Acoustic devices for breathing investigations

Semyon Shkundin, Valentina Rumyantseva
National Investigation Technical University,
Electroengineering and InfoSystems dpt.,
Moscow, Russia;
shkundin@mail.ru; rumyanceva_v@mail.ru

***Abstract*— The problem of spirometry control in medicine and medical engineering still remains urgent. The necessity of getting more and more information from spirometry investigations imposes more and more stringent requirements for spirometers, volumeters and bodypletizmographs, first of all, to the primary spiroflow transdusers. Practice shows that these requirements can not be met by improving devices which use conventional spirometric principles. The new acoustic means for pulsating air-gas flow rate measurement has been created in Russia and is described in the paper. The main feature - special air-metric channel, supplied with ceramics electro-acoustic transducers. The principle of its operation is based on the dependence of the velocity of the acoustic vibrations arriving at the receiver upon the air-gas velocity. The device does not disturb the air dynamic structure of the flow, has no inertia or moving elements and unsurpassed sensitivity and precision.**

Keywords — Acoustic waves; in channel media; spiroanalyser; breathing; flow rate; measurement; air-gas velocity; microprocessor.

I. Introduction

Currently, there is an increase of the number of persons registered for the first time in connection with respiratory diseases. The increased incidence is largely due to the progressive deterioration of the ecological state of the environment. The growth of cities and industrial areas cause pollution in local streams, rivers and airspace. High morbidity associated with the respiratory system, is a priority problem in health care and medical science.

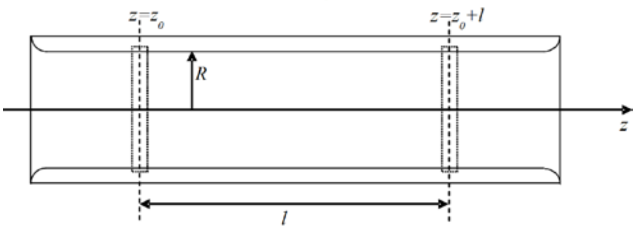

Fig. 1. Acoustic sensor spirometer.

The main causes of COPD (chronic obstructive pulmonary disease) are smoking, industrial dust and gases, adverse environmental conditions. The danger of this disease lies in the fact that the formation of irreversible effects starts long before the first symptoms. Due to the fact that COPD develops slowly, it is frequently diagnosed in people aged 40 years and older. Experts in the field of health care strongly recommend that everyone go through the simple procedure - spirometry. If the result shows the lung disfunction, you should consult with your doctor about methods of prevention and treatment of chronic obstructive pulmonary disease. The main requirements to modern spirometers and methodics they have to support: low inertia, precision, low flow resistance. The measurement of volumes and characteristics of the exhaled and inhaled air can be implemented in different ways, based on variety of methods.

Acoustic method for the rate of air flow measurement has several advantages comparatively to other methods: the precision, reliability, low inertia, no moving parts and obstacles for the air flow in the sensor, relatively low cost. Traditionally, the disadvantages of the technique is the dependence of the readings on the speed of sound. However, currently, with the development of computer and microprocessor technologies it became possible to process the sensor information and eliminate the speed of sound error at each step of measurement with the help of specially developed algorithms. Therefore, the development of such algorithms is an actual scientific-technical problem. The creature of them requires a description of the velocity field and the aeroacoustic interaction in the channel that makes the tasks of modeling and description of the physical processes underlying the acoustic measurement method of flow velocity implementation.

In this simulation, the authors solved a number of aerodynamics and acoustics problems, allowing to model and then, as a result of researches, to create new devices plague level with unmatched performance.

II. Modeling acoustic interaction with a homogeneous flow

Acoustic spirometer needs to have such properties as reliability, low inertia, accuracy, a wide dynamic range. At the National Investigation Research University under the leadership of prof. Shkundin S. Z. the number of spirometric acoustics devices has been developed [1].

The acoustic sensor of the spirometer is a cylindrical wave guide-air duct with built-in wall piezoelectric transducers, which are alternately in time are transmitter or receiver of acoustic waves. According to the phase difference of acoustic signals, propagating along and against the air flow, one can determine its speed. This can be shown in a simple model of propagation of a plane wave in a homogeneous flow in unlimited space.

However, in reality it's not so simple. Acoustic field in the spirometric channel is a complex wave pattern that can be approximately described with the help of basic system of aerohydrodynamics equations with boundary conditions defined by parameters of the waveguide and the used approximation. In the case of homogeneous flow the acoustic field potential and the system of hydrodynamics can be reduced to the wave equation (1) with respect to the acoustic potential.

We introduce a cylindrical coordinate system z-axis which is the axis of symmetry of the cylindrical wave guide-air duct (Fig. 1). If we ignore the reflections of the acoustic wave from the open ends of the waveguide, using the approximation of a cylindrical waveguide with infinite lengths.

A. An infinite cylindrical waveguide

Rationale for acoustic measurement of air velocity methods was given by Skundin S. Z. [2] using the results of theoretical work [3]. He has solved the problem of acoustic waves in infinite cylindrical waveguide with perfectly rigid walls propagation description with an annular source of acoustic oscillations in the presence of uniform flow. The system of hydrodynamics for an ideal environment equations allows to get the wave equation in a uniform form.

$$-\frac{1}{c^2}\frac{\partial^2\varphi}{\partial t^2}-\frac{2M}{c}\frac{\partial^2\varphi}{\partial z\partial t}+\Delta\varphi-M^2\frac{\partial^2\varphi}{\partial z^2}=0 \qquad (1)$$

Here φ – acoustic potential ($\vec{v}'=\nabla\varphi$; $p'=-\rho_0\frac{\partial\varphi}{\partial t}-\rho_0(\vec{V}\nabla)\varphi$), c - the adiabatic speed of sound, M - Mach number, where are $\rho(\vec{r},t), \vec{v}(\vec{r},t), p(\vec{r},t)$, respectively, density, velocity, pressure, characteristics of the environment, as a function of position $\vec{r}$ and time t. They are represented as the sum of a constant and a variable component:

$$p=p_0+p', \rho=\rho_0+\rho', \vec{v}=\vec{v}'+\vec{V}.$$

The solution of the wave equation (1) with boundary conditions (2):

$$\frac{\partial\varphi}{\partial r}\Big|_{r=R}=\begin{cases}V_0\exp(i\omega\cdot t), & |z-z_0|\le h/2\\ 0, & |z-z_0|>h/2\end{cases}, \qquad (2)$$

the corresponding infinite waveguide with perfectly rigid walls and a source of acoustic oscillations in the form of a ring located at the origin has the form:

$$\phi_{\pm}(r,z)=\sum_{n=0}^{\infty}\frac{-2V_0 i\cdot\sin\left(\frac{kM\mp\sigma_n}{\beta^2}\cdot h\right)\cdot J_0\left(\frac{\mu_n r}{R}\right)\cdot\exp\left(i\cdot\frac{kM\mp\sigma_n}{\beta^2}(z-z_0)\right)}{\frac{kM\mp\sigma_n}{\beta^2}\cdot R\cdot\sigma_n\cdot J_2(\mu_n)\cdot\theta_n}$$

(3)

where $sn_n=\frac{kM+\sigma_n}{\beta^2}$, $sp_n=\frac{kM-\sigma_n}{\beta^2}$,

$$\sigma_n=\begin{cases}\sqrt{k^2-\beta^2\frac{\mu_n{}^2}{R^2}} & n\le M_2\\ -i\cdot\sqrt{\beta^2\frac{\mu_n{}^2}{R^2}-k^2} & n>M_2\end{cases},$$

$$\theta_n=\begin{cases}2 & n=0\\ 1 & n\ne 0\end{cases}, \beta=\sqrt{1-M^2}, k=\frac{\omega}{c}.$$

Decision: $\varphi_{\pm}(r,z,t)=\begin{cases}\phi_+(r,z)\exp(i\omega t) & z-z_0\ge 0;\\ \phi_-(r,z)\exp(i\omega t) & z-z_0<0;\end{cases}$, it was obtained the solution as a sum of normal modes – harmonic components propagating in the waveguide when $n\le M_2$ and exponentially damped $n>M_2$. M_2 – the number of the last propagating fashion.

B. A cylindrical waveguide of finite size

Acoustic wave propagating from the source along the axis of the waveguide, is reflected from its edges. The reflected

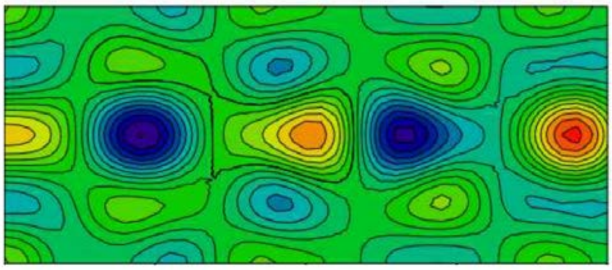

Fig. 2. The acoustic potential at a fixed time. A fragment of the infinite waveguide

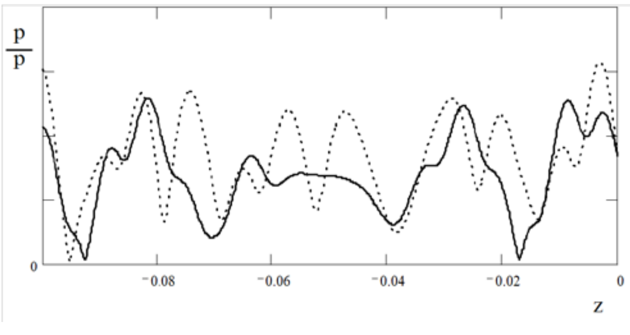

Fig. 3. The amplitude of the acoustic pressure on the wall of the waveguide.

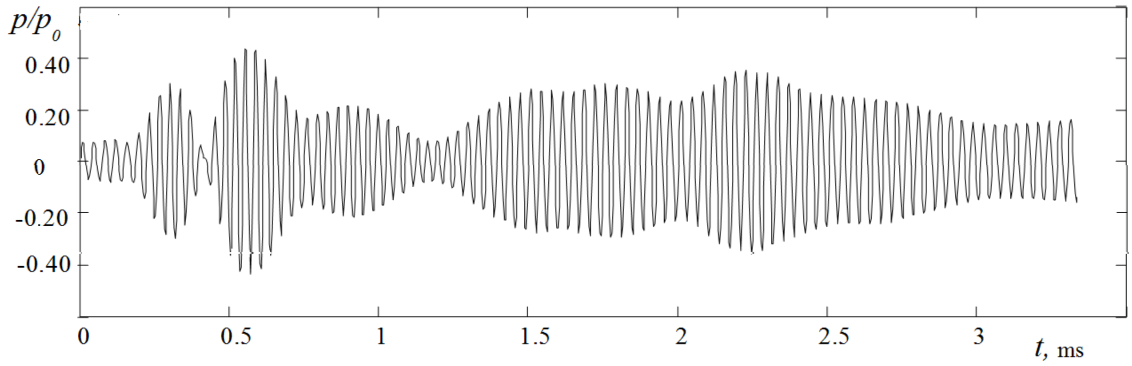

Fig. 4. The propagation of a pulse in the anemometer channel based on two reflections.

wave, flowing into a straight line, form a standing wave. Thus, the wave field in a waveguide of finite length is the sum of running from source, and standing waves. As an informative parameter of acoustic anemometer is a phase, it is important to track the impact of reflections on phase of the received signal.

The problem of propagation of acoustic waves in a uniform flow in a waveguide of finite length was solved by S.Z. Shkundin method of Wiener-Hopf [4]. The walls of the waveguide were assumed to be infinitely thin. When the solution was used the results obtained by Johnson and Ogimoto [5] for an elementary source. In our case, the source was modeled as a synchronously oscillating ring. The same problem was solved later O. A. Kremleva [6] the method of the generalized scattering matrix, by analogy with works [7], where we consider the case of the medium without flow. The coefficients of reflection and transformation at the edges of the waveguide in this case was calculated by the method of crosslinking.

The problem of wave propagation in a channel with walls of finite length and thickness was solved Rumyantseva V.A. [8, 9] the method of the generalized scattering matrix. The coefficients of reflection and transformation was calculated by the method of Wiener-Hopf, as the decision about the propagation of waves in semi-infinite waveguide, by analogy with the work of Ando [10], where a similar problem is solved for environments without thread for channel cut-off diameter.

Figure 3 shows graphs of the distribution of amplitude of acoustic oscillations along the axis of the anemometer channel. The dotted line is the graphics for the waveguide with infinitely thin walls, solid for a waveguide with walls of finite thickness, with rectangular flanges. The vertical axis represents the pressure in relative units (relative to the pressure amplitude at the emitter). The graphics are designed for the following values of parameters [11]: a_1=1.7 cm (external radius) R=a_2=1.4 cm (inner radius) l =10 cm (base length), $z_0 = -7$ cm, $\omega = 2\pi\, 30$ kHz, c = 343 m/s, h = 3.5 mm.

C. *Simulation of the sensor of acoustic anemometer with pulse mode radiation*

From the graph shown in figure 3 it can be seen that the reflection have a significant impact on the field in the waveguide, and the case walls, small but finite thickness differs from the case of infinitely thin significantly. It turns out that the field in the waveguide is the superposition of many comparable components, so consideration of all the factors significantly affecting the phase of the received signal, in the theoretical model is rather complicated. Therefore an instrument that uses a pulsed irradiation mode developed. This method allows to separate in time different fashion and reflection and in a certain time range only work with one of the normal modes.

Theoretical justification and calculation of parameters of such devices was carried out by Buyanov S. I. [12]. Model of the propagation of acoustic pulse in a cylindrical waveguide was obtained using the Fourier method. The simulation result of the received signal in a pulsed mode, taking into account the double reflection shown in figure 4. In this model the walls of the waveguide was considered to be infinitely thin and hard. The remaining parameters correspond to the real sensor.

III. Modeling Acoustic Interaction with Non-Uniform Flow

Acoustic spirometer should have a broad dynamic range, spanning both turbulent and laminar flow regime of the air. If in the turbulent regime, at higher speeds, we can plot the average velocity in the pipe is approximately regarded as flat, for small speeds, for laminar regime this condition is not met. To account for the characteristics of aeroacoustic interaction associated with the heterogeneity of the flow Petrov and A.G. Rumyantseva, V.A. [13, 14], a model was developed that takes into account the flow having a parabolic velocity plot. In this case, to calculate the shape of the velocity used in the Navier-Stokes equation taking into account viscosity of air. However, when calculating the acoustic field viscosity can be ignored because its rate is small comparatively with the Mach number, which is the magnitude of the first order of smallness in our equations. Taking into account the heterogeneity of the flow velocity field is no longer a potential, therefore, for its description we need not only the scalar potential and vector, which in our case, due to the cylindrical symmetry has one component – a function of current.

Substitutable component particle velocity the following expression:

$$v_z = \frac{\partial\Phi}{\partial z} + \frac{1}{r}\frac{\partial\Psi}{\partial r}, \quad v_r = \frac{\partial\Phi}{\partial r} - \frac{1}{r}\frac{\partial\Psi}{\partial z},$$

After a series of transformations, we obtain the system of equations (4-7) to describe the acoustic field in non-uniform flow relative to F , where F is some auxiliary function, introduced for computational convenience.

$$\left(\frac{\partial}{\partial t} + u\frac{\partial}{\partial z}\right)\left(\frac{1}{r}\frac{\partial^2\Psi}{\partial r^2} - \frac{1}{r^2}\frac{\partial\Psi}{\partial r} + \frac{1}{r}\frac{\partial^2\Psi}{\partial z^2}\right) - 4\bar{u}\frac{r}{R^2}\Delta\Phi = 0 \tag{4}$$

$$\frac{\partial}{\partial t}\Phi + u\frac{\partial\Phi}{\partial z} + c^2\tilde{\rho} + F = 0 \tag{5}$$

$$\left(\frac{\partial}{\partial t} + u\frac{\partial}{\partial z}\right)\tilde{\rho} + \Delta\Phi = 0 \tag{6}$$

$$\frac{\partial F}{\partial z} = \frac{\partial u}{\partial r}\left(\frac{\partial\Phi}{\partial r} - \frac{1}{r}\frac{\partial\Psi}{\partial z}\right) + \left(\frac{\partial}{\partial t} + u\frac{\partial}{\partial z}\right)\frac{1}{r}\frac{\partial\Psi}{\partial r} = 0 \tag{7}$$

It was obtained the solution of this system in the linear approximation on the Mach number. This gave the opportunity to compare the theoretical phase characteristic based on the phase of the received signal from flow velocity averaged over the cross section, for rectangular and parabolic plots of the speeds.

IV. Numerical simulation of flow structure in a waveguide of finite size.

In the previous section velocity was assumed constant along the z-axis. This assumption is true for very long pipes, in the approximation of an infinite waveguide. Spirometric channel has usually a length of only 4-5 times greater than the diameter. Therefore, the structure of the stream curve has no time to set. For its description Vorontsov A.V. [15] developed a numerical model that takes into account the real shape of the anemometer sensor. The model was built in Solid Works.

Figure 5 shows the velocity in the center of the waveguide. It is seen that at low speeds approaching a parabolic curve, and at high speeds there is a flat plot. The model allows to

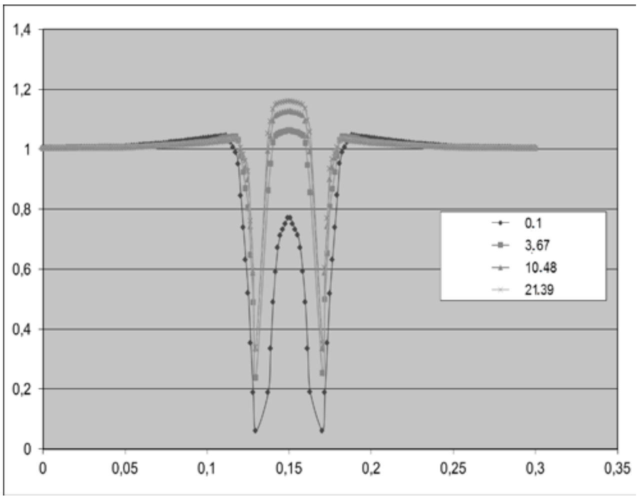

Fig. 5. Normalized plots for the four speeds.

quantitatively assess the validity of assumptions about idealized plots.

V. Conclusion

The results of modeling of aeroacoustic interaction in spirometric channel help to explain the phase method of measuring the speed of the air flow, and also to consider the impact on the operation of the device the most significant factors. The use of theoretical models in the development of payment methods and eliminate various errors will help to improve the accuracy of measurement of costs and volumes of exhaled and inhaled air, and consequently to improve the diagnosis of pulmonary diseases using spirometry.

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