Design and Construction of a Pulsed Ultrasonic Air Flowmeter

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Abstract—**The construction and specific function of a new ultrasonic flowmeter are described. The mean velocity of the respiratory air flow is calculated by measuring the transit times of short ultrasonic pulse-trains simultaneously transmitted upstream and downstream at a 650 Hz rate. The flowmeter system consists of a control unit and a separate flowhead. The former includes the power supplies, a controlling microprocessor, most of the signal processing circuitry, and three analog outputs for flow, volume, and temperature, respectively. The flowhead contains the respiratory tube with a constant circular cross section (length 90 mm, diameter 20 mm, dead space 35 cm^3), a fast temperature sensor, two electronic circuits for processing of flow and temperature data, and a sound transmission channel with two capacitive ultrasonic wide-band transducers. This respiratory air flowmeter is extremely fast (response time 1–2 ms) and accurate, with low noise (below 9 ml/s), with a wide flow range (bidirectional from 0 to 9 l/s) and with a linear frequency response up to 70 Hz.**

INTRODUCTION

PNEUMOTACHOGRAPHS and flowmeters are medical instruments that measure the instantaneous flowrate in the respiratory gas streams. Although flowmeters directly measure only flow rates, they can also be used to measure absolute volume changes of the lung (spirometry) by integrating the flow signal. In contrast to closed systems like piston and bellows type mechanical spirometers, the open flowmeter systems are relatively nonobstructive to the patient.

For an accurate computation of volume changes, the sensitivity and baseline of the flowmeter system have to be stable over long periods. This demands bidirectional flowmeters which are not influenced by changes of gas temperature, gas composition, humidity, and viscosity. Furthermore, the system should have a small dead space and large dynamic range: the required resolution of a typical flowmeter is estimated to 5–10 ml/s, the maximum flow range about 10 l/s [1], [2]. In addition, the demand for a good frequency response becomes apparent: experiments with high frequency ventilation [3], the measurement of human breathing dynamics [1], and the measurement of the acoustical impedance of the lung–thorax system by spectral analysis of forced random noise, need a flowmeter with a linear frequency response up to 50–100 Hz.

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The most popular flowmeters for clinical and physiological research are the following devices.

1) Linear Resistance or Fleisch Pneumotachograph: A fixed resistance in the gas flow (usually a bundle of narrow tubes or a mesh screen) causes a pressure drop which is linearly related to the value of volume flow. The dynamic range of these devices is limited by the requirement of laminar gas flow; turbulent flow results in a nonlinear relationship between pressure drop and flow. Consequently, there exist several flowheads to cover the whole range up to 14 l/s [4]. Owing to the operating principle, the pneumotachographs of Fleisch have the tendency to become clogged with condensed water or saliva, which increases the effective flow resistance and changes the characteristics of the device. Heating the resistance element reduces condensation, but leads to thermal expansion and viscosity changes of the flowing gas, which again alters the measurement. At the circumference of the tube, the pressure drop is sensed with a differential pressure transducer. The latter mainly determines the characteristics of the entire flow measurement unit [5].

2) Mechanical Vane or Turbine Devices: Owing to the significant mass of turbines and vanes, the latter tend to react rather slowly on changes in gas velocity; moreover, they depend strongly on the density, viscosity, and humidity of gases respired.

3) Thermal Dissipation Devices: They are based on thermistors or heated resistance wires which are convectively cooled by the flowing gas. The computation of the gas-flow is based on complicated time functions of the sensor's temperature, gas temperature, gas density, humidity, and specific heat. The velocity of the gas flow is registered at only a single point of the cross section and has to be extrapolated to the mean velocity. To measure bidirectional flows, two thermistors or resistance wires in a tandem arrangement are required.

In addition to these types of flowmeters there exist two different ultrasonic devices.

1) Vortex Shedding: Vortexes are waves which may be generated in a fluid stream. They are caused by a fixed vortex shedding object (bluff body) in the path of the flowstream. As the air passing off the bluff body moves down the flow tube, vortexes are created. The rate of vortexes generated is detected by an ultrasonic beam [6]. The "Vortex Principle" is only available for unidirectional flow measurement.

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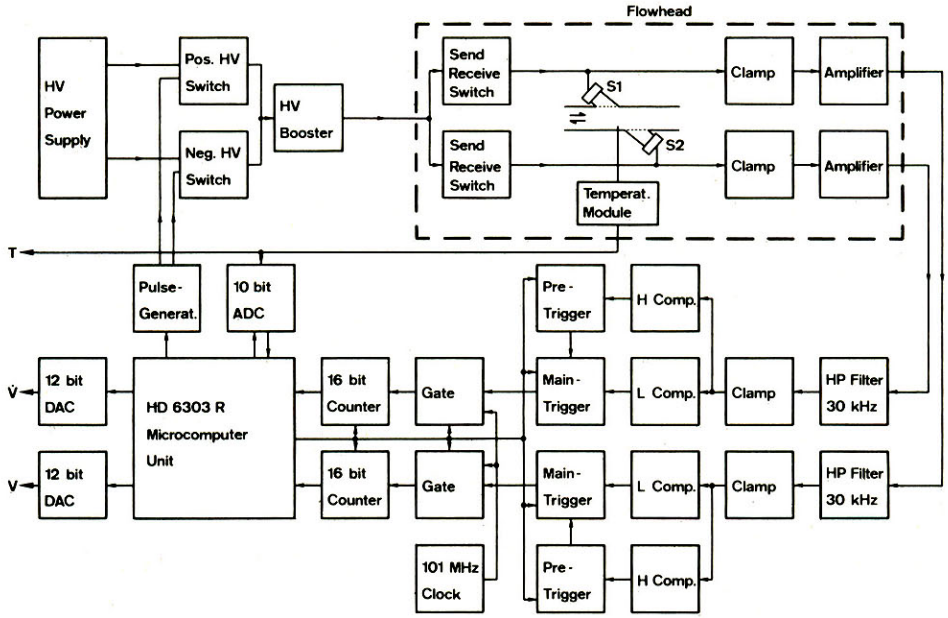

Fig. 1. Detailed block diagram of the ultrasonic air flowmeter system.

2) Time of Flight Measurement: The velocity of the air-flow is calculated by measuring the changes in transit time of contrapropagating ultrasonic signals along a respiratory tube.

The flowmeter presented belongs to the latter type of ultrasonic devices. In an evaluation, we compared our laboratory ultrasonic flowmeter to various differential pneumotachograph units.

Principle of the Ultrasonic "Time-of-Flight" Measurement

Ultrasonic flowmeters of this class are based on the principle that sound, traveling through a streaming medium, is sped up or slowed down by the movement of the medium, causing, for a fixed distance across the medium, a decrease in the downstream transit time and an increase in the upstream transit time. The changes in transit time can be related to the flow velocity.

For the measurement of "direct time-of-flight," the flowmeter presented uses two ultrasonic transducers, $S1$ and $S2$ (Fig. 1), which are mounted in recessed wells on opposite sides of the tube at an angle of 40° to the flow axis. Both transducers emit ultrasonic pulses traveling against each other through the moving medium. The speed of propagation is increased by an amount equal to the magnitude of the flow velocity vector in the direction of the straight line connecting the two transducers. The downstream and upstream transit times (td, tu) are

$$td = \frac{L}{c + u \cdot \cos(\beta)}; \qquad tu = \frac{L}{c - u \cdot \cos(\beta)} \tag{1}$$

where L is the length of the sound transmission path, u is the mean flow velocity along the sound path, c is the sound velocity, and β is the angle between the transducer- and the flow-axis. The difference of transit times is

$$dt = tu - td = \frac{2 \cdot L \cdot u \cdot \cos(\beta)}{c^2 - u^2 \cdot \cos^2(\beta)} \cong \frac{2 \cdot L \cdot \cos(\beta)}{c^2} \cdot u \tag{2}$$

for $u << c$. Changes in sound velocity c—owing to alterations in gas composition and temperature [7]—may be taken into account, using the sum or the product of tu and td [2]. During air-breathing, the maximum changes in c^2 are limited to ± 3 percent; therefore, in a first approximation, we ignored this variation in c^2 and assumed a linear relationship between u and dt.

New Wide-Band Design

All flowmeters reported up to now use piezoelectric transducers that can act as both transmitters and receivers [1], [8]–[10]. Because almost all the ultrasonic energy is lost at the transducer–air interface, the piezoelectric transducers have to be operated at high efficiency, that means near their characteristic resonance frequency. The transmitting–receiving pairs must have resonant frequencies which are closely matched, and because of their high Q factor, the transducers will have ringing characteristics like $L - C$ tank circuits. Used as transmitter or receiver, it will take 8–15 cycles before the transducers fully respond to the signal [9]. This ringing property has two consequences: first, it limits the sampling rate of the flowmeter, because the ringing must die out before the transducers can be used for another cycle of transmission or reception; second, the ringing makes it impossible to separate phase distortion originating from multiple reflections of the ultrasonic signal. Mechanical and/or electrical damping can be used to achieve a higher sampling rate, but this further reduces the ultrasonic energy transmitted into the medium which is already critically low in

gas flowmeters. The second problem was partially solved by a "sampling window technique" [9]: only the first few cycles of the sound waves arriving at the receiving transducer were analyzed for flow rate information. Thus, the influence of reflected waves that take a longer path between the transducers is reduced. In order to avoid the problem of phase distortion, the flowmeter presented in this paper uses commercially available capacitive ultrasonic wide-band transducers with a low Q and hence practically no ringing. The transducers permit the transmission of very short ultrasonic pulse-trains; furthermore the upstream and downstream pulses may be transmitted simultaneously. This leads to a high maximum flow sampling rate of the system.

Another problem arising from ultrasonic flowmeters based on phase detection [9] results from the 360° phase detection limitation. Because our system measures direct time-of-flight, the highest measurable flow rate is only a problem of pulse-detection; one has not to compromise the resolution for a larger full scale range.

Operation of the System

The flowmeter consists of a control system and a separate flowhead. The operation can be explained with the aid of the block diagram (Fig. 1) and a description of the operations that are executed during one measuring cycle of 1–2 ms: the microprocessor which controls the operation of the whole system starts a cycle by triggering the digital pulse generator. The latter consists of three monoflops with individually adjustable time constants. These monoflops control two high-voltage transistors which switch either the positive or the negative voltage of the high voltage power supply to the common output. The signal at this output is a square wave pulse-train with a duration of 20 μs (Fig. 3) and having a center frequency near 75 kHz. After the third pulse, both high-voltage transistors are switched off, and the common output is tied to ground. The resulting pulse-train is amplified by a push-pull arrangement and transmitted to the flowhead by one of two multicore cables which connect flowhead and control unit.

One channel of the circuitry inside the flowhead is shown in Fig. 2. The pulse-train generated by the control unit first arrives at two send–receive switches. These passive switches discriminate between emission and reception. They consist of four p-i-n diodes in antiparallel connection. In the case of emission, the high-voltage pulse-train is directly switched to the transmitter capsule; in the case of reception, the small signals at the output of the transducer are isolated from the pulse-generator. In order to achieve a high sensitivity, the capacitive transmitter S (Sennheiser KU 11-H-21) is polarized with a dc voltage V_p. The received signals are amplified by an operational amplifier A. This amplifier has to be protected against the high-voltage pulses by a clamp circuit ($D5$ and $D6$) with a current limiting resistor ($R2$). The whole circuitry connected to the output of the transmitter capsule must have

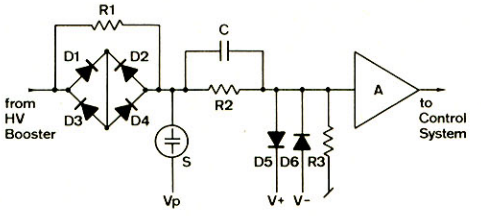

Fig. 2. Circuitry inside the flowhead (one channel): send–receive switch, transducer S, clamp, and amplifier.

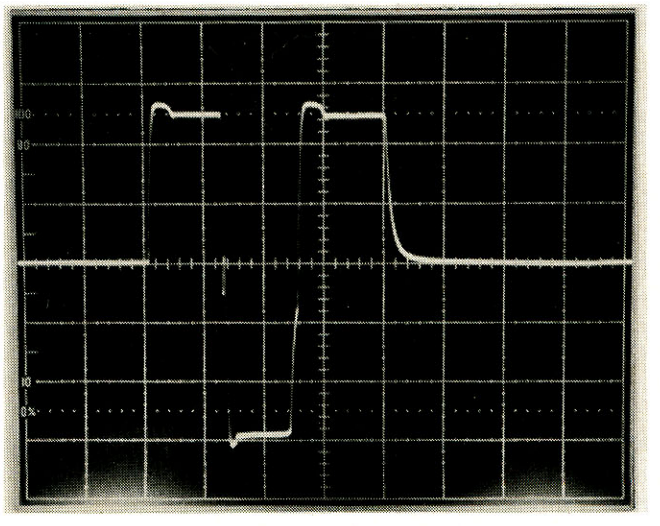

Fig. 3. Oscillogram of driving voltage simultaneously applied to both transducers. Vertical scale = 50 V/div. Horizontal scale = 5 μs/div.

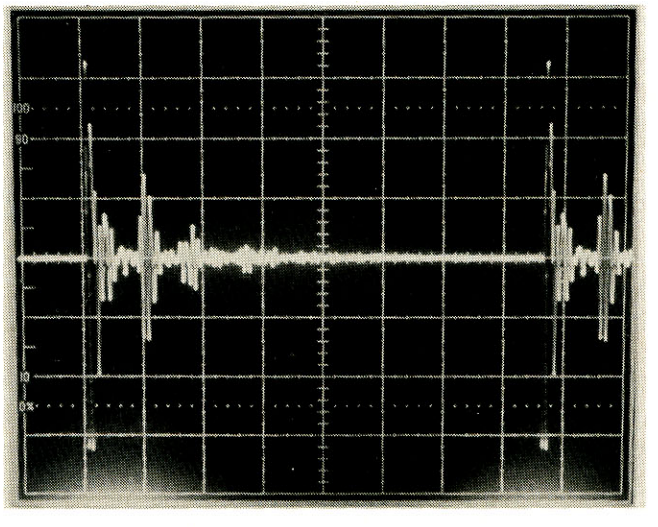

Fig. 4. Oscillogram of the voltage at the output of the buffer amplifier inside the flowhead. Vertical scale = 1 V/div. Horizontal scale = 0.2 ms/div.

a very low capacity to ground (realized with the choice of p-i-n diodes and the use of a JFET Op Amp).

Starting with the send–receive switches, the system includes two symmetrical paths for the processing of the two channels. The signal at the output of the amplifier described above can be divided into three parts (Fig. 4): first, the clamped response of the amplifier on the emitted pulse-train, second, the received pulse (approximately 0.2

ms after the emission at the opposite transducer), and third, the spurious reflections of the ultrasonic pulses. In the picture, the pulse repetition frequency is set to approximately 650 Hz, but it can be seen that the sampling rate of the flowmeter could be increased without problems to 1 kHz or more. The signals at the output of the two amplifiers inside the flowhead are returned to the control unit.

The transducers, because of the wide-band design, also receive components with frequencies below the used ultrasonic range. In consequence, the signals include the audible noise produced in the environment of the capsules. This noise—which is mainly caused by the flowing air in the respiratory tube—is attenuated by a high-pass filter at 30 kHz (fourth-order Bessel type). The filter which includes a further amplification is succeeded by another clamp unit that protects the following comparator circuits.

In contrast to flowmeters with high Q piezoelectric transducers, in which reliable and accurate determination of the arrival time is one of the most difficult problems, the wide-band design presents less difficulties to trigger on a specific wave of the received pulse-train. The system presented uses a two-stage trigger for the determination of a pulse's arrival time: the H comparator (high level) sets the pretrigger when the first pulse exceeds the adjustable high-level. When the pretrigger is set, the main trigger is armed, so that it triggers on the next negative-going zero crossing—detected by the L comparator (low level). This zero crossing is taken as the arrival time of the pulse-train.

The microprocessor inhibits the main, as well as the pretriggers, during the emission of the ultrasonic pulse-train. At the beginning of each measuring cycle it also resets the two digital counters, opens the clock-gates to start the time-of-flight measurement, and initializes the trigger logic. The counters which operate at a frequency of 101 MHz are stopped when the arrival of the corresponding pulse-train is detected. The two counters measure the upstream and downstream transit time with a resolution of 9.9 ns. This minimal measurable difference in transit time corresponds to a resolution in flow velocity of 9 ml/s. The counters are built up using FAST-TTL logic: the least significant two bits are counted with 74 F 74 flip-flops (guaranteed operating frequency 100 MHz), the following stages use 74 F 161 counters in an asynchronous connection. The 101 MHz quartz clock generator is realized on a separate unit using discrete electronics and a 74 F 04.

At the end of the measuring cycle, the microprocessor reads the values of the two 16 bit counters. In the succeeding computation it calculates the flow [see (2)] and—by a digital integration of the flow values—the volume. Both values—flow and volume—are converted into analog signals using two 12 bit digital to analog converters.

For use with a fast breath-by-breath respiration analyzing system, the flowmeter in addition includes an electronic gas-temperature measurement. The flowhead itself contains a type K thermocouple (diameter 0.05 mm, response time 10 ms) and a pretrimmed monolithic thermocouple amplifier with cold junction compensation (AD 595 C from Analog Devices). The temperature signal (10 mV/K) is sent to the control system where it is amplified. The analog signal is available for external use, and in addition a 10 bit ADC converts it into a digital word that can be read by the microprocessor.

Mechanical Construction of the Flowhead

A cross section of the flowhead—constructed of aluminum—is shown in Fig. 5. The two ultrasonic transducers $S1$ and $S2$ (diameter 13 mm, length 5 mm) are mounted in the cavities 1 and 2 (referring to Fig. 5). The capsules are positioned with a rigid synthetic rubber (PVC) that serves as electrical and acoustical isolation to the aluminum housing (which is electrically grounded). Both transducer cavities have internal connection to the upper chamber 7. This chamber contains the electronic circuitry that controls the two transducers (send–receive switch, clamp, and amplifier); furthermore, the connectors for the two multicore cables are installed at one of the side walls. The upper chamber is also connected to the lower chamber 6, which contains the electronic circuits for the gas-temperature measurement (thermocouple signal conditioner). The thermocouple is positioned by a plastic element which is pressed into a screw 11. This construction allows an easy exchange of the thermocouple and makes the connection between measuring channel 5 and lower chamber 6 watertight.

The apertures 3 and 4 between ultrasonic transmission channel and the respiratory tube are covered with fine nets 14 (PTFE), so that the tube has a constant circular cross section over its whole length, hence exhibiting a minimal flow resistance (approximately 0.005 mbar · s/l) and a small dead space volume of 35 cm^3. Multiple reflections of the ultrasonic pulses are attenuated by an absorbing coat 15 (soft rubber) on the inner surface of the respiratory tube and by a diffuser material 12 (same PTFE material as 14) covering both transducers. In addition to the absorption of multiple reflections, the diffuser material, moreover, makes the sensitive capsules relatively immune to mechanical contamination. During use, saliva may flow along the tube without affecting the measuring sensitivity (provided, however, that the nets are not fouled with saliva). After use, the tube may be cleaned simply by rinsing with a disinfectant followed by water.

At both ends of the respiratory tube, two additional damping elements 10 are installed (foamed synthetic rubber) which again suppress multiple reflections. The measuring channel can be terminated with two different elements, 8 and 9: the short version exhibits a minimal dead space, the long version allows the installation of an exchangeable mouth piece.

Measuring Results and Discussion

The new ultrasonic flowmeter was evaluated in comparison to the linear resistance pneumotachographs of Fleisch (PT1, PT2, and PT3), connected with a differ-

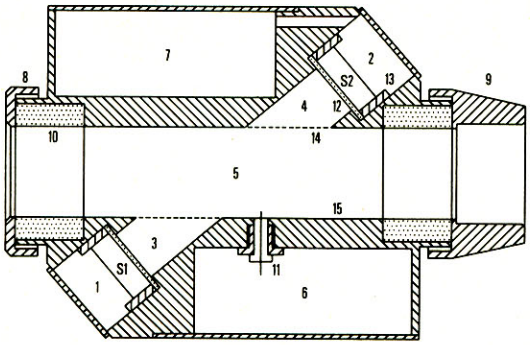

Fig. 5. Cross section through the experimental flowhead. Diameter of the respiratory tube is 20 mm.

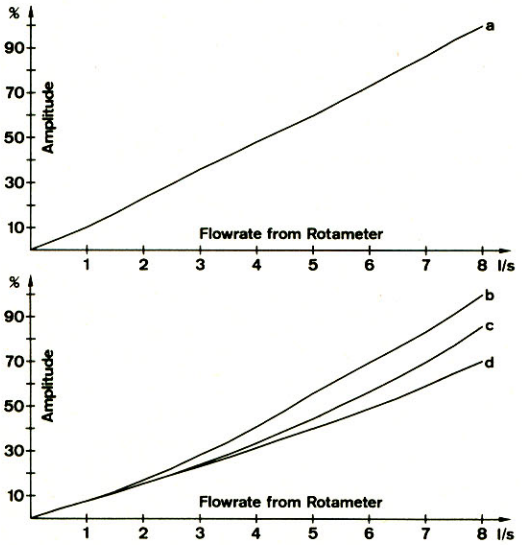

Fig. 6. Relation of output voltage and air flow. Top: ultrasonic air flowmeter (a). Bottom: pneumotachographs of Fleisch [PT1 (b), PT2 (c), and PT3 (d)] with Morgan differential pressure transducer.

ential pressure transducer (Morgan MP 45-1). All the measurements have been carried out under the control of a digital data acquisition system (PDP 11, normally used for the on-line breath-by-breath respiration analysis [11]). The sampling rate of the PDP 11's analog to digital converters was set at 100 Hz; for the analysis of frequency response, the sampling rate was further increased to 1 kHz. It has to be emphasized that the sampling rate of this computer has nothing to do with the flow sampling rate of the ultrasonic flowmeter (which was set at 650 Hz).

Linearity

The linearity of the flowmeters was measured by connecting the Fleisch pneumotachometer and the ultrasonic flowmeter—single or combined—in series with a calibrated rotameter (± 1.6 percent Fisher and Porter FP 1 27 G 10 80 with two different floats). Sucking with a precisely adjustable vacuum cleaner, we introduced a step-function of air-flows up to 9 l/s. The air-flow step function of the four different flowmeters was analyzed with the computer and converted into the corresponding representations (Fig. 6).

The ultrasonic flowmeter described in this paper showed

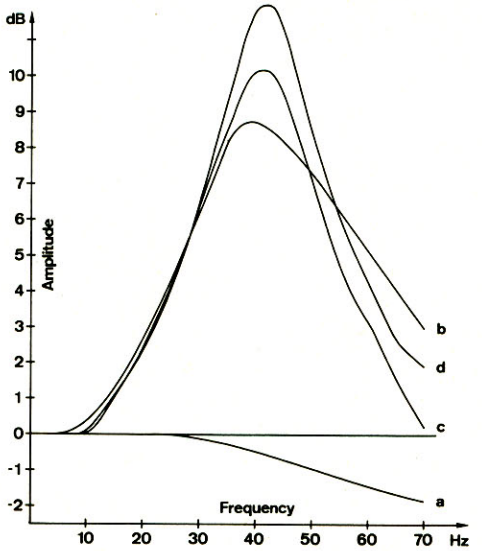

Fig. 7. Frequency response of the ultrasonic air flowmeter (a) in comparison to pneumotachographs PT1 (b), PT2 (c), and PT3 (d) of Fleisch with Morgan differential pressure transducer.

a linear response all over the tested flow range. As expected, the linear resistance flowmeters showed relatively small linear ranges, above which the relation between flow and output signal was not linear.

Frequency Response

The frequency response of the flowmeters was measured with a high frequency ventilation pump— frequency range 5–70 Hz, volume 25 ml—described by Kohl and Koller [3]. The distance between the flowmeters and the outlet of the pump was reduced to approximately 2 cm. Under these conditions, the peak-to-peak amplitude of flow velocity can be expected to be linearly related to frequency. The result of these measurements can be seen in Fig. 7. The ultrasonic flowmeter shows a nearly linear response over the whole tested frequency range. The deviation from linearity at high frequencies (30–70 Hz), however, is caused by the filter at the output of the 12 bit DAC (first-order *RC* low-pass filter, 3 dB point above 70 Hz). This problem could be avoided by using a better filter at higher frequencies (200–300 Hz).

At frequencies above 10 Hz, the motor of the high frequency ventilation pump leads, because of the short connection between flowmeter and pump, to intense vibrations of the flowhead. The curves reported demonstrate that the flowhead, including the internal electronic circuits and the two ultrasonic transducers, is practically insensitive to vibrations.

The response of the Fleisch pneumotachographs, however, deviates grossly from the result we obtained with the ultrasonic system. With the Morgan differential pressure transducer, the Fleisch systems had a resonance frequency of approximately 40 Hz. Frequency components of 40 Hz are therefore overestimated by a factor of 3–4 (10–12 dB); at 20 Hz the error is about 2.5 dB. As already reported by Jackson and Vinegar [5], it has to be taken into account that the connecting tubes between differen-

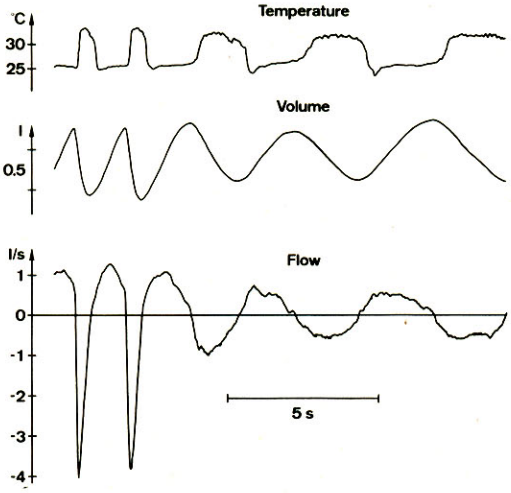

Fig. 8. Temperature, volume (BTPS) and flow during intentional changes in breathing measured with the ultrasonic air flowmeter.

tial pressure transducer and pneumotachograph strongly influence the measurement. With regard to length, diameter, and hardness of the tubes, a compromise has to be made between frequency response, amount of overshooting, and installation of pneumotachograph and pressure transducer. A short connection between the two devices results in an improved frequency response, but leads to problems with vibrations and humidity. A long connection on the other hand gives a poor frequency response.

Noise, Stability, and Reliability

Absolute volume changes of the lung are computed by a digital integration of the flow signal. An essential point for this calculation is the long-term stability of the baseline (output signal of the flowmeter at flow zero); a small baseline-drift leads to an error in the volume computation increasing with measuring time. Both mechanical and electrical layout are important to avoid temperature drifts of the electronic system.

The baseline of the ultrasonic air flowmeter is stable within 1 bit (corresponding to a flow of 9 ml/s), if the flowhead temperature is fixed. Under these conditions, repeatability of test measurements was maintained over a period of more than two months. Under isothermal conditions, changes in flowhead temperature from 20 to 34°C result in a baseline drift of 3–4 bits. There are two reasons for this baseline drift: first, a change in the superposition of multiple reflections on the received ultrasonic signal, second, a variation in the sensitivity of the ultrasonic transducers.

Over the whole actual range of the flowmeter, the noise at the output is below 9 ml/s, corresponding to a time jitter far below 10 ns. It has to be emphasized that in spite of the extremely fast response time (approximately 1–2 ms) the respiratory flow and volume curves (Fig. 8) are very smooth, without oscillations or overshootings. The volume in this figure is computed by a breath-by-breath respiration analysis system [11] and expressed in terms of BTPS (body temperature pressure saturated).

Conclusions

In comparison to other ultrasonic flowmeters [1], [8]–[10], the type presented in this paper shows the following new features:

1) use of capacitive ultrasonic wide-band transducers (frequency range 20–100 kHz),

2) use of extremely short ultrasonic pulse-trains (20 μs),

3) simultaneous transmission of upstream and downstream pulses.

Through the use of short ultrasonic pulses, the superposition of multiple reflections on the ultrasonic signal is essentially reduced. This allows the measurement of the direct transit times (in contrast to the common phase shift detection), which results in a wide flow range in conjunction with a high flow resolution (1000 : 1 bidirectional flow range).

The new ultrasonic flowmeter, as tested in our laboratory, is fast and accurate with low noise, with a wide flow range and a linear frequency response up to 70 Hz. For practical use in a broad range of applications further investigations are needed in order to suppress the dependence of the measurement on temperature and gas-composition and to make easy sterilization possible.

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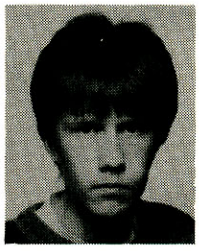

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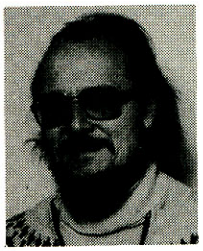

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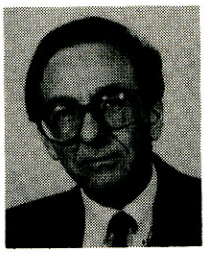

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