Wearout-Free Oxygen Sensor for Concentration and Flow Measurement

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Abstract—**This document gives an overview on the ultrasonic measuring principle to determine the oxygen concentration in air. Usually the oxygen concentration is measured with electrochemical sensors, e.g. lambda sonde, which suffer from wear due to chemical reaction. The simultaneous measurement of flow requires an additional sensor. The novel sensor described in this paper can measure both the oxygen concentration and the flow velocity. This is useful for oxygen generating systems since oxygen concentration and airflow are interdependent. Exemplarily, in his paper attention has been turned to the application area of aviation and its particular boundary conditions. These boundary conditions are weight, energy demand, size, price and most important lifetime and reliability.**

Keywords-oxygen; ultrasonic; flow velocity

I. Introduction

Due to the fact that the number of applications that rely on the measurement of oxygen concentration is growing, oxygen sensors are gaining more and more importance. The most widespread application area is medicine where sensors need to be enormously reliable. Similar precision is also needed in aviation, with additional attention given to: lifetime, reliability, shock resistance, weight and environmental conditions.

In general, the output signal of such a sensor is proportional to the oxygen concentration. This document presents a method to measure the oxygen concentration on the basis of ultrasonic velocity. This method is advantageous, in comparison to other methods, because its measuring range is broader (from 0 % to 100 % oxygen concentration). Some known sensors can only measure in a small range, e.g. from 70 % to 98 % oxygen concentration [1]. There are sensors that measure in the same range (from 0 % to 100 %), like the acousto-magnetic oxygen sensor [2], which works on the paramagnetic principle. The problem with this sensor is that it is sensitive towards vibrations and noise, due to the optical fiber microphone used. Furthermore, the signal to noise ratio below 20 % oxygen concentration is too low for reliable and accurate measurements. However the fact is that the ultrasonic sensor is non-expendable is advantageous. Many sensors that are used nowadays are expendable, e.g. the lambda sonde [3] which mean their lifetime is limited.

Here we present a novel oxygen measuring principle which is analyzed and evaluated showing the benefits of this sensor e.g. for airborne systems. In this application area several environmental conditions are of enormous importance such as operating temperature, ambient pressure, altitude, as well as vibration and shock. The lifetime of the sensor in an airplane application should be ideally at least 50 000 hours [4].

II. Theoretical Backround

A. Air

Air is usually a mixture of 21 % oxygen, 78 % nitrogen and 1 % of other gases, e.g. argon. The oxygen concentration depends on the height due to the change in partial pressure. At higher elevations the partial pressure decreases and so the oxygen concentration decreases. For this reason an oxygen sensor that measures constantly is important such that when the concentration is too low more oxygen needs to be generated.

B. Sonic velocity

The sonic velocity of a gas mixture changes with its composition (concentration of components). Due to this fact, it is possible to determine the oxygen concentration in air when measuring the sonic velocity of the mixture.

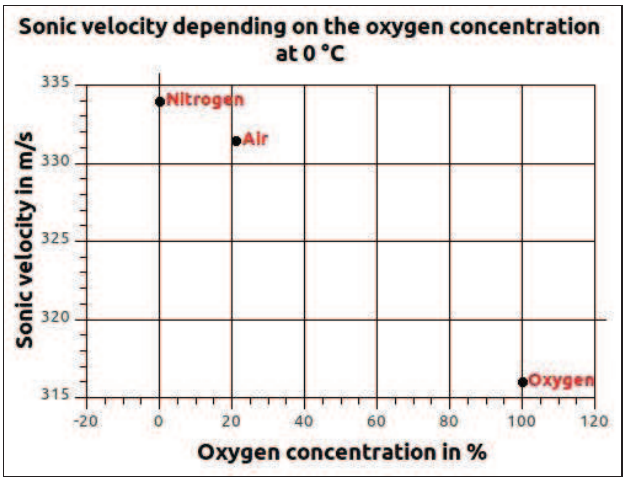

Figure 1. Sonic velocity depending on oxygen concentration [5]

In Figure 1 values of literature are illustrated to show this dependence.

The sonic velocity also depends on temperature. The dependency is linear in the range from -25 °C and 35 °C. This is shown in Figure 2 for the typical air mixture with an oxygen concentration of 21 %. The values are taken from literature and can be calculated from the following formula [6]:

$$c_{gas} = (331.5 + 0.6\ T)\ m/s \quad (1)$$

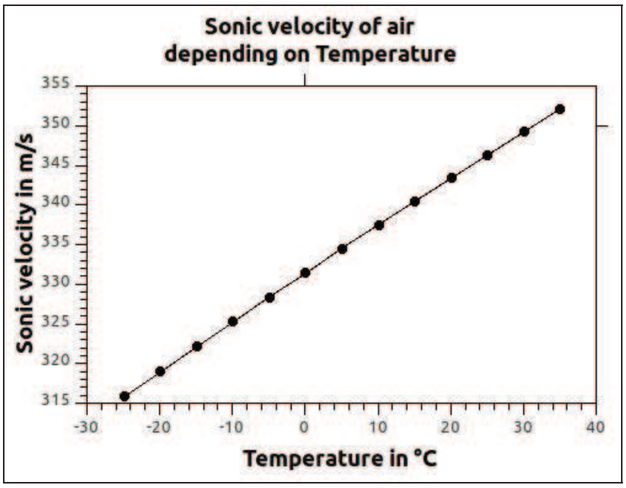

Figure 2. Sonic velocity depending on temperature [7]

The figure shows that with a temperature increase of 10 °C the sonic velocity raises to ~ 6 m/s. That means that the sonic velocity needs to be corrected for the temperature change. This is done by a mathematical description. That is why it is important to measure the temperature during the experiment. The change in velocity due to temperature is compared to the change due to concentration in section V Analysis.

The influence of humidity on the sonic velocity is very small and therefor there is no need to compensate for this [8].

III. MEASURING PRINCIPLES

In principle there are two ways to measure the oxygen concentration via ultrasonic velocity. One is the phase shift measurement and another one is the time difference measurement. In this chapter an overview of these two principles is given. The exact experimental setup is described in Section IV Experimental Setup and Measurement.

A. *Phase shift measurement*

A continuous signal, which is a sine-wave with a fixed frequency, is produced by an ultrasonic transmitter. This sine-wave is influenced in delay by different gas mixtures through the different sonic velocities. Due to this, the sine-wave is faster or slower depending on the mixture of the air. When the signal arrives at an ultrasonic receiver it is shifted to a certain extent due to the gaseous medium. This shift is measured as a phase-angle. Figure 3 shows the transmitted wave and the received wave, which is shifted in comparison to the transmitted wave.

When this method was first used, it showed the following difficulty. The measured phase shift was not definitely allocated to a concentration, because in the course of the concentration change from 0 % to 100 % a phase shift higher than 360 ° was observed.

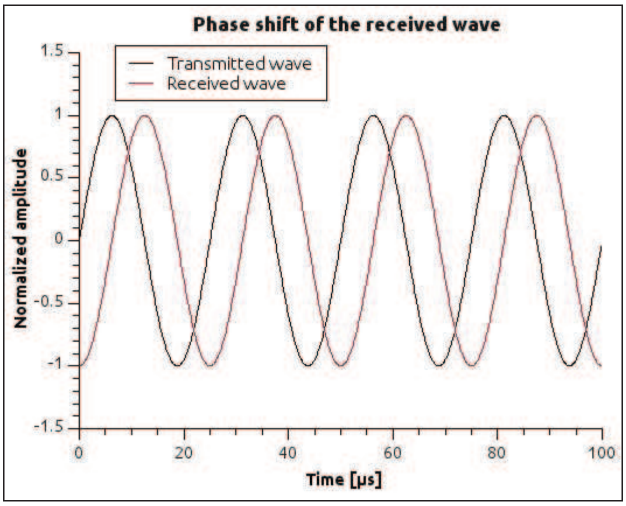

Figure 3. Phase shift of a sine-wave

B. *Time difference measurement*

The time difference measurement uses the time between the beginning of a send burst (black trace in Figure 4) and its arrival (red trace in Figure 4) at the receiver side. The transmitted signal is a burst of sine-waves with a constant length and frequency. This time is dependent on the gaseous medium between transmitter and receiver. The length of the measurement chamber does not change, so the velocity can be calculated by:

$$v = s/t \quad (2)$$

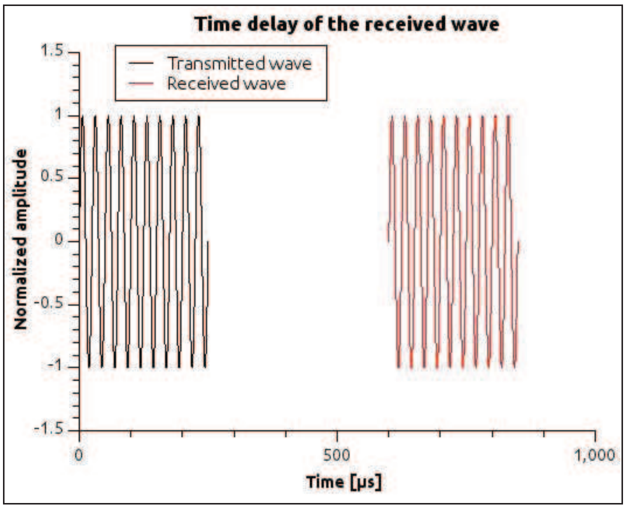

Figure 4. Time delay of a sine-wave

This method was used in an experiment and is explained further in the following section.

IV. Experimental Setup and Measurement

The experiment is based on time-difference measurement. The schematic drawing of this is shown in Figure 5 and the assembly of the test sensor in Figure 6.

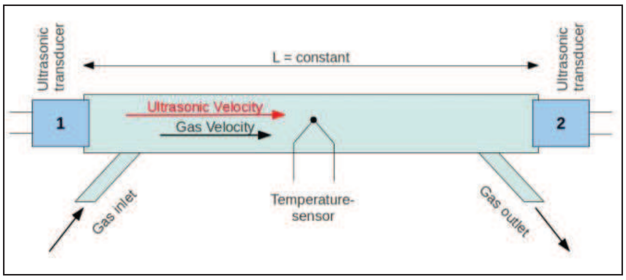

Figure 5. Ultrasonic measuring chamber (layout)

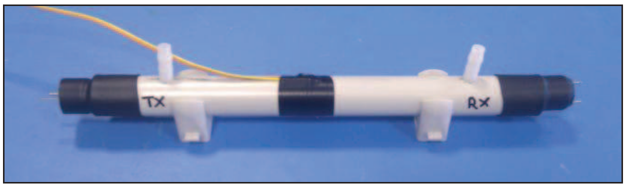

Figure 6. Ultrasonic measuring chamber (assembly)

The sensor consists of one transmitter (1) and one receiver (2). They are fixed at the ends of a tube. The tube, with length L, has a temperature sensor built in. The measured gas flows through the gas inlet into the tube and then out through the gas outlet. The send wave propagates into the same direction the gas flows. So the following equation holds:

$$c + v_g = L/\Delta t. \quad (3)$$

c is the ultrasonic velocity, v_g is the gas velocity and Δt is the time the wave needs to propagate from transmitter to receiver.

During the experiment the gas velocity v_g was kept constant. A mixture of oxygen and nitrogen was used as the measuring gas. The oxygen concentration in the gas was changed from 0 % to 100 % in steps of 5 %. The time was measured with an oscilloscope and the temperature was also recorded in parallel. The ultrasonic transmitter sends a burst with a frequency of 40 kHz and a length of 0.5 ms. The beginning of the burst is used to trigger the oscilloscope. The receiver detects the wave after a delay and generates a signal for the oscilloscope, which measures the time delay from the sending of a burst and its arrival.

In this experimental setup a known oxygen concentration is given through the tube and the time difference is measured. This procedure is important for further use of the sensor as it is needed for calibration before it can be used. With the calibration the pairs of values are defined that combine a measured time difference to the corresponding oxygen concentration.

V. Analysis

The measured values show that the time t gets longer the higher the oxygen concentration in the gas is. Figure 7 shows the trace of the transmitted signal and the received signal for one measured gas mixture. Furthermore the time difference is also declared.

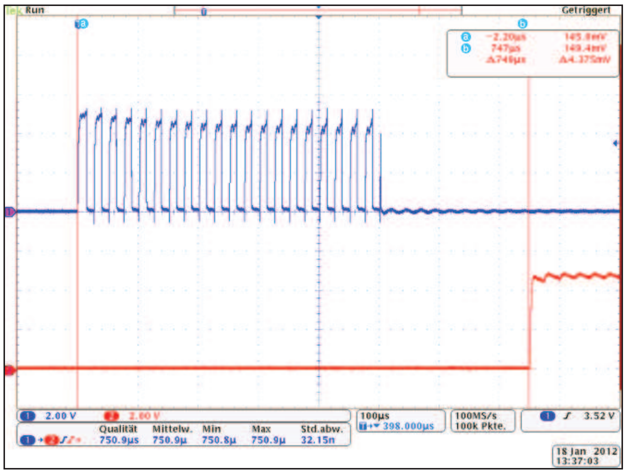

Figure 7. Trace of the electrical signals

When the time difference increases, the sonic velocity decreases. This can be seen when transforming the equation (3) to the following form:

$$c = L/\Delta t - v_g \quad (4)$$

With equation (4), the sonic velocity can be calculated from the time difference and the two constants gas velocity and length of the tube. The plotted graph is revealed by Figure 8 and shows a linear dependency on the oxygen concentration.

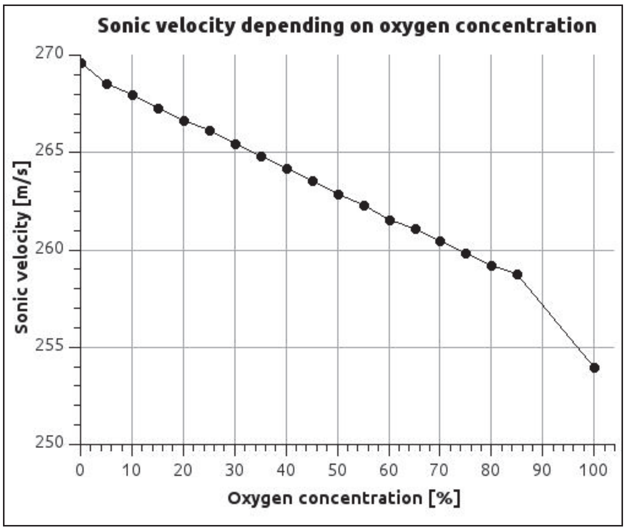

Figure 8. Sonic velocity depending on oxygen concentration at room temperature

In the range between 85 % oxygen concentration and 95 % no time difference could be measured, because the nitrogen flow was too low to adjust with the given measuring equipment. That may also be the reason for the non-linearity at high oxygen concentration.

From the graph it can be seen that the change in velocity is very small with changing oxygen concentration. When the concentration changes by 10 %, the sonic velocity changes approximately by 1.2 m/s. In comparison to the velocity change with temperature (6 m/s every 10 °C) this change is very small. The temperature effect is higher than the concentration effect. That is why the error is high when a change in temperature is neglected. This error can be avoided when correcting mathematically the change in temperature. With the correlations given above, a temperature change of 1 °C would correspond to a concentration change of 5 %. This is the error made when not considering the temperature change. For a temperature change of 10 °C the error in concentration would be 50 %.

To simplify matters, the experiment was carried out at room temperature such that the temperature was constant.

In this experimental setup, the time was only measured for the wave propagating in one direction. Nevertheless it is possible to use two transducers, which can transmit and receive signals, instead of one transmitter and one receiver. Thus, it is possible to measure in both directions, from transducer 1 to transducer 2 and vice versa. That is needed if the gas velocity is not known or when it is not constant.

For the first direction from transducer 1 to transducer 2 the following equation holds:

$$c + v_g = L/t_1. \quad (5)$$

t_1 is the time the wave needs to propagate from transducer 1 to transducer 2.

For the other direction the equation is the following:

$$c - v_g = L/t_2. \quad (6)$$

t_2 is the time the wave needs to propagate from transducer 2 to transducer 1.

Adding up both equations gives a new equation to calculate the sonic velocity c:

$$c = 0.5 * (L/t_1 + L/t_2). \quad (7)$$

When subtracting equation (6) from equation (5) an equation for the gas velocity v_g comes out:

$$v_g = 0.5 * (L/t_1 - L/t_2). \quad (8)$$

So it is possible to determine both, the sonic velocity and the gas velocity, from the time measurement.

VI. CONCLUSION

The linear dependency of sonic velocity on oxygen concentration shows that this measuring principle works well. With the right measuring equipment it should be possible to measure the range between 85 % and 95 % oxygen concentration also. This would allow measuring the whole concentration range from 0 % to 100 % oxygen concentration.

The sensor needs to be calibrated before it can be used for the first time. After that it need not be recalibrated. To correct for the temperature effects it would be necessary to calibrate the sensor at different concentrations as well as at different temperatures. Another possibility is to calibrate only at different concentrations and correct mathematically for the temperature effect.

Actually, the measurements were done with an oscilloscope and an arbitrary function generator. Future work will base on a micro controller which generates the burst and detects the arrival of it. Furthermore the micro controller measures the sonic velocity in both directions to calculate the gas velocity and the sonic velocity. The detection of the burst at the receiver should base on a correlation of the transmitted burst and the arrival of it.

Due to the fact that this is a first experimental setup, the weight cannot be determined. First this sensor has to be set up in microelectronic mechanical system (MEMS) and then the weight can be determined. The energy can then be measured as well. In the experimental setup the size of the sensor is determined by the length of the tube which is 20 cm. When the setup is built up in MEMS the size can be reduced. Assuming a very relaxed timing resolution of 1 µs, the sensor length can be easily reduced to 0.27 mm. This size could be embedded in MEMS with additional evaluation electronics. The price of the sensor in MEMS should be low, because no special components are needed. All used components are standard devices and ought to be cheap. All electronic devices used in the sensor are solid state devices which do not age as fast as for example chemical devices. Therefore, the anticipated lifetime of the sensor is quite high.

REFERENCES

[1] Medicap GmbH: "Gerätebeschreibung und Gebrauchsanweisung Precise 1100 S", p. 7, www.medicap.de/medicap/deutsch/homecare/pdfs/pr1100s_bedienungsanleitung.pdf; 28.02.12

[2] Jun Han-Lee, Cheng-Lun Tsai, Chi-Shyan Fann, Shyh-Hau Wang: Design of an Acousto-Magnetic Oxygen Sensor, Journal of Medical and Biological Engineering, 22(4): 193-198, 2002

[3] H. Lohninger: „Lambda Sonde", http://www.vias.org/mikroelektronik/sensor_lamdasonde.html; 28.02.12

[4] The national academic press: "Fire- and Smoke-Resistant Interior Materials for Commercial Transport Aircraft", pp.12–20, http://www.nap.edu/openbook.php?record_id=5073&page=20; 28.12.12

[5] RF Cafe: „Velocity of Sound in Various Media", http://www.rfcafe.com/references/general/velocity-sound-media.htm; 30.04.12

[6] Georg August Universität Göttingen: „Schallwellen und die Schallgeschwindigkeit in verschiedenen Medien", https://lp.uni-goettingen.de/get/text/5138

[7] Dipl.-Ing. Eberhard Sengpiel: "Die Wirkung der Temperatur", http://www.sengpielaudio.com/Rechner-schallgeschw.htm; 30.04.12

[8] Hering, Ekbert; Schönfelder, Gert: „Sensoren in Wissenschaft Und Technik: Funktionsweise Und Einsatzgebiete", p. 110, Springer