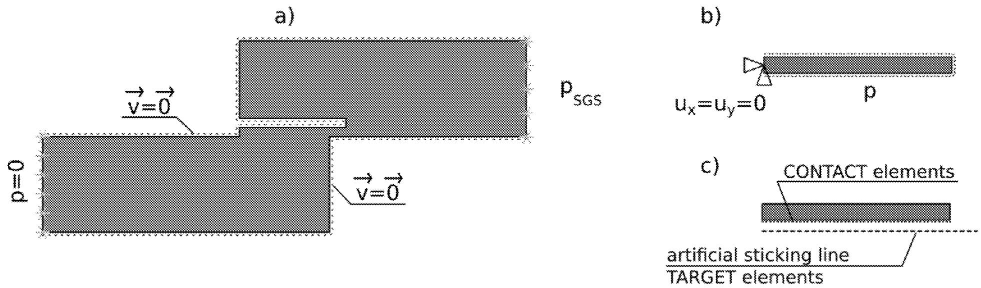

Fig.2: Boundary conditions prescribed to the reed and the air cavity boundaries

AIR-SI material is used in Ansys for modeling the compressible viscous fluid (physical constants are set for air using SI units). Turbulent flow is not considered.

Values of the monitored quantities, specifically fluid pressures in front of (p_{SG}) as well as behind (p_{SPG}) the reed and the reed-end deflection (u_{Y}), are stored at each time step. By processing these values, important characteristics describing the reed-element behavior when p_{SGS} is changed are obtained. The processing of the output files is done in Matlab R2009b. Above all, the spectral distribution of acoustic pressure p_{SPG} at the model outlet is important. The requirement for a sufficient number of higher harmonic components in the generated source voice arises from generally accepted Source-Filter theory which describes the formation of vowels as filtering the source voice p_{SPG} by the vocal tract (tunable filter). Evaluation of spectra is performed on the basis of FFT function. The theory of phonation based on the principle of 'compressed air bubbles' [5], which introduces g–p_{SPG} characteristic, is based on generating pressure pulses. These pulses occur due to periodical reed movement during which the air from subglottal region expands into the supraglottal space. To make it clearer, only a convex envelope of g–p_{SPG} relation is shown in the graph.

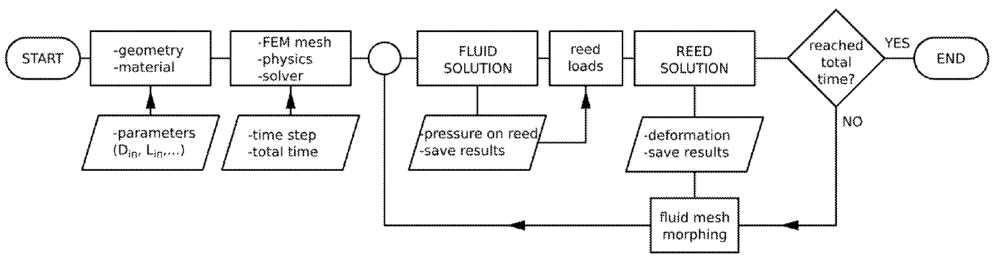

Fig.3: Algorithm flowchart

The calculation is carried out in repetitive cycles until the final time of simulation is achieved. Parts of the algorithm and their interconnections are shown in Fig. 3.

A significant effect of the finite element mesh-change on the calculation stability turned out during the tuning of the algorithm. In Ansys this change is normally performed using *demorph* command which automatically changes the shape of finite element mesh. This automatic change, however, fails when the mesh deformation is too large in comparison to its previous state. In addition, the mesh deforms only in the reed vicinity which cannot be set. Therefore new procedure allowing this setting was developed. With this procedure the algorithm is stable.

3. Results

3.1. Acoustic pressure distribution in the reed vicinity and during its deformation

In this part, distribution of the reed deformation along its length and at different times is examined. Fig. 4 shows the contact of the reed with stopper.

Simultaneously, acoustic pressures in air cavities around the deformed reed and at the same times were monitored (see Fig. 5). Fig. 5 shows situation at $t = 0.75\times10^{-3}$ s when the

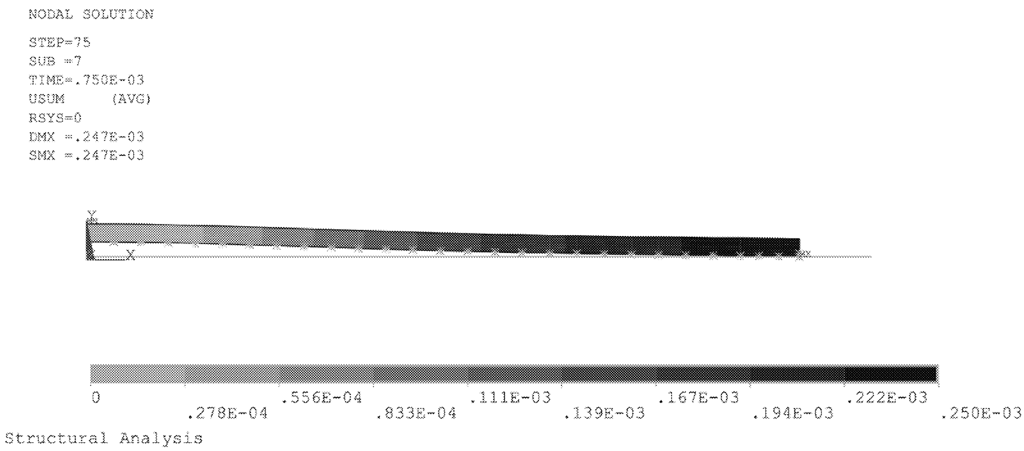

Fig.4: Reed deformation at $t = 0.75\times10^{-3}$ s in millimeters (reed-stopper contact occurred)

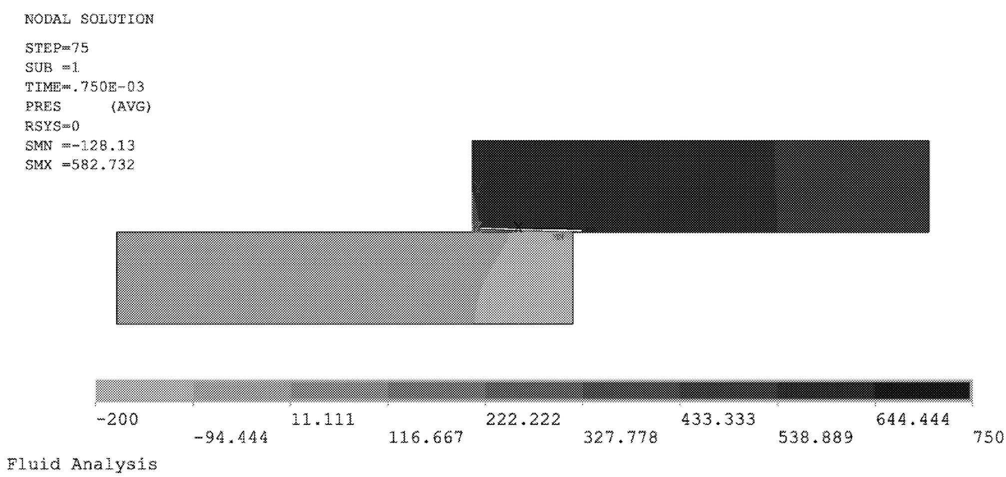

Fig.5: Acoustic pressure at $t = 0.75\times10^{-3}$ s in Pascals

reed is in contact with the stopper. In this case the subglottal pressure above the reed is positive while supraglottal pressure just below the reed is negative.

3.2. Spectral distribution of generated signal

From the values stored in each time step, time behavior of g, p_{SG} and p_{SPG} can be reconstructed. In all three cases, these time relationships are periodic. It is necessary to create and to evaluate inlet-outlet characteristics, particularly the dependence of the fundamental frequency (f_0) of the supraglottal pressure $p_{SPG}(t)$ on inlet mean subglottal pressure (p_{SGS}). This characteristic is shown in Fig. 6b.

Transformation into the frequency domain is performed using FFT (edge effects are eliminated using Hanning's window). An example of p_{SPG} spectrum is shown in Fig. 6a.

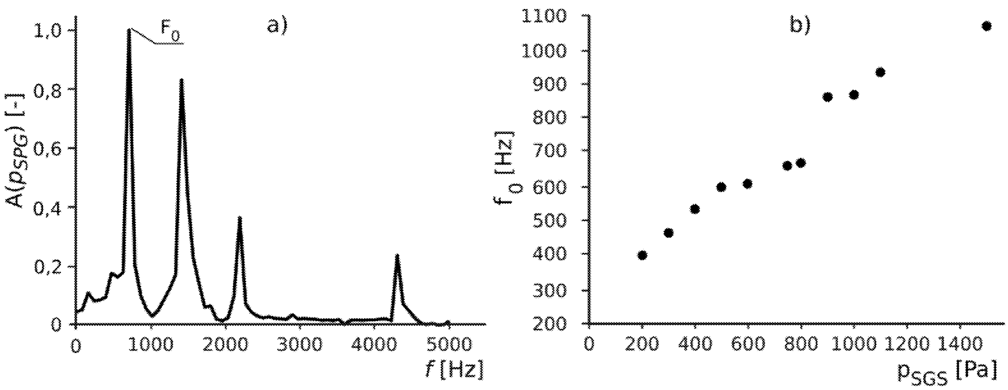

Fig.6: a) Frequency spectrum p_{SPG} for inlet pressure $p_{SGS} = 500\,Pa$
b) Dependence of the fundamental frequency f_0 on the inlet pressure p_{SGS}

3.3. g–p_{SG} characteristics

One of the most important characteristics in the theory of phonation based on the 'compressed air bubbles' [2], is $p_{SG}(t)$–g relationship which is suitable for quantitative comparison of individual voices. This characteristic is created from time solutions of the pressure $p_{SG}(t)$ and the gap $g(t)$ by plotting points in p_{SG}–g diagram at a corresponding time. Subsequent time steps are connected to the loop. Method of construction of p_{SG}–g diagram is shown by the bold loop in Fig. 7. The loop direction is indicated by an arrow.

These characteristics can be created for each of inlet pressures p_{SGS} (see Fig. 8). Results for $p_{SGS} = 800\,\mathrm{Pa}$ at each time step are plotted by dotted line in this figure. Other characteristics are for better clarity represented only by their convex envelopes. Moreover, for better clarity characteristics for $p_{SGS} = 200\,\mathrm{Pa}$; $300\,\mathrm{Pa}$; $800\,\mathrm{Pa}$ and $1500\,\mathrm{Pa}$ are plotted only.

4. Experimental model

Design and the production of the experimental model have been carried out in the line with the computational model's preparation (Fig. 9). Functionality and credibility of the computational model should be verified by this experimental model. The experimental model should be able to measure important quantities, which are necessary to plot the

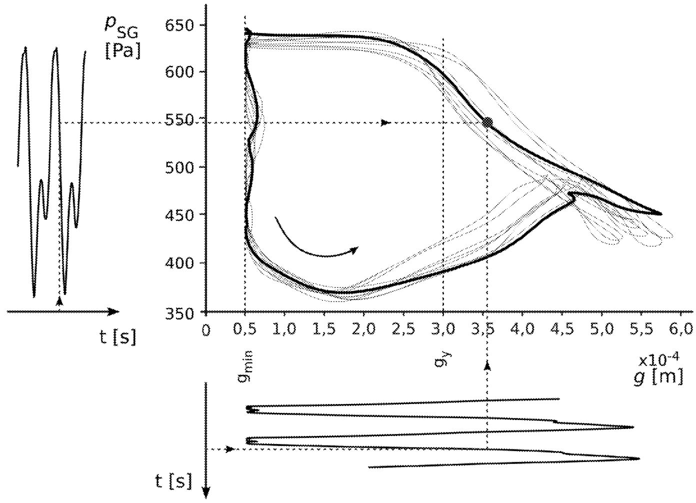

Fig.7: Method of g–p_{SG} diagram construction

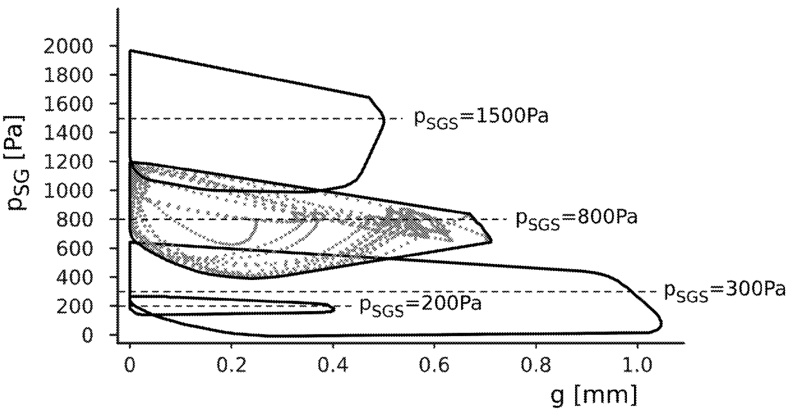

Fig.8: g–p_{SG} characteristic for selected inlet pressure $p_{SGS} = [200, 300, 800, 1500]$ Pa

p_{SG}–g diagram. Dimensions like length, width, material, size of the gap between the reed element and the stopper are alterable. Circular opening for pressured air connection has diameter of 14 mm. Static and dynamic values of subglottic pressure p_{SG} are able to be measured by this model too. Mean values of p_{SG} are measured by the U-tube manometer. Dynamical values of the p_{SG} are measured by the capacitor microphone, placed into input cavity through the opening in the model's surface (Fig. 9c). Model is made of aluminium alloy with the surface finishing treatment. In front side of the model is placed an optical eye-slit, which allows tracking the movement of the reed element (Fig. 9b).

Firstly, the model allows acoustical measurement, i.e. an acoustical pressure in exact location could be recorded. Processing and the evaluation of the signal are followed after measurement. Dependence of acoustical quantities on the model's geometry and on the air flow could be obtained by this measurement.

Secondly, model allows acoustical-optical measurement. It means behavior of the reed element could be followed by the high-speed camera. Data processing gives time based dependency of the reed element's position.

Finally, model allows the PIV (Particle Image Velocimetry) measurement. The velocity of the flow inside the fluid could by measurement by this way. Because of necessary model's modification, this method has not been applied yet.

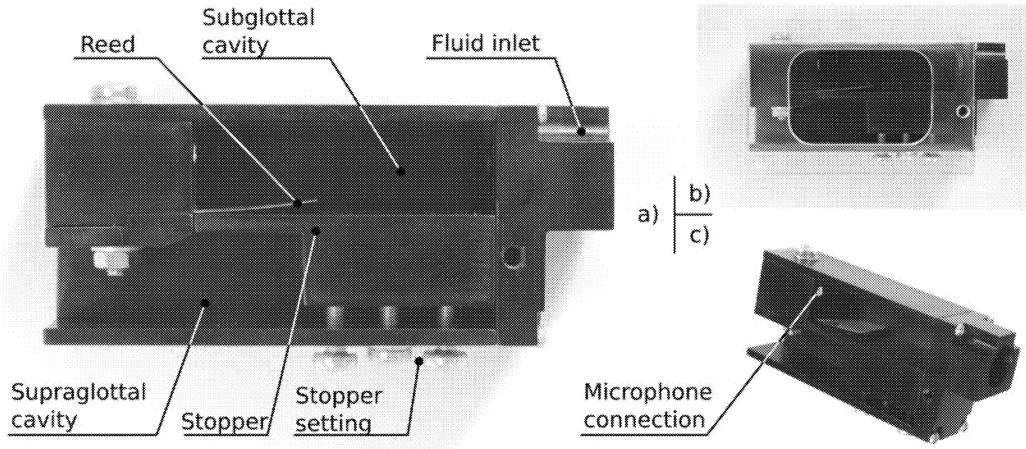

Fig.9: Experimental model

5. Discussion

Presented computational model's results are in many cases similar to characteristics of a healthy source voice, particularly the spectral composition of the output pressure p_{SPG}. It is obvious that the spectrum of generated source voice contains several high harmonic frequencies, which are important for vowels creating. Some of characteristics are different, particularly the dependence of the fundamental frequency f_0 on the input pressure p_{SGS}. In dependency on available information, the healthy source voice does not behave by this way. The fundamental frequency of the source voice is independent on the magnitude of the input pressure in lungs (f_0 configuration is set by a group of laryngeal muscles, which are changing position and the tension of the vocal folds).

The g–p_{SG} characteristic shows something interesting that deserves more attention and closer examination in the future. For the pressure $p_{\mathrm{SGS}} = 300\,\mathrm{Pa}$ is obvious, that the reed element model's response (deformation) is very significant. Deformation of the reed element is by far the largest in comparison with all pressure sets p_{SGS} measured on the model's input.

6. Conclusion

Presented results describe behavior of the reed-based element in the model's condition, which works as a generator of the source voice. The source of the energy is flowing air with input pressure p_{SGS}. Changes of the mean 'subglottic' pressure p_{SGS} of the reed-based element are studied. By comparison of characteristics, particularly fundamental frequency f_0–p_{SGS} and g–p_{SG} with the experimental model, the computational model will be improved in the future.

For the future application of the computational model in the alternative source voice's research, the trustworthy of the results is very important. For this reason improvement of the model is essential and obtained results should be compared with the experimental data in the future.

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