Method and Device for Researching and Diagnostics of Respiratory Diseases

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Abstract: - Researching of dynamics process of breathing is presented. There are three branches of the researching. It’s solid 3D model, virtual 3D model, and sensor device. Method and device for diagnostics of the respiratory diseases are designed according to the results of the modeling. The innovation of this device is that sensors are placed directly into nasal cavity without using tubes and masks. The method of diagnostic is based on the idea of studying the breathing as a dynamic process.

Key-Words: - study of breathing, respiratory diseases, virtual model, solid model, sensor device, nonlinear dynamics, NARMAX

1 Introduction

Behavior of the studied objects can be investigated in more details by the research of the dynamic processes. The term “dynamic” is often interpreted not in terms of the passing of the test process, as, for example, of the possibilities of the sensors used in the measurements.

This information can be used to refine existing models of the processes and, in turn, allows better understand the evolution of the processes.

Everybody can agree that breathing is a dynamic process. However, it is necessary to define in what context the term “dynamic” is used. Widespread and applied research methods often deal with the rhythm of breathing and with some averaged characteristics. Studies realized by as indicate that the information on the faster process, allows more accurate assessment of the human condition. These processes include for example the information of air vortices in the sinuses and at the vestibule of nose. Sensor, based on high-response rate is presenting. The miniature temperature sensors are the basis of this sensor.

2 Problem Formulation

Breathing is a complicated dynamic process. Inside the nasal cavities observed turbulent vortices and laminar flows. The study of the dynamic process of respiration requires development a sensor device. We have also developed a virtual model of respiratory system (nasal cavities) and 3D solid model for approbation sensor.

2.1 Method and Device

The sensor [1] is designed for measuring rapid fluctuations of temperature, pressure and velocity of air flow at the vestibule of nose (in nostrils). Now we use the sensor now with slight modifications. The basic requirements for the created sensor were – to receive the lowest possible distortion of air flow and to have response to extremely fast changes in temperature, pressure and velocity. The device has two miniaturized and highly sensitive temperature sensor and two miniaturized and highly sensitive pressure sensor. The air flow velocity is not measured at present time. Previous studies have shown that the curves of fluctuations of temperature, pressure and air velocity repeat each other, therefore, it is not required to measure directly all
the parameters to perform diagnostics. In principle, one parameter is enough for the diagnosis. Thermocouple wires (diameter of 0.08 mm) and a shunt tubes to pressure sensors (0.5 mm diameter) placed on the diagnostic clip sensor device. The signals of the sensors are supplied to the amplifier and then to the multi-channel device data acquisition National Instruments.

The basis of diagnosis is methods of nonlinear dynamics:
- calculation correlation sum, \( C(\varepsilon) \), correlation dimension, \( D_2 \), and the correlation entropy, \( K_2 \):

\[
C(\varepsilon) = \lim_{m \to \infty} \frac{1}{m^2} \sum_{i,j=1, i \neq j}^{m} H\left(\varepsilon - \|x_i - x_j\|\right)
\]

(1),

\[
H = \begin{cases} 
1, & \varepsilon - \|x_i - x_j\| \geq 0; \\
0, & \varepsilon - \|x_i - x_j\| < 0 
\end{cases}
\]

(2),

\[
D_2 = \lim_{\varepsilon \to \infty} \frac{\log C(\varepsilon)}{\log \varepsilon}
\]

(3),

\[
K_2 = \lim_{\tau \to 0} \lim_{\varepsilon \to \infty} \lim_{ED \to \infty} \log \left( \frac{C_{ED}(\varepsilon)}{C_{ED+1}(\varepsilon)} \right)
\]

(4),

where, \( H \) - Heaviside step function, \( \varepsilon \) - diameter of volume elements covered an attractor, \( x_i \), \( x_j \) - points in some metric space with distances \( \|x_i - x_j\| \) between any pair of points, \( C_{ED}(\varepsilon) \) - correlation integral of embedding dimension;
- calculation of power spectral density through the discrete Fourier transform;
- attractor reconstruction from time series data.

The sample measurements of sensor and the calculation results are given in the Problem Solution section below. We have also measured the EKG simultaneously with measurements of respiratory parameters. These measurements allowed us to determine the relationship between the respiratory rhythm and ECG rhythm [2].

2.2 Virtual 3D Model

Virtual 3D model is designed to simulate the air flow inside the nasal cavity. The geometric shape recovery in the model was performed by using the software package Mercury Amira. The allocation of borders "entrance", "exit", "wall" was made with a software package Altair Hypermesh. The reconstruction of the finite element computational grid was made by using a software package Ansys Icem CFD.

The model basic requirements are to preserve of breathing rhythms in the extreme and to observe internal vortex motion of the air flow in the nasal cavity. For this goals we applied the derivative Detached Eddy Simulation model (DES-model) [3]. Nonstationary calculation is first performed. The feature of the model is to preserve all of the information about the high-frequency pulsations of the studied variables when filtering by the field of space. The mathematical formula of the filtration velocity of vector field \( \mathbf{u}(x, t) \):

\[
\mathbf{u}(x, t) = \int G(r, x) u(x - r, t) \, dr
\]

(5),

where, \( G(r, x) \) - filtered operation, the width of which is correlated to the size of the computational grid.

In this computational model the volumetric irregular grid was given from 1,5x10^7 tetrahedral finite element. In the model the following boundary conditions were set:

\( \Delta P = 0 \), \( T = 293K \), - for the vestibule of nose area ("entrance");

\( V_x = V_y = V_z = 0 \), \( T = 310K \), - for internal surface of nose canal ("wall");

\[
\begin{cases} 
P = 50 \cdot \sin \left( \pi \left( 1.18 \tau + 0.5 \right) \right) & - 50 \to \tau < 1.7c \\
P = 50 \cdot \cos \left( \pi \left( 0.87 \tau + 0.5 \right) \right) & + 50 \to \tau > 1.7c 
\end{cases}
\]

\( T = 310K \)

for nasopharynx ("exit").

2.3 3D Solid Model

The detailed description of the 3D solid model is given in [4]. The 3D solid model was made by using 3D printer technology by the results of multislice computer tomography. For measurement airflow vortices we used pressure sensors. The shunt tubes (diameter of 0.5 mm) from the pressure sensors were placed in the following parts of the 3D solid model of the nose:

2 - in the area of left and right vestibule of nose;
2 - in the area of left and right maxillary sinus;
6 - at ethmoidal labyrinth (front, middle, posterior left and right area);
2 - in the area of left and right frontal sinus;
2 - in the area of left and right sphenoid sinus;
2 - in the area of left and right common nasal passage.
Altogether 17 pressure sensors were applied. All sensors through the reinforcing elements were connected to a multi-channel National Instruments Data Collector.

2.4 NARMAX-Model
The general description of the processes studied can be performed in compressed form diagnosed data storage. For this method NARMAX (Nonlinear Autoregressive Moving Average with eXogenous Inputs) [4] revealed the characteristic parameters of the model - the degree of the polynomial and the time delay which allows to restore the model.

3 Problem Solution
Sensor for measuring rapid fluctuations of the parameters of breathing is presented on the Fig.1.

![Sensing device and gain block](image)

Fig.1. Sensing device and gain block
The typical results of measuring made with it are shown in the Fig.2 and Fig.3. For example, the results of measuring the air flow velocities for healthy person and for patient with asthma in the vestibule of nose are in Fig.2. As you can see in the picture, patient with asthma has more chaotic rhythm of breathing.

The results of measuring this sensor at vestibule of nose carried parallel with measurement of heat rate are shown in Fig.3. The measurements have shown the synchronization of rotational speed of air vortices with the frequency of R-prong on the cardiogram.

The results of data processing as a dynamical chaotic process in packet of mathematical modeling MATLAB are shown in Fig. 4 and Fig.5.

![Results of measuring velocity fluctuations of air flow in the vestibule of nose: a – for healthy person; b – for asthma patient](image)

Table 1 shows the results of calculating the correlation dimension and the correlation entropy for the group of patients with upper airways diseases.

<table>
<thead>
<tr>
<th>Patient</th>
<th>Correlation dimension before treatment</th>
<th>Correlation dimension after treatment</th>
<th>Correlation entropy before treatment</th>
<th>Correlation entropy after treatment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Patient1</td>
<td>2.22</td>
<td>2.09</td>
<td>0.36</td>
<td>0.32</td>
</tr>
<tr>
<td>Patient2</td>
<td>2.05</td>
<td>2.05</td>
<td>0.34</td>
<td>0.38</td>
</tr>
<tr>
<td>Patient3</td>
<td>2.19</td>
<td>2.10</td>
<td>0.38</td>
<td>0.35</td>
</tr>
<tr>
<td>Patient4</td>
<td>2.34</td>
<td>2.09</td>
<td>0.42</td>
<td>0.33</td>
</tr>
<tr>
<td>Patient5</td>
<td>2.21</td>
<td>2.08</td>
<td>0.36</td>
<td>0.35</td>
</tr>
<tr>
<td>Patient6</td>
<td>2.15</td>
<td>2.08</td>
<td>0.39</td>
<td>0.40</td>
</tr>
<tr>
<td>Patient7</td>
<td>2.18</td>
<td>2.08</td>
<td>0.39</td>
<td>0.33</td>
</tr>
<tr>
<td>Patient8</td>
<td>2.20</td>
<td>2.09</td>
<td>0.25</td>
<td>0.26</td>
</tr>
<tr>
<td>Patient9</td>
<td>2.33</td>
<td>2.11</td>
<td>0.40</td>
<td>0.27</td>
</tr>
<tr>
<td>Patient10</td>
<td>2.23</td>
<td>2.16</td>
<td>0.26</td>
<td>0.34</td>
</tr>
</tbody>
</table>
Fig. 6 shows the measurement of the process and the model of this process recovered by NARMAX methods.

The results of computer simulation with using the virtual 3D Model are shown in Fig. 7.

In Fig. 8 you can see the solid 3D model. Results of pressure fluctuations in the vestibule of nose and in the solid 3D model are shown in Fig. 9.

Fig. 3. Synchronization of rotational speed of air vortices in the vestibule of nose with the frequency of R-wave on the cardiogram

Fig. 4. Power spectral density for fluctuation of air flow vortex in the vestibule of nose: a - for healthy person; b – for asthma patient

Fig. 5. Reconstructed attractor for fluctuation of velocity of air flow vortex in the vestibule of nose: a - for healthy person; b – for asthma patient

Fig. 6. Results of NARMAX model, there the blue is the fluctuation of temperature during the motion of air flow in the vestibule of nose, the red is the NARMAX model of this process
4 Conclusion

Application of tiny high-speed sensors allows to receive essential information about the studied process and it is better to understand its behavior at fast changes of conditions. For deeper understanding, it is also necessary to apply various models, to specify them on the basis of comparison to results of measurements. Among such models there can be numerical computer models, natural models, and also dynamic models.

References: