THE INFLUENCE OF BERNOULLI'S EFFECT ON THE FUNCTION OF THE VOCAL CORDS

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This research is a follow-up to the previous research which was dealing with the creation of the simulation of the vocal cords function using FEM. This paper focuses on how the vocal cords function is affected by Bernoulli's effect, while using model [1] is used. It is well known, that Bernoulli's effect is connected with the suction in the air space between the vocal cords. This is caused by the high air flow in glottis. The fastest and easiest way how to eliminate the influence of this effect is the change of every negative air pressure on the vocal cords to zero (i.e. the pressure applied as the loads on the vocal cords). Authors of some vocal cords models presume that Bernoulli's effect is the main force causing vocal cords vibrations. Changing the negative pressures to zero should cause that the vocal cords would not vibrate. However, the results of this research show the opposite.

Key words : *vocal cords, Bernoulli's effect, fluid-structure interaction, suction, frequency*

1. Introduction

People can produce a voiced sound owing to the vocal cords and that means that our speech depends on the vocal cords function. Vocal cords create the so-called source voice. This voice is identical for all vowels and in the vocal tract it is converted to a vowel we want to pronounce – the source voice is filtered by the vocal tract. The source voice is created by the vocal cords vibrations that alter the airflow running through them. At early stages of the research on vocal cords vibrations there were 2 major theories on how these vibrations are excited. The fact, that the nerve system excitation was proved as wrong, has made a presumption to create a model based on the fluid-structure interaction so that the vibrations of the vocal cords are excited by the air flowing through them.

This model is created and computed by using the computational software ANSYS 10.0 that contains both a structural and a fluid solver. Regarding the fact, that it is the only software used, the data from one solver to another can be transferred rapidly and without any serious problems. The possibility of writing command sequences, the so-called macros that are used to programme the whole computation, represents the next advantage of the ANSYS.

The Bernoulli's effect is very often considered as one of the main forces of the vocal cords vibration excitation. However, there are some doubts about this and a model of vocal cords function was created that is capable to prove this at an earlier stage so it was decided to find out how much is the Bernoulli's effect responsible for the vocal cords vibrations.

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2. Model of geometry

A planar model was used for computation, in which the vocal cords are symmetrical with three tissue layers that differ by their material characteristics. The air is simulated as a space with two cavities where supraglottal cavity is the one and subglottal cavity the second. The complete model of geometry used for this computation is in the Fig. 1. Both air and structure four-node elements were used for mesh generation. To be specific, it was the Fluid 141 element for air and the Plane 182 element for the structure in ANSYS. Material characteristic of the vocal cords were defined as follows:

- Epithelium (outer layer):
  - density: $\varrho = 1040\,\mathrm{kg/m^3}$,
  - Poisson's ratio: $\mu = 0.49$,
  - Young's modulus: $E = 25000\,\mathrm{Pa}$,
- Ligament (intermediate layer):
  - density: $\varrho = 1040\,\mathrm{kg/m^3}$,
  - Poisson's ratio: $\mu = 0.49$,
  - Young's modulus: $E = 20000\,\mathrm{Pa}$,
- Muscle (inner layer):
  - density: $\varrho = 1040\,\mathrm{kg/m^3}$,
  - Poisson's ratio: $\mu = 0.49$,
  - Young's modulus: $E = 17000\,\mathrm{Pa}$.

For air default values pre-set in ANSYS was used (density, viscosity) and 343 m/s was used as sound velocity. Air is considered as a compressible fluid and airflow is laminar.

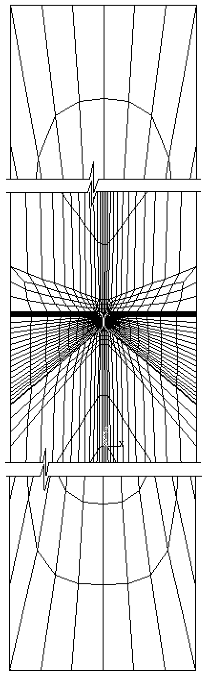

Fig.1: Mesh used for analysis

3. Applied model

First of all, two preparative computations must be done. The vocal cords must be brought together first, and then slightly pressed together. By this, the vocal cords are set to 'phonatory' position.

The main simulation of fluid-structure interaction is computed as a transient analysis with the time step $\mathrm{d}t = 0.00015\,\mathrm{s}$ and the number of these steps were considered to be 800. During this number of steps the steady vibration of the vocal cords is achieved. The interaction consists of three consequent analyses. The first one is the fluid analysis with the time step $\mathrm{d}t$ performed to obtain pressure of the air that influences the vocal cords motion. Then are these pressures applied as loads in the structural analysis, because the vocal cords are surrounded by air. This pressure causes deformation and displacement in time $\mathrm{d}t$. The third analysis is used to modify the air mesh to conform the changes in the structure. There exists an automatic remesh in the ANSYS, but it is not possible to use it in this case, because of its unreliability (even though latter version of ANSYS were markedly improved) and because there is little space between the vocal cords in contact, where the air is completely displaced. This would in not well-controlled mesh change produce its collapse. This simulation is schematically shown in a flowchart on the Figure 2.

4. Modification of the simulation model for our purposes

In principle, there is only one modification needed and it is the modification of the way how the pressures from air analysis are applied as loads onto the vocal cords. As stated above, the proof of the Bernoulli's effect influence on the vocal cords function is based on elimination of negative pressures on the vocal cords. To transfer the results (pressures) from fluid analysis to the loads in structural analysis, one ANSYS command is usually used. However, this cannot be used in our analysis. The computed pressures on nodes that are common for the fluid and structural mesh are stored in the matrix in the end of the fluid analysis (in every time step). Every negative value is in this matrix reset to zero and then these values are applied as loads on the vocal cords. This modification is schematically shown in Fig. 3 and 4. We can see original signal from the results of fluid analysis of this simulation there as well as the modified signal used as a load in the structural analysis (Fig. 3 is indeed result from this analysis, but it is connected with loads applying so it is necessary to mention it in this chapter). Both these signals are on the same node in the vocal cords contact – intraglottal pressure.

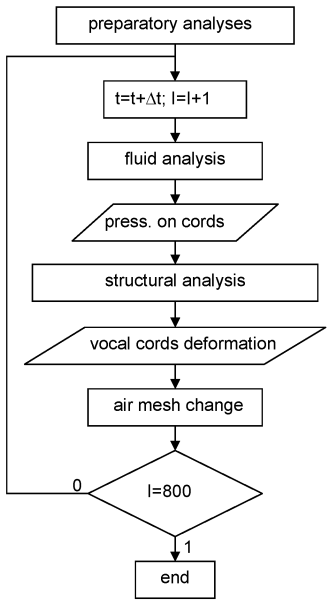

Fig.2: Flowchart of fluid-structure interaction

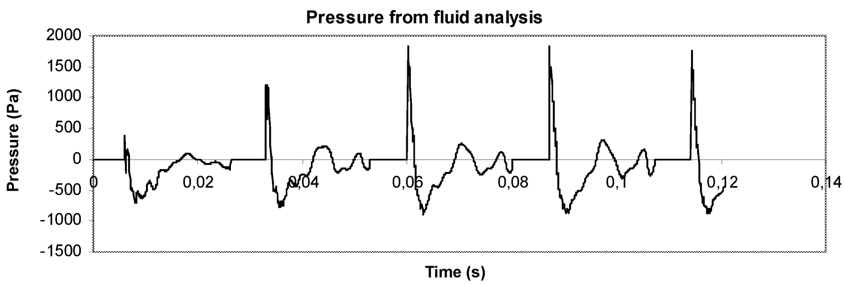

Fig.3: Pressure computed in fluid analysis

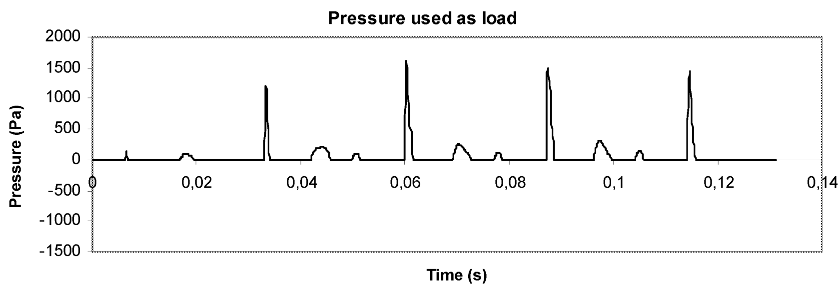

Fig.4: Pressure applied as load in structural analysis

5. Results

One result was shown in the previous chapter, where the modification of the pressure loads was shown. It is the intraglottal pressure in Fig. 3.

More important and illustrative is the comparison of the results computed by the classic simulation, i.e. by the computation, where negative pressures are included, and the results are computed by simulation, in which the negative pressures were replaced by zero. These results are shown for 2 different intensities of one frequency and for 2 different frequencies with the same intensity.

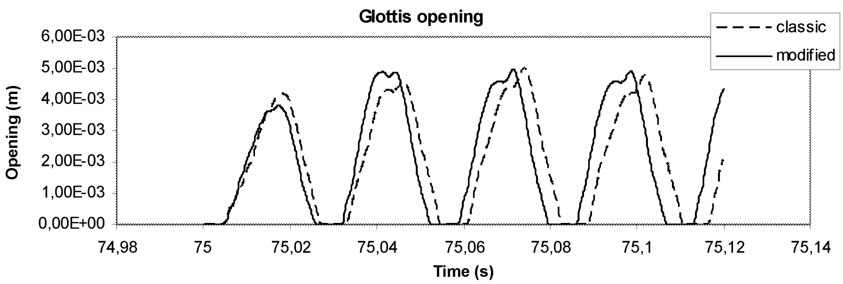

Fig.5: Graph of glottis opening, $f = 36\,Hz$

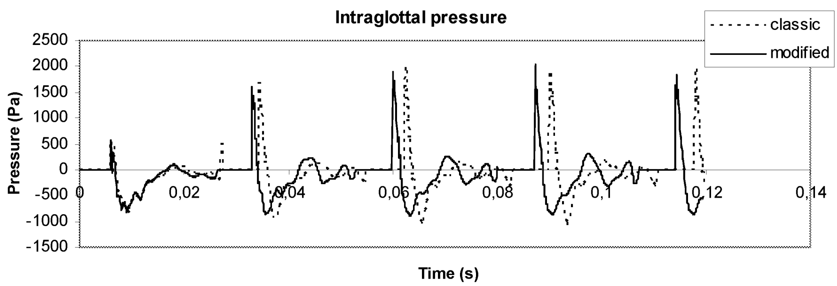

Fig.6: Graph of intraglottal pressure at $f = 36\,Hz$

In Fig. 5 and Fig. 6 we can see the results from simulations where the frequency is approximately 36 Hz. This frequency is very low and it is not possible to speak with such frequency, but that is not a problem for our purpose. On the graph in Fig. 5 a glottis opening for a classical simulation and for a modified simulation are illustrated in comparison. On the graph in Fig. 5 there are intraglottal pressures for both simulations. We can see differences between the simulations on both graphs. Signals on graphs start at the same point, and after the start of the first opening we can see there, that these signals start to differ from one another. There are not big differences in amplitudes, but we can clearly see the difference between the periods of signals from the classical and modified simulation there. This means, that the frequency of classic simulation is different from the modified simulation. Namely, the frequency of the classic simulation is lower.

From the simulations with higher intensity and higher frequency from the following results we can see the same differences as in Fig. 5 and Fig. 6, i.e. difference in frequencies and some difference in amplitudes.

6. Conclusion

The software ANSYS can be used with advantage for the simulation of the processes of the fluid-structure interaction. Moreover, it is possible to modify the parameters of simulation automatically by using the command macros. These potentials were used to simulate the vocal cords function.

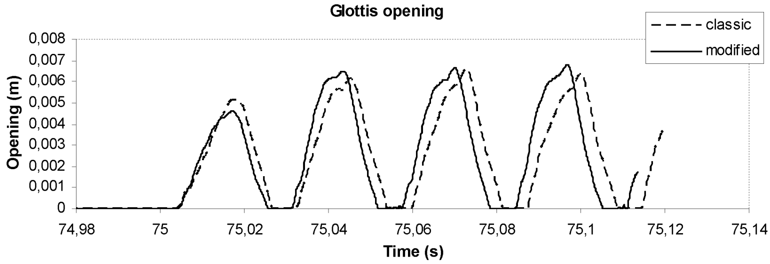

Fig.7: Graph of glottis opening with higher intensity

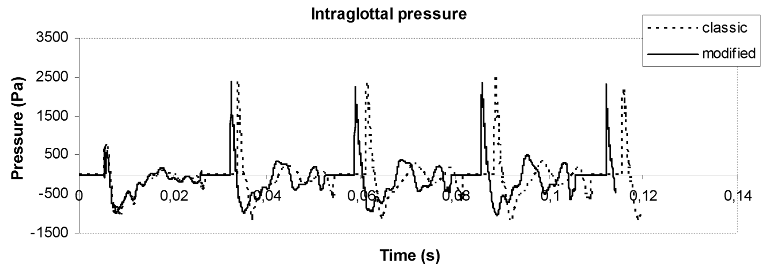

Fig.8: Graph of intraglottal pressure with higher intensity

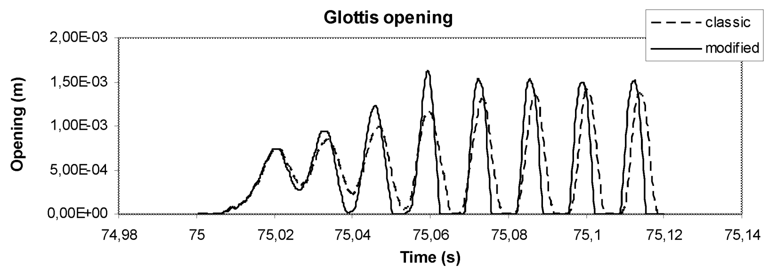

Fig.9: Graph of glottis opening with higher frequency, 73 Hz

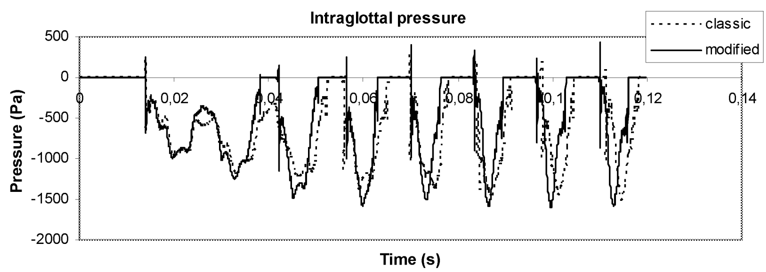

Fig.10: Graph of intraglottal pressure with higher frequency, 73 Hz

Modification used in the simulation is not the exact Bernoulli's effect elimination, it would be better to call it elimination of negative pressures. The reason for it is that by this modification the negative pressures that are not connected to Bernoulli's effect are eliminated too, e.g. negative pressures from air vibrations. In principle, the simulation can be done this way.

By a close look on the results we can see, that the biggest difference is in the change of the frequency of the vocal cords vibration and thereby in the frequency of the air vibration. The frequency of the vibrations in the modified simulation is higher than in the classical simulation. This conclusion is well illustrated on the graph of glottis opening and on the graph of intraglottal pressure. In Figures 7 and 9 we can also see, that there is a little difference in amplitudes of the glottal opening. Again, the amplitude of the opening computed by the modified simulation is slightly higher than the opening from the classic simulation. From these results we can make a conclusion that the suction, caused mainly by the Bernoulli's effect, contributes to the damping of the vocal cords vibrations. Thus the Bernoulli's effect cannot act as one of the main forces exciting the vocal cords vibrations.

It is necessary to state that these conclusions are made for simulations with low frequencies of vocal cords vibrations and research must continue on simulations with higher frequencies where Bernoulli's effect can have bigger influence on vocal cords vibrations because the intraglottal pressure is almost always negative – as we can see in Fig. 10.

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