Ultrasonic Respiration Analysis

Ch. Buess, R. Burger and W. Guggenbühl

Department of Electronics, Swiss Federal Institute of Technology,
Gloriastrasse 35, CH-8092 Zürich, Switzerland.

ABSTRACT

We present the design of an ultrasonic respiration analysis system. The system determines the velocity of the respiratory gas flow by measuring absolute transit-times of ultrasonic pulse trains. Besides this standard flow meter function the system computes the 'equivalent molecular weight' M^* of the gas flow: M^* is calculated by combining the results of the ultrasonic transit-time measurements with temperature measurements along the sound transmission path. The gas composition dependent parameter M^* can be used to determine additional respiratory parameters, e.g. functional dead space or total lung volume.

INTRODUCTION

The respiratory analyzer originates from the ultrasonic airflow meter presented in [1]. The system consists of a control unit and various flow sensors of different size. The control unit includes the power supplies, the driver unit for the ultrasonic transducers, the receiver circuitry and a 8 bit microcontroller with keyboard, serial interface, display, and analog outputs. The transit-times of the ultrasonic pulse-trains are measured by a digital counter running at 500 MHz. The following table lists the maximum measurable flow $F_{\max}$, the flow resolution F_{res} and the sensor dead space V_D of the available flow sensors.

type	$F_{\max}$	F_{res}	V_D
large	15 l/s	2.50 ml/s	35 ml
small	7 l/s	1.25 ml/s	8 ml
tiny*	4 l/s	0.63 ml/s	2.5 ml

* preliminary data

The large flow sensor was developed for the use in adults, the small and tiny sensors are for the use in childrens and premature babies. Figure 1 shows a cross-sectional view of the small flow sensor: The open flow path 1 has a length of 69 mm and a diameter of 13 mm. The sensor is equipped with standard flow tube connectors 2 and/or a short terminating element 3. The two ultrasonic transducers 4 and 5 (condenser microphones) are mounted in recessed cavities on both sides of the flow path. Two thermocouples 6 and 7 are used to determine the gas temperature along the sound transmission path. Two printed circuit boards, which are located on opposite sides of the flow tube, are used for preamplification of the received ultrasonic signals, and for preprocessing of the temperature signals.

FLOW

The velocity of the gas flow can be determined by the following equation [1, 2]:

$$F = k \cdot \frac{t_1 - t_2}{(t_1 - t_d) \cdot (t_2 - t_d)}, \qquad (1)$$

where F [l/s] is the flow velocity, k [l] is a constant, t_1, t_2, t_d [s] are the transit-times and the meas-

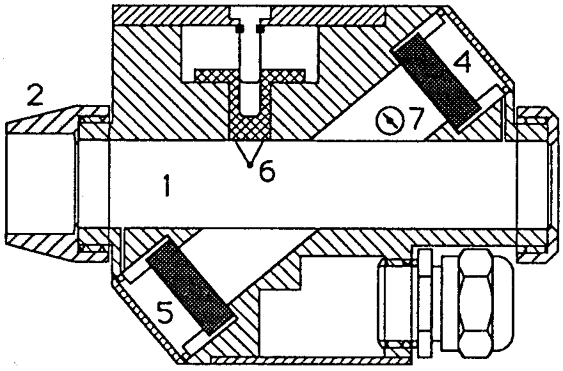

Figure 1: Cross-sectional view of small flow sensor.

urement delay of the ultrasonic pulse trains. F is determined independent of gas composition, pressure, humidity and temperature; the flow sampling rate is 321 Hz, in 'fast' mode 541 Hz.

In the very low flow range ($F<0.4$ l/s for large flow sensor), the flow within the flow tube is laminar; above this limit, the flow is turbulent. Owing to this transition from laminar to turbulent flow geometry, a nonlinear correction function must be applied to equation (1). The corresponding correction table is generated by using an algorithm presented by Yeh et al. [3].

MOLECULAR WEIGHT

For ideal gases the speed of sound can be computed by the following equation:

$$c = \sqrt{\frac{R \cdot T}{\sum_i n_i \cdot M_i / \kappa_i}}, \qquad (2)$$

where c [m/s] is the speed of sound, R [J mol^{-1}K^{-1}], is the gas constant, T [K] is the gas temperature, n_i is the relative concentration of gas i, M_i [g/mol] is the molecular weight, κ_i is the relation of the specific heat capacities c_p/c_v. By combining equation (2) with the equations for the ultrasonic flow meter [1, 2], the 'equivalent molecular weight' M^* of the gas can be determined:

$$M^* = \kappa_{\mathrm{air}} \cdot \frac{M_n}{\kappa_n} = f(T, t_1, t_2, t_d), \qquad (3)$$

M^* is a function of temperature T (mean temperature along the sound transmission path), transit times t_1, t_2 and transit time delay t_d. The measurement range of M^* extends from ~20 g/mol up to ~46 g/mol, with a resolution <0.05 g/mol. Figure 2 shows a plot of F, M^* and T versus time. During the inspiratory part (phase 1, negative flow) M^* is constant at ~28.95 g/mol, corresponding to ambient air. During the first expiratory part (phase 2) M^* decreases because of the sudden increase in humidity. In the second expiratory part (phase 3) M^* increases due to the rise in CO_2 concentration, and the reduction in O_2 concentration.

CONCLUSION

The ultrasonic respiration analyzer allows fast determination of the gas flow velocity independent of gas composition, pressure, humidity and temperature. Measurement of the equivalent molecular weight permits computation of additional respiratory parameters like functional dead space or, by performing and analyzing wash-out tests, total lung volume. The combination of flow and molecular weight measurement in a single device may lead to new and interesting applications.

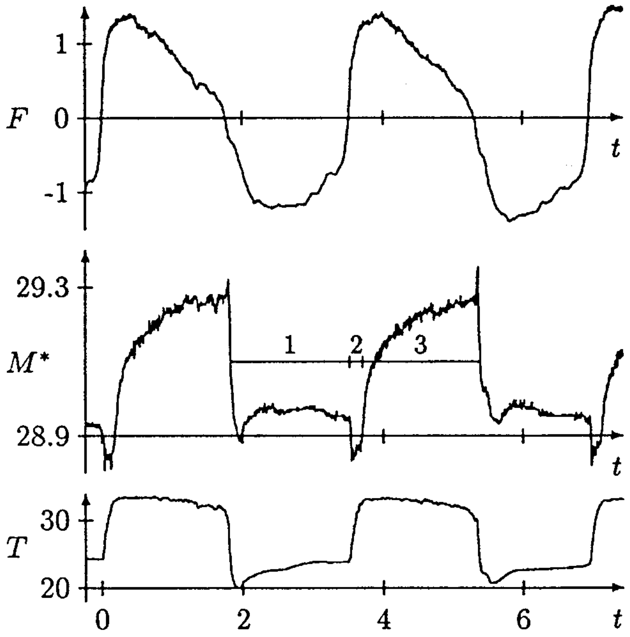

Figure 2: Plot of flow F [l/s], equiv. molecular weight M^* [g/mol] and temperature T [°C] versus time t [s].

REFERENCES

[1] Ch. Buess, P. Pietsch, W. Guggenbühl, and E. A. Koller. Design and construction of a pulsed ultrasonic air flowmeter. *IEEE Trans. Biomed. Eng.*, 33(8):768–774, August 1986.

[2] D. I. Plaut and J. G. Webster. Ultrasonic measurement of respiratory flow. *IEEE Trans. Biomed. Eng.*, 27(10):549–558, October 1980.

[3] M.P. Yeh, R.M. Gardner, T.D. Adams, and F.G. Yanowitz. Computerized determination of pneumotachometer characteristics using a calibrated syringe. *J.Appl.Physiol.*, 53(1):280–285, 1982.

ADDRESS

Dr. Ch. Buess, Department of Electronics, Swiss Federal Institute of Technology, Gloriastrasse 35, CH-8092 Zürich, Switzerland. Tel.: 41 1 2565159, FAX: 41 1 2621655.