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Design of an Acousto-Magnetic Oxygen Sensor

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Abstract

The purpose of this study is to build an oxygen measurement system based on acousto-magnetic principle. Oxygen molecule can be attracted by a magnetic field due to its paramagnetic property. When oxygen molecules are driven by an alternative magnetic field, they vibrate and generate an acoustic signal. In consequence, the concentration of oxygen in the air can be measured by detecting the amplitude of acoustic pressure generated in the gap of a C-type electromagnet. Finite element analysis is also used to simulate the distribution of magnetic field intensity and force applied on oxygen molecules near the gap of electromagnet. The correlation coefficient of calibration using gases with known oxygen concentration is 0.9998 in the range from 0% to 100%. At the low concentration range, between 0% and 20%, the correlation coefficient is 0.9951.

Keywords**:** Acousto-magnetic, Oxygen concentration, Paramagnetic, Optical fiber microphone

Introduction

The monitoring of oxygen concentration is of great importance in medical and industrial applications. Major types of oxygen concentration sensor are zirconium oxide cells, electrochemical sensors, and paramagnetic sensors [1-4]. These sensors are used in different fields depend on their characteristics. Zirconium oxide cells working at high temperature are mostly used in car engine control. Inexpensive electrochemical sensors are most popular in clinical applications. However, electrochemical sensors suffer a short lifetime and have a slow response. The advantage of paramagnetic oxygen sensors is their stability, but they are relatively complex and expensive. Magnetic wind cells, magneto-acoustic cells, and dumb-bell cells are three major types of oxygen sensor based on paramagnetic principle [2,5]. Paramagnetic oxygen sensors generally perform side-stream measurement in which only a small amount of air is sampled from the mainstream airway. The separation between sensor and sampling site causes a time delay in measurement reading.

In our previous study, a fiber optics microphone was used to detect the acoustic signal generated in the mainstream of airflow. The acousto-magnetic oxygen measurement system has high linearity in the range from 20% to 100%. However, the acoustic signal for oxygen concentration below 20% was too low for detection [6]. In order to measure oxygen concentration below 20%, the signal level has to be elevated. The easiest way is to increase the strength of magnetic field by increasing the driving current of electromagnet. Core material with higher magnetic susceptibility is also helpful. Therefore, the object of this study is to improve the sensitivity of the acousto-magnetic oxygen measurement system to measure oxygen concentration below 20%.

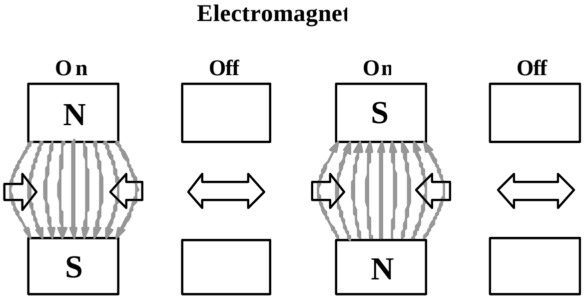

Figure 1. Frequency doubling of acousto-magnetic signal in an alternative electromagnetic field.

An oxygen molecule behaves like a small magnetic dipole. The force that a magnetic field applies on a magnetic dipole is proportional to the multiplication of the magnetic field intensity and its derivative as well as the magnetic susceptibility, see equation (1) [2].

$$\mathbf{F} = c\,\mathbf{H}\frac{d\mathbf{H}}{dx} \qquad (1)$$

Where **F** is the applied force, *c* is the magnetic susceptibility, and **H** is the magnetic field intensity

The generation of an acoustic signal at a gap of electromagnet is shown in figure 1. When the magnetic field is turned on, oxygen molecules are attracted to the gap like small

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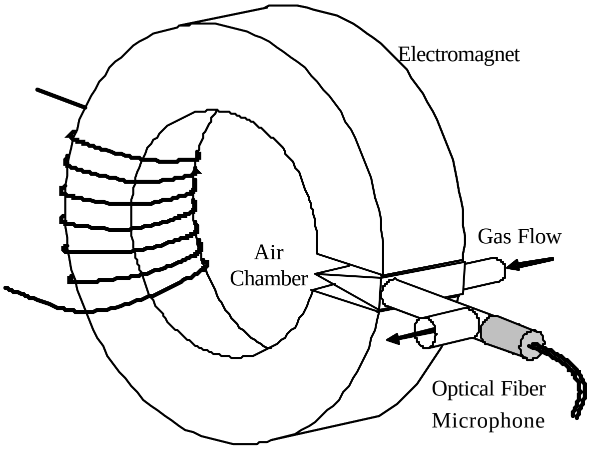

Figure 2. The structure of an acousto-magnetic oxygen sensing probe.

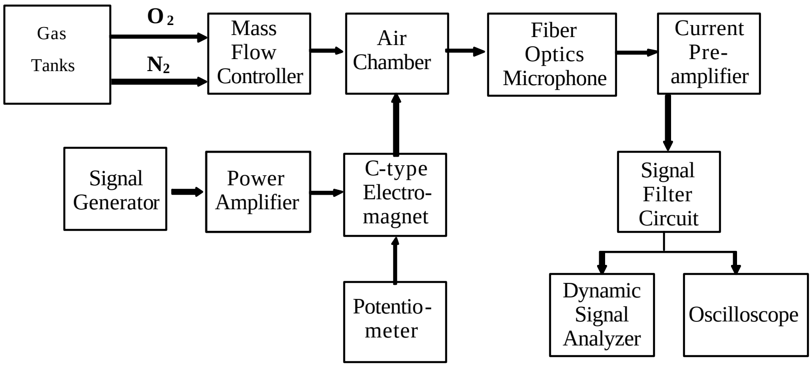

Figure 3. The block diagram of calibration system for oxygen concentration measurement.

magnets. This causes a temporary increase of air pressure at the gap. The pressure will relax when the magnetic filed is off. When the electromagnet is driven by a 60 Hz of alternative current, the contraction and relax of air the gap will correspond and radiate a 120 Hz of acoustic signal. The frequency doubling is because oxygen molecules are attracted to the gap regardless the polarity of magnetic field. In each cycle, the strength of magnetic field reaches both the maximum and minimum twice. Therefore, there are two cycles of contraction and relax correspond to each cycle of alternative magnetic field. The acoustic pressure generated at the gap of an electromagnet is also proportional to the concentration of oxygen molecules near the gap [7]. By detecting the acoustic signal with a very sensitive microphone, oxygen concentration can be calculated from the magnitude of signal. In traditional acousto-magnetic oxygen sensor, microphone and circuits have to be placed at a distance from the electromagnet to prevent the interference of strong electromagnetic field radiated by the electromagnet. In this study, an optical fiber microphone was used to detect the acoustic signal. The optical fiber microphone is immune to electromagnetic interference because no electric conducting wire is used to carry the detected signal. The acoustic signal is carried and guided to the electronic circuit by a long optical fiber. Therefore, the microphone can be placed at the gap where the acoustic signal is generated. Consequently, the size of measurement system is also reduced. The magnitude of acoustic signal is also larger when it is detected close to the gap.

Materials and Methods

Measurement system and Calibration setup

The oxygen sensor includes two major parts: an electromagnet and an air chamber as shown in figure 2. The C-type electromagnet has a core with 70 mm of external diameter and a 6 mm of gap. There are 300 turns of wire (AWG #16) winding on the core (only a few turns are drown in the figure). Air chamber is fitted in the gap without touching the electromagnet to prevent directly coupling of mechanical vibration. A commercial fiber optics microphone (Phone-Or, OM-10) was used to detect the acoustic signal. It works by modulating light reflectance from a thin membrane in the microphone. This thin membrane picks up acoustic signal by vibrating with the acoustic pressure. Source light and reflected light are guided through multiple mode optical fibers [8]. A Gaussmeter (Walker, MG-5DAR) was used to measure the magnetic flux density across the gap. The temperature of electromagnet was also monitored by a precision thermometer (Cole-Parmer, H-08502-16).

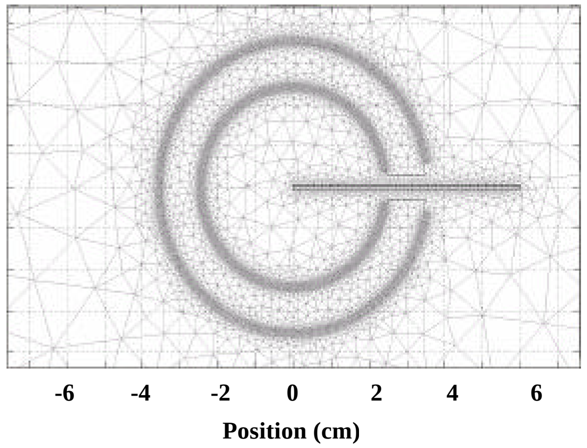

Figure 4. The mesh diagram of finite element model for simulating the electromagnetic field generated by the C-type electromagnet.

In order to calculate oxygen concentration from the amplitude of acoustic signal, a calibration curve between them has to be obtained first. This is done by measuring air samples with controlled oxygen concentration. The block diagram of oxygen concentration measurement and calibration system is shown in figure 3. Oxygen, nitrogen, and carbon dioxide were mixed together by a mass flow controller (BROOKS, 5850E). Carbon dioxide and nitrogen mixture is used to make sure that not acoustic signal is generated when oxygen concentration is 0%. The mass flow controller adjusts gas concentration by changing the flow rate of different gases. Air sample with known concentration was guided to the sample chamber for measurement. A 60 Hz sinusoid signal was first generated by a signal generator (Topward, 8120). It was amplified by a power amplifier (Pioneer, SA-V210) to drive the electromagnet. The root-mean-square value of driving current was set at 2 A. The detected acoustic signal was amplified and filtered by an 120 Hz bandpass filter. Finally, the signal was sent to a dynamic signal analyzer (Stanford, SR785) and an oscilloscope (Tektronix, TDS360). The amplitude of signal read on the dynamic signal analyzer was recorded.

To achieve high accuracy in controlling sample oxygen concentration, calibration experiment was performed at two different ranges. One is from 0% to 100% with 10% of increment, and the other is from 0% to 20% with 2% of increment. For the range from 0% to 100%, air sample was mixed using 100% of nitrogen and 100% of oxygen. For the range below 20%, a reference air (80% nitrogen and 20% oxygen) was mixed with 100% of nitrogen. To prevent bias in calibration, the oxygen concentration of sample air was increased and decreased alternatively in each run of calibration. Experiments were all carried out in an air-conditioned room with temperature set at 25°C.

Electromagnetic field simulation

Finite element model was established for simulating the magnetic field intensity of the electromagnet. Simulation was carried out by using a commercial finite element software, FEMLAB®(COMSOL v2.0). The total number of elements used in simulation was 129440. To have a higher accuracy in simulation, most elements were assigned to the gap and coils of electromagnet, as shown in figure 4. The result of magnetic flux density simulation was verified by comparing with the measurement result.

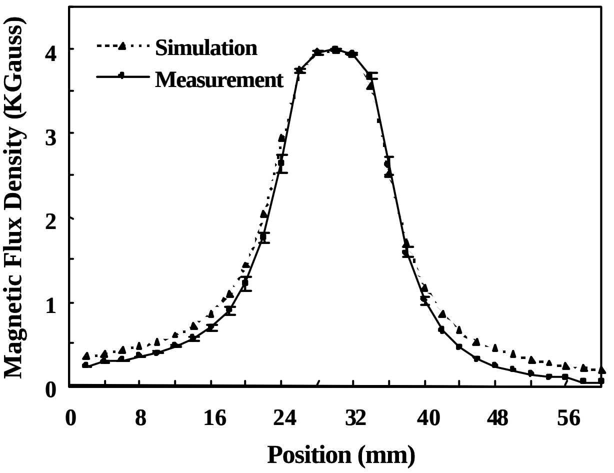

Figure 5. Simulation and measurement of magnetic flux density across the gap.

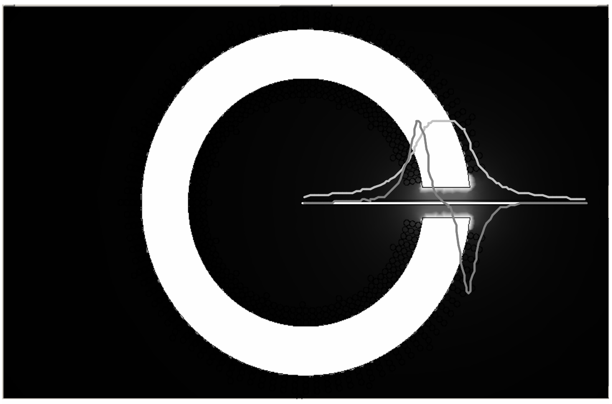

Figure 6. Finite element model simulation of the magnetic flux density distribution at the gap. Curves of magnetic flux density and the distribution of force applied to oxygen molecules are plotted in arbitrary unit.

Results

Simulation results

Figure 5 shows the comparison between the simulation result and measurement of magnetic flux density. Error bars show the standard deviation of ten measurements. The curve is almost symmetry across the gap. The two curves are quite similar both in shape and in magnitude. The result of finite element simulation provides the magnetic flux density and its derivative across the gap. The gradient of magnetic flux density and the force applies on oxygen molecules can also be calculated from the simulation result. Based on the result shown in figure 6, the position where oxygen experienced the maximum force is not at the center of the gap. Acoustic signal is generated at a ring around the gap. To receive maximal

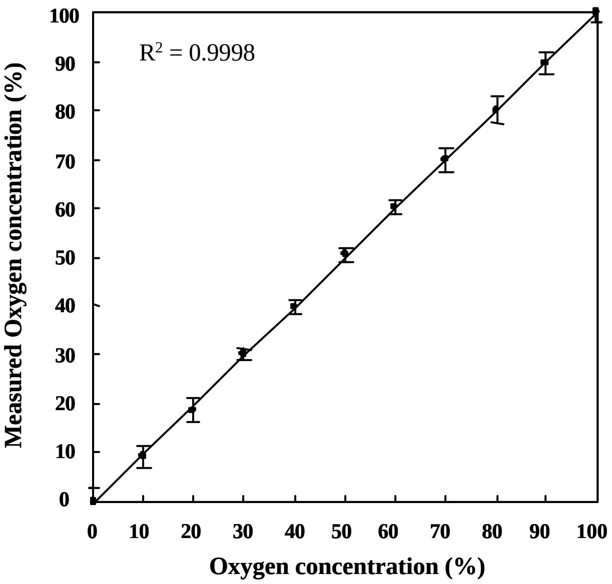

Figure 7. Calibration result of oxygen concentration measurement at the range from 0% to 100% with 10% of interval. Error bars show the standard deviation of ten measurements. The correlation coefficient is 0.9998.

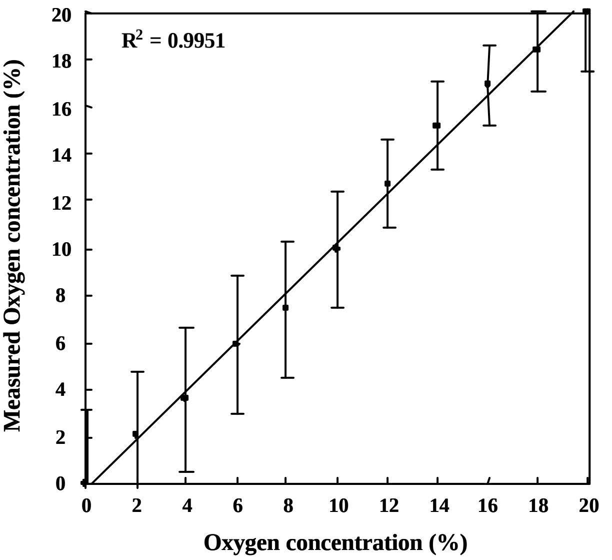

Figure 8. Calibration result of oxygen concentration measurement at the range from 0% to 20% with 2% of interval. Error bars show the standard deviation of ten measurements. The correlation coefficient is 0.9951.

acoustic signal, the vibration membrane of fiber optic microphone should be placed slightly away from the edge of the gap.

Calibration of oxygen concentration measurement

Figure 7 shows the result of calibration experiment of oxygen concentration from 0% to 100% with 10% of increment. Error bars show the standard deviations of ten measurements. Calibration experiments using carbon dioxide and nitrogen mixture as well as pure nitrogen all showed a small and stable acoustic signal. Therefore, the acoustic signal for sample with 0% of oxygen was treated as the background noise. After subtracting the background noise, the correlation coefficient is 0.9998. The result of calibration experiment for oxygen concentration from 0% to 20% with 2% of increment is shown in figure 8. The correlation coefficient over this range is 0.9951.

Discussion

Since the measurement system is designed to work at low frequency, silicon steel was chosen as the core material of electromagnet. The core was made by wrapping a long sheet of silicon steel into a laminated toroid. The magnetic susceptibility of the core is about 40% higher than that of sheet stacking core. The C-type core also increased the efficiency of electromagnet by preventing magnetic flux loss, such as at the corners of a rectangular core.

There are two kinds of vibration noise found in the measurement system. Since there is a metal ring inside the commercial fiber optic microphone, the ring vibrates with the alternating magnetic field and generates a vibration noise. To reduce this noise, the microphone has to put away from the electromagnet. The microphone was placed at a distance of 3 cm away from the gap as shown in figure 2. The strength of magnetic field drops greatly with separation, and the noise is effectively limited. When a large current flows through the coil, the relative movement between core and winding coil also generate a vibration noise. The movement of the core is similar to oxygen molecules attracted by the magnetic field. Therefore, it also vibrates at a frequency twice of the current frequency. This is the audio signal that is detected when there in no oxygen in the sample air. This signal amplitude does not change with oxygen concentration.

Although a 60 Hz alternative current was used to drive the electromagnet, the 60 Hz component in the detected signal amplitude was very small and stable. This 60 Hz signal amplitude also does not change with different oxygen concentration. Therefore, the possibility that the detected 120 Hz signal is an overtone of the 60 Hz power line interference can be excluded. Since the frequency of acoustic signal is twice of the magnetic field, filter circuit also can be used to reject other possible 60 Hz electromagnetic interference in the electronic circuit.

In the calibration experiment, the signal amplitude increased linearly with oxygen concentration while the frequency and strength of magnetic field remained constant. Both calibration curves at low and high concentration show very good linearity. The standard deviations of measurement have about the same magnitude over the whole range from 0% to 100%. The accuracy of measurement is 2.92% over the same range. The accuracy can be increased by taking the average of multiple measurements or by increasing the integration time of reading. However, oxygen concentration measurement in an air flow still suffer a great background noise. This noise is caused by turbulent flow and resonant vibration of air pressure in the airway pipe. Sophisticated method like phase-lock demodulation will have to be used to extract the signal from the noisy background.

Conclusion

An acousto-magnetic oxygen measurement system using optical fiber microphone was demonstrated to detect oxygen concentration from 0% to 100%. The use of optical fiber microphone greatly reduces the size of acousto-magnetic measurement system. Calibration curve has a 1.17% of linearity and a 0.9998 of correlation coefficient. The accuracy is 2.92 % over the whole range. The sensitivity of sensing probe is 2.82 μV/%. Calibration over the range from 0% to 20% alone also has a high correlation coefficient of 0.9951. If an optical-fiber microphone with higher sensitivity was developed, the performance of acousto-magnetic oxygen measurement system can be further improved and the size of system can be further reduced.

Acknowledgment

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