Transit-Time Ultrasonic Flow Meters for Medical Applications

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The paper describes the theory of operation and the implementation of the technology of ultrasonic flow meters based on the principle of transit-time measurement. All ultrasonic flow meters of ndd Medical Technologies use this measurement principle.

Theory of Operation

The fundamental measurement principle of transit-time ultrasonic flow meters can be explained with the following schematic representation:

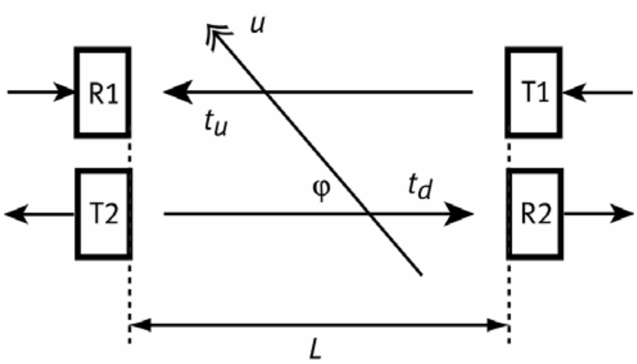

Figure 1: Fundamental measurement principle

With the use of two acoustical transmitters (T1, T2) and corresponding. receivers (R1, R2), two sound transmission paths parallel to each other, but with contrapropagating sound waves, are built up. The medium between the acoustical transducers moves with velocity u in the direction of the flow velocity vector. The transit-times t_u, t_d of sound waves on the two transmission paths of length L are:

$$t_u = \frac{L}{c + \bar{u} \cdot \cos\varphi}; \quad t_d = \frac{L}{c - \bar{u} \cdot \cos\varphi}; \tag{1}$$

where c is the velocity of sound in a still medium, $\bar{u}$ the mean velocity of the medium, and φ the angle between the flow velocity vector and the sound transmission path. Knowing t_u, t_d, L and φ, the sound velocity c can be eliminated, and the flow velocity $\bar{u}$ can be calculated:

$$\bar{u} = \frac{L}{2\cos\varphi} \cdot \frac{t_d - t_u}{t_d \cdot t_u} \tag{2}$$

When converting equations (1) into equation (2) the velocity of sound c is eliminated. The constant term $L/2\cos\varphi$ depends only on the geometry of the flow meter. Due to the independence of sound velocity c the mean flow velocity $\bar{u}$ is therefore not influenced by gas composition, pressure, temperature and/or humidity of the gas. Knowing the flow sensor geometry the flow velocity can therefore be computed by measuring the transit times t_u and t_d.

The term $\bar{u}$ denotes the mean velocity of the gas flow along the sound transmission path. This path ranges from the transmitting and receiving surface of transducer 1 to the corresponding surface of transducer 2. The gas velocity distribution and a mechanical sketch of the sound transmission path is presented in Figure 2:

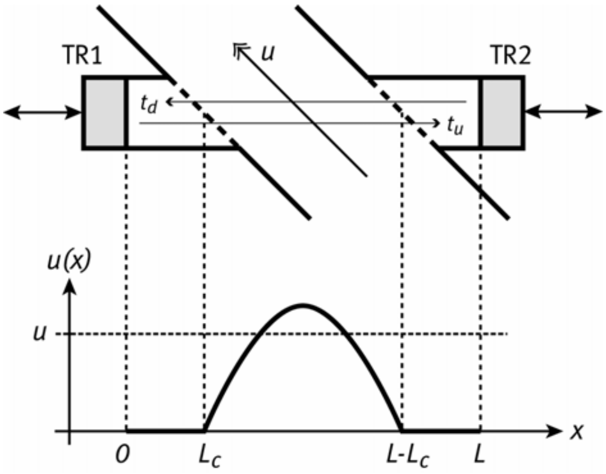

Figure 2: Velocity profile (laminar) on sound transmission path

The sound transmission path consists of three parts: Two parts are inside the two transducer chambers, and one part is inside the flow tube itself. The velocity of the gas flow inside the two transducer chambers is zero. The mean gas flow velocity on the sound transmission path is $\overline{u}$. The interesting quantity, on the other hand, is the average gas flow velocity $\widetilde{u}$ in the respiratory tube:

$$\overline{u} = \frac{1}{L} \cdot \int_0^L u(x)\, dx = \frac{1}{L} \cdot \widetilde{u}(L - 2L_c) \quad \Rightarrow \quad \widetilde{u} = \overline{u} \cdot \frac{L}{L - 2L_c} \tag{3}$$

Using equation (3) and the cross sectional area of the respiratory tube, the volume flow $\dot{V}$ can be calculated:

$$\dot{V} = \widetilde{u} \cdot \pi r^2 = \frac{\pi r^2}{2\cos\varphi} \cdot \frac{L^2}{L - 2L_c} \cdot \frac{t_d - t_u}{t_d \cdot t_u} \tag{4}$$

This formula is based on an ideal arrangement as shown in figure 2; pulse transmission and transit-time measurement are ideal. In addition, the relationship between measured average flow velocity of the medium along the sound transmission path and true average flow velocity is neglected. In [2] Plaut and Webster showed that the relation between measured average flow velocity $\widetilde{u}$ and true average velocity u' is

$$\widetilde{u} = 1.33 \cdot u' \tag{5}$$

in laminar flow, and

$$\widetilde{u} = (1 + 0.01\sqrt{6.25 + 431 \cdot R_e^{-0.237}}) \cdot u'; \quad R_e = \rho \cdot 2r \cdot \widetilde{u} / \mu \tag{6}$$

in turbulent flow. The flow becomes turbulent at Reynolds number R_e › 2000. When R_e exceeds 2000 the flow begins a transition to turbulence and the velocity profile becomes more uniform [2]. Figure 3 shows the predicted changes in the ratio $\widetilde{u} / u'$ over u' (Reynolds number R_e has been calculated for dry air, using ρ = 1.2929 kg/m^3 and μ = 18.46·10^6 kg·m^{-1}·s^{-1}). In an ideal tube with r = 10 mm, the transition from laminar to turbulent flow theoretically happens at $\widetilde{u}$ = 0.45 l/s. In practical use, however, the transition from laminar to turbulent flow will be even lower: The exhaled air is mostly turbulent, and additional turbulences are generated at the mouthpiece and the in/outlet of the flow meter.

In practical use, the geometry of each flow sensor (i.e. arrangement of ultrasonic transducers and flow tube) is individually corrected for using a linearity correction table. Figure 3 shows the linearity correction implemented in the spirometry devices with an internal flow tube diameter of 20 mm. The correction values have been determined using constant flow velocities generated with a motor driven calibration syringe (Pulmonary Waveform Generator, MHC Custom Design, 8012 South Pioneer St., Midvale, Utah 84047, USA).

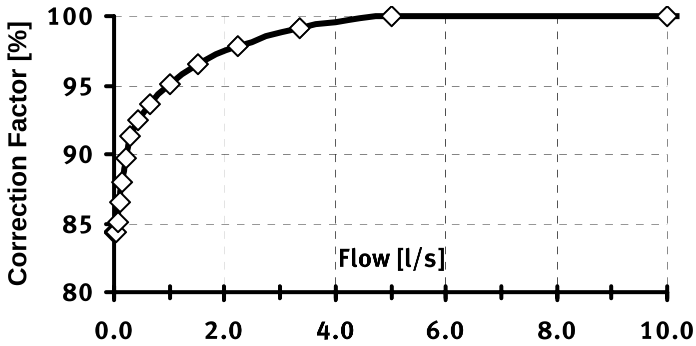

Figure 3: Linearity correction for flow tube with 20 mm diameter

It can be seen that the maximum correction is approx. 15% at very low flows, and ‹5% at flows above 1 l/s. Due to the dependency of the Reynolds numbers from the gas composition, the linearity correction changes with variations in gas composition. Simulations with strongly varying gas compositions show, that the influence on the linearity correction is ‹1%.

References

[1] Ch. Buess. Transit-Time Ultrasonic Airflow Meter for Medical Application. Thesis, Swiss Federal Institute of Technology, 1988.

[2] D. Plaut and J. Webster. Ultrasonic measurement of respiratory flow. IEEE Trans. Biomed. Eng., 27(19): 549-558, October 1980.

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