

Turbine Spirometers Metrological Support

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Abstract — This article deals with the description of the device and principle of the turbine spirometer action. Mathematic model of the rotation of the rotor of the measuring turbine is shown. According to the results of the turbine research the method of determine the coefficients of the conversion function is proposed. In this paper experimental studies of the proposed method are conducted. Research results have shown the adequacy of the description of the transformation function and methods for determining the coefficients.

Keywords — medical equipment; turbine spirometer; metrological control; measurement error.

I. INTRODUCTION

Modern medical diagnosis equipment should not only have high medical and technological performance, that is achieved mainly using effective methods of monitoring biomedical parameters of a patient with the use of modern element base of microelectronics and computer technology, but also provide a sufficiently high metrological indicators of the measured parameters.

Features of metrological control of diagnostic devices and required level of measurement quality of biomedical parameters are defined by number of normative and technical documents [1–3]. The measurement error of the basic parameter setting and its stabilization in time are among of the main parameters of the diagnostic devices.

Currently, the digital turbine spirometers (DTS) are widely used for the diagnosis of patient's respiratory function (PRF). That is due to their relatively high medical and technological parameters. These devices have good transducer dimensions and weight indexes, sufficiently high sensitivity and noise immunity, low pneumatic resistance of the measuring turbine (MT) (about 25–50 Pa·l/s at a flow rate of 10 l/s) and their time constant is less than 1 ms, and their production costs are relatively low [4].

However, ever-increasing quality requirements for measuring parameters of the patient's respiratory organs necessitated the improvement of methods previously used in the evaluation of the measurement errors of the main parameters of PRF.

The aim of this work is to improve the quality of patient measurement PRF parameters by improving the methods of metrological control of the digital turbine spirometer. For this method was proposed for determining the coefficients of transformation, based on the development of a mathematical model of the measuring rotor of the turbine, and then using them in determining the parameters of PRF.

II. THE MAIN FEATURES OF THE CONSTRUCTION DTS

To solve this problem we have been considered the main features of the construction of the digital turbine spirometers. In general, the turbine air flow transducer (TAFT) is a device that converts the flow of air into the rotation of the rotor and then to the electrical output signal. Block diagram of measuring channel of a modern spirometer based on the turbine flow transducer is shown in Fig. 1.

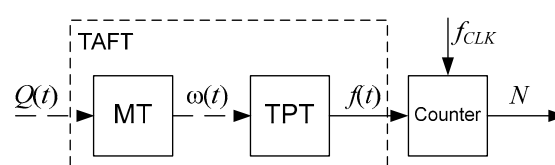


Fig. 1. Measuring channel of spirometer based on TAFT.

The measuring turbine (MT), which is shown in Fig. 2, is used as the primary air flow converter. It converts the volumetric rate of air $Q(t)$ into the rotor angular velocity (t). The secondary sensor is a tachometric photoelectric transducer (TPT) which converts the rotation of the plate into the electrical signal with the frequency $f(t)$ that is proportional to $f(t)$.

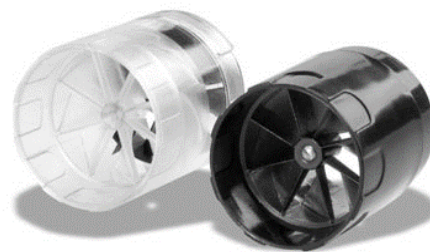


Fig. 2. Measuring turbine.

However, the TAFT usually has a low accuracy of measurements due to the linear representation of the conversion function in the whole range of air velocity measurement [5]:

$$Q = \alpha + \omega/\varphi, \quad (1)$$

where Q is the air flow through the turbine, α is a constant shift; ω is the angular speed of the rotor, φ is the conversion coefficient of the turbine converter.

That is, to improve the metrological reliability it is necessary to use the real (generally nonlinear) dependency of the conversion function.

Also, the dynamic properties of the turbine is generally not taken into account, which further reduces the accuracy of measurement, and therefore hinders the correct diagnosis statement.

Consider that modern TAFT is a device that converts an input air volume $Q(t)$ into a sequence of pulses, the repetition frequency of which depends on the flow rate and the number depends of the amount of air passing through the converter [6].

Therefore, to improve the accuracy of the measurement of the output signal corresponding to the input air flow, we propose a method for measuring metrological data. Let us take into account that among the factors affecting the accuracy of the DTS electromechanical system one can select a static (Q_{st}) and dynamic (Q_D) components. That is, the DTS conversion function can generally be represented as

$$Q = F(Q_{st}, Q_D). \quad (2)$$

To determine the total error of the DTS we propose initially to calibrate the specific device for each component separately and then generalize the result. These tasks are implemented independently of each other that simplify the processing and analysis of the results.

III. DETERMINING THE STATIC COMPONENT OF THE DTS CONVERSION FUNCTION

The theoretical justification for the static part of the DTS conversion function was obtained by analyzing the influence of the turbine rotor torque and resistance.

In order to obtain an analytic dependence of the air flow Q_{st} in a static mode on the rotor rotation frequency f of M_T we initially have analyzed the equation of the turbine rotor motion at a constant flow rate, which can be written as follows

$$M_T + \sum M_R = 0, \quad (3)$$

where M_T is a rotor torque, M_R is the sum of the resistance torque (preventing the rotation of the rotor).

According to the *theorem of angular momentum* [3] the rotor torque of the turbine is determined by the *Euler equation*:

$$M_T = m_g (r_{1mid}v_1 - r_{2mid}v_2), \quad (4)$$

where m_g is a mass flow per second for the cylindrical layer of circular lattice of the unit height, r_{1mid} and r_{2mid} are mean radii of the cylindrical layer at the inlet and outlet respectively, v_1 and v_2 are the circumferential component of the absolute velocity of the gas before and after the turbine respectively.

Substituting the velocity values to (3), taking into account their distribution over the cross section of the blade, replacing the line indicators with volume, and taking into account the equivalence of input and output range of MT ($r_{1mid} + r_{2mid}$), the expression for the torque will be

$$M_T = \frac{2\pi}{PF} k_v k_\Delta \frac{\rho r_{1mid}^2 Q_{ST}^2}{\eta} - \frac{\rho r_{2mid}^2 Q_{ST}^2}{\eta}, \quad (5)$$

where P is the axial force of the impact of the flow onto the rotor, F is the effective turbine area, k_v is the coefficient of uneven air flow in the normal section of the turbine, k_Δ is the coefficient of the air passage through the radial gap, ρ is the density of the air, η is the coefficient of flow structure.

Using coefficients K_1 and K_2 expression (5) can be rewritten as

$$M_T = K_1 Q_{ST}^2 + K_2 Q_{ST}. \quad (6)$$

In addition, it follows from (5) we can determine the value of the MT transmission coefficient ϕ , expressing it through the value of ω :

$$\phi = \frac{k_v k_\Delta}{PF} - \frac{\eta M_T}{2\pi \rho r_{mid}^2 Q_{ST}^2}, \quad (7)$$

Detailed analysis of the results of experimental studies of the MT rotor movement as set out in [6], allowed to identify the main components of the total torque of resistance movement M_R :

$$\sum M_R = M_{fr} + M_{gap} + M_{im} + M_{das}, \quad (8)$$

where M_{fr} is the friction torque in MT supports, M_{gap} is the resistance torque that occurs in the gap between MT and the rotor surface, M_{im} is the air friction torque on the surface of the impeller, M_{das} is the resistance torque of the data acquisition system.

These torques are also features of the kinematic properties of the gas flow, the turbine geometry, rotor speed and airflow volume.

Using M_{fr} , M_{gap} , M_{im} , M_{das} from [9] the equation (3) can be written as follows

$$k_{A1} Q_{ST}^2 + k_{B1} Q_{ST} + k_{C1} Q_{ST} f + k_{D1} f = 0, \quad (9)$$

where $f = 1/(2\pi)$ is a rotor rotation frequency, k_{A1} , k_{B1} , k_{C1} , k_{D1} are coefficients that depend on the geometry of the turbine and the flow properties.

For a particular TAFT one can get a practical dependency, taking into account the effect of all the above factors, which can be used to calibrate the measurements and reduce their error.

The composition of the experimental setup for determining the static component of the DTS conversion function, which is represented in Fig. 3, includes: compressor (C), reference rotameter (RR), a digital turbine spirometer (DTS), as well as a laptop computer (PC).

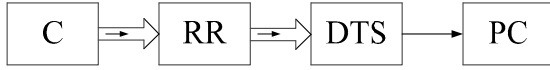


Fig. 3. Fitting scheme for investigating static characteristics DTS.

Using compressor the measuring stand input is supplied with air stream at a flow rate of 0,2 to 7 l/s. The exact values of consumption were recorded using a reference meter RR. Output of the spirometer as a digital code was fed to a laptop computer input (PC) via RS232 protocol.

The result of the experiments allows us to mathematically describe the static component of the transfer function of a particular DTS.

For example, the static component of the DTS transform function for the exhalation function V_{out} is shown in Fig. 4.

Approximation of the obtained function showed that there are two characteristic regions can be distinguished, which are described by the expression

$$Q = \begin{cases} T \leq x_1 & b_0 - k_0(x_1 - T); \\ T > x_1 & b_1 + k_1(T - x_1), \end{cases} \quad (10)$$

where $T = 1/f$; x_1 is coordinate, b_0, b_1 is constant, k_0, k_1 is slope of the approximation.

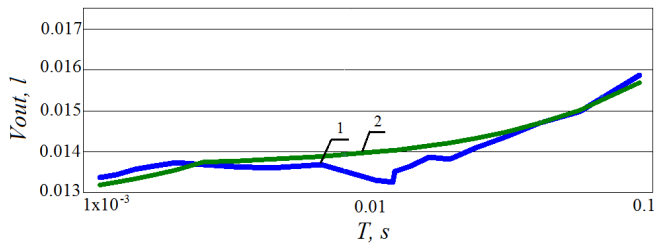


Fig. 4. Static component of the DTS transform function: 1 – characteristic; 2 – approximation.

This relationship is the real characteristic of a particular DTS and can be taken into account when calibrating during the metrological certification.

IV. DETERMINATION OF THE DYNAMIC COMPONENT OF THE DTS CONVERSION FUNCTION

To determine the dynamic component we must take into account the effect of the inertia of the rotor of the turbine on the measuring result of the conversion. The dynamic component of the TAFT transfer function conventionally considered as the sum of the reaction of the rotor with the attached flow and reaction of the tachometric devices [4, 7].

Due to the use of the photoelectric conversion method the second component in the further analysis will not be considered.

As a first approximation MT rotor with the attached flow can be represented as an aperiodic inertial element of the first order and is described by the equation

$$\tau \cdot df / dt + f = Q\phi, \quad (11)$$

where τ is a time constant.

It should be noted that this expression assumes a linear relationship between input flow and rotor speed for constant expenditure, i.e. constant transmission coefficient ϕ for the turbine.

When changing the air flow rate during the patient inspiratory/expiratory the converter transfer function becomes non-linear and the current time constant τ of the equation (11) will depend on the input signal (in a certain range). Expressing from (11) the inlet flow, we get

$$Q = \frac{f}{\phi} \left(\tau \frac{df}{dt} + 1 \right), \quad (12)$$

where in the first factor is a linear static component of the transfer function, and the second factor (in parentheses) is a dynamic component.

Finally, the DTS conversion function can be written as

$$Q = Q_{ST}(f) \cdot \left(\tau \frac{df}{dt} + 1 \right), \quad (13)$$

where $Q_{ST}(f)$ is the static component of the non-linear conversion function.

Experiments on the dynamic characteristics of the digital portable spirometer were performed using the installation, which is shown in Fig. 5.

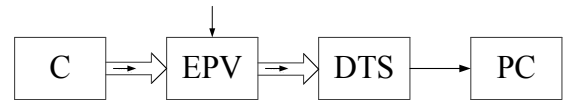
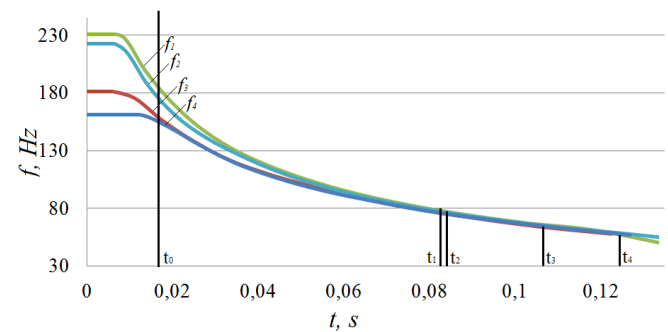


Fig. 5. Fitting scheme for investigating dynamic characteristics DTS.

The measuring stand consists of the following blocks: compressor (C), electro-pneumatic valve (EPV), a digital turbine spirometer (DTS) and a laptop computer (PC).

The air flow is provided by the compressor (C) at the entrance to the measuring stand. Switching of the air flow was carried out using a electro-pneumatic valve (EPV). Output of the spirometer as a digital code was fed to a laptop computer input (PC) via RS232 protocol.

The resulting output waveform $f(t)$ are shown in Fig. 6.


 Fig. 6. Resulting output waveform $f(t)$.

Graphical analysis of the curves allowed us to determine the time constant τ_{mid} , which can be taken into account when calibrating during the metrological certification of DTS.

To confirm the effectiveness of this method a series of experiments was carried out. The syringe dispenser of $31 \pm 0,01$ capacity was used as the reference volume. Research was conducted in the three different speeds of air flow: 0.5 l/s; 3 l/s; 9 l/s (average values are given).

The experimental results are shown in the diagram Fig. 7.

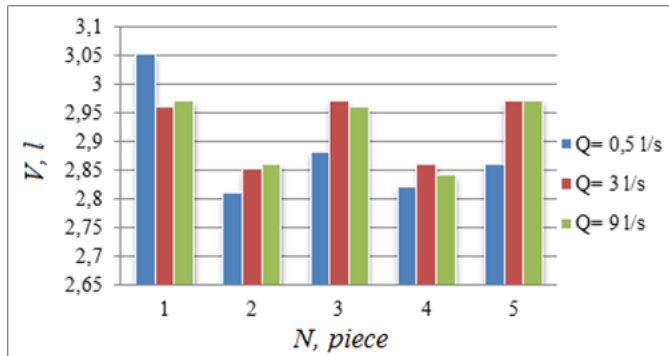


Fig. 7. The experimental results for a particular spirometer.

Studies have shown that the measurement error does not exceed 3%, which corresponds to the requirements of American Thoracic Society and European Respiratory Society.

V. CONCLUSIONS

The mathematical model developed for the processes in the turbine flow transducer, and the following results were obtained.

The conversion function of the turbine of type $Q_t = F(f)$ has been proposed and investigated. Original method was developed to determine its factors. Analysis of the torque acting on the rotor of the turbine yielded the static component of the conversion function of the TAFT in the form of approximating expressions with three coefficients. Research of dynamic properties of rotor IT revealed that it is an aperiodic element of the first order with the corresponding dynamic characteristic whose time constant is independent of the input flow.

The proposed method has been tested in the laboratory Biomedical electronic laboratory (BMEL) of NTU "KhPI" in the study of measuring turbine by Medical International Research Company (Rome, Italy).

This method of estimating the parameters of turbine spirometers was the basis for the metrological provision of digital portable spirometer DTS-14/1 (Fig. 8), developed in BMEL of NTU "KhPI" [2, 8–10].



Fig. 8. The digital portable spirometer DTS -14/1.

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