**Introduction**

Acoustic gas sensors relying on the measurement of sound velocity have been reported by several authors[1-4]. Applications include concentration measurements of binary gas mixtures, and humidity sensing at high temperatures. Previous and present devices have mainly operated in the percentage concentration range, and the physical and technological potential of extensions towards ppm ranges has not been thoroughly investigated.

Recently, we suggested acoustic gas sensors for indoor environmental control[5,6]. In this paper, we will outline the design considerations of high resolution acoustic gas sensors, and report prototype experimental results.

**Theory and design**

The velocity of sound $c$ in a gas is given by[7]

$$c = \sqrt{RT \gamma / M}$$

where $R = 8.314$ J/mol K is the general gas constant, $T$ the absolute temperature (K), $\gamma$ the ratio between the heat capacities at constant pressure and volume, respectively, and $M$ the molecular mass (kg/mol) of the gas. Sound velocity may be continuously measured with high resolution in a gas-filled cell, by controlling the frequency of an oscillator via the transit time of sound between an ultrasound transmitter and receiver element kept at a constant distance. The static error band is better than +/-3 per cent of full scale, response time less than two minutes, and short-term resolutions of 0.3 ppm rms, and 3 ppm rms have been obtained in terms of frequency and CO$_2$ concentration, respectively.

Here $A$ is a calibration constant which is mainly depending on the oscillator design (typically, $A = 0.3$). In many cases, $\gamma/\gamma$ may be disregarded. In our design, temperature is

$$\frac{\Delta f}{f} = \frac{\Delta c}{c} = A/2$$

$$\Delta T/T + \Delta \gamma/\gamma - \Delta M/M$$

**Research articles**

**Acoustic gas sensor with ppm resolution**

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**Keywords**

Gas sensors, Acoustics, Environment

**Abstract**

Acoustic sensors based on the well-known relation between sound velocity and mean molecular mass are suggested for the determination of small concentrations of "pollutants", such as CO$_2$, in air. The theoretical basis for high resolution is outlined, and a basic design is presented, together with experimental results. Sound velocity is measured continuously at high resolution in an oscillator controlled by the acoustic transit time between a transmitter/receiver pair operating in the 40kHz range. The static error band is better than +/-3 per cent of full scale, response time less than two minutes, and short-term resolutions of 0.3 ppm rms, and 3 ppm rms have been obtained in terms of frequency and CO$_2$ concentration, respectively.

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kept constant by operating the measuring cell at an elevated and well controlled temperature. From (2) the required thermal stability may be easily calculated. In order to achieve a resolution of 1ppm in terms of the ratio \( \Delta M / M \), temperature must be controlled within 0.3mK.

The noise-limited resolution will vary as the square root of the integrating time of the frequency counting device.

We suggest that equation (2) be used for determining deviations from a “fresh air condition”. The calculated concentration \( C_x \) of a pollutant \( x \) will then be given by

\[
C_x = \frac{2M_{\text{air}}}{A(M_x - M_{\text{air}})} \Delta f / f \tag{3}
\]

Table I shows the calibration factors \( (M_x - M_{\text{air}}) / M_{\text{air}} \) of some “pollutants” of interest. It should be noted that no selectivity mechanism exists for this operational mode. However, after compensating for humidity variations, the main contribution in normal indoor environments is the CO\(_2\) concentration[5].

From equation (3) and the magnitude of the coefficients shown in Table I, it is clear that concentration levels in the ppm range may be detectable, provided that frequency variations of approximately the same order of magnitude can be resolved.

Figure 1 shows the basic sensor design. A pair of ultrasonic transmitter/receivers operating at 40kHz are mounted at the ends of a cylindrical cell, the mantle of which is enclosed by a heating coil and an inner and outer mantle (not shown in the Figure) of copper and a thermally insulating material, respectively. A control loop, including a thermistor, maintains the cell at approximately 40°C. Passive exchange of gas to the sensor cell is provided by openings in the mantle. Outer diameter of the prototype sensor is 15mm and length 30mm.

Table I Calibration factors \( (M_x - M_{\text{air}}) / M_{\text{air}} \) for some variable air “pollutants”

<table>
<thead>
<tr>
<th>Gas</th>
<th>( (M_x - M_{\text{air}}) / M_{\text{air}} )</th>
<th>Typical range (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H(_2)O</td>
<td>-0.38</td>
<td>1,000-20,000</td>
</tr>
<tr>
<td>CO</td>
<td>-0.03</td>
<td>0-50</td>
</tr>
<tr>
<td>CO(_2)</td>
<td>0.52</td>
<td>400-2,000</td>
</tr>
<tr>
<td>NO(_2)</td>
<td>0.59</td>
<td>0-5</td>
</tr>
<tr>
<td>SO(_2)</td>
<td>1.21</td>
<td>0-5</td>
</tr>
<tr>
<td>C(_8)H(_16) (octane)</td>
<td>2.94</td>
<td>0-5</td>
</tr>
<tr>
<td>C(_2)HBrClF(_3) (halothane)</td>
<td>5.8</td>
<td>0-50,000</td>
</tr>
</tbody>
</table>

Experimental results

Figure 3 shows the experimental static characteristics of a prototype sensor. Controlled volumes of CO\(_2\) were injected into a measuring chamber containing the prototype sensor and a reference sensor (Ventostat, Telaire Europe, Sweden). The output frequency difference is plotted against CO\(_2\) concentration measured with the reference sensor. A maximal deviation of less than ±3 per cent from the regression line is found. It was not concluded whether the observed variations were determined by properties of the prototype, the reference sensor, or the calibration procedure.

Figure 4 shows the experimental step response of the prototype sensor, both for increasing and decreasing concentration steps. Response times of less than two minutes can be noted, with a slightly slower down-slope than the corresponding up-slope.
indicating that the response is diffusion controlled. Indeed, it is determined by the opening area, and the inner volume of the sensor element. It was not optimized for fast response in this design.

Figure 5 shows a recording in a realistic environment of the output signal from our sensor ("Q-air"), calibrated in terms of CO₂ concentration. Also shown is the output of the reference CO₂ sensor. Elevated CO₂ concentrations were applied on five occasions, then relaxed to the “fresh air” level of approximately 400ppm. A deviation of less than 50ppm between the two sensors was noted during this recording (72 hours).

In Table II, our results in terms of resolution are summarized. The short- and long-term (ten seconds and days or weeks, respectively) CO₂ resolution is 3ppm and 50-100ppm.

**Discussion**

The dominating factor for the molecular constitution variations of outdoor air is humidity variations. The absolute volume concentration of H₂O in air may vary from close to zero to 6 per cent at 40°C. The use of acoustic gas sensors for humidity measurements at such concentration levels has been reported earlier[1-4].

In cold outdoor climates, the indoor humidity variations are more modest, and can be handled by simple compensation techniques. We have previously demonstrated[5] that humidity compensation may be performed with capacitive humidity sensors. Then it is possible to directly relate the “rest term” of the acoustic sensor signal to CO₂ variations. It should be noted that this signal is not selective to CO₂, but will evolve from any gas having a molecular mass different from air. For ventilation control,
however, the demands on specificity are limited. In fact, the presence of any “pollutant” should have the same result, namely to increase the ventilation flow.

We believe that high resolution acoustic sensors will find many uses in the monitoring of biological and medical processes. The CO$_2$ balance in air is crucial in photosynthetic and metabolic processes. The growth rate of biological materials by photosynthesis can thus be controlled by adding CO$_2$ to the ambient air. Conversely, it is possible to monitor the opposite process, that of respiration, in the vicinity but remote from the process itself.

Acoustic gas sensors may find further application areas when combined with other sensor principles, especially those having low cost potential. For example, sensors based on catalysts for the oxidation of volatile gases are complementary to the molecular mass principle of acoustic sensors, and may be a candidate for applications requiring a higher degree of specificity.

In this paper, we demonstrate that interesting and useful properties can be obtained with acoustic sensors built from low cost, off-the-shelf components. Superior characteristics, in terms of both resolution and response time, would result if the sensor element is further miniaturized. This would implicate higher operating frequencies, which could probably be extended to the MHz range, before serious technological difficulties will appear. The linear sensor dimensions are approximately related to the operating frequency, whereas response time is related to volume, i.e. the cube of linear dimensions. The response time can thus be expected to decrease dramatically upon miniaturization.

Further extensions of the applicability of acoustic gas sensors will evolve from broadband, rather than single-frequency operation. Equation (1) excludes effects of molecular dynamics and interactions. It is well-known that these effects manifest themselves in the fine structure of sound velocity and absorption spectra[8,9], and may be exploited in sensor design[10,11].

Conclusions

The feasibility of high-resolution acoustic gas sensors has been theoretically and experimentally verified. The experimentally achieved resolution in the ppm range does not represent a fundamental limitation but rather practical ones of the present implementation.

Potential applications range from ventilation control, medical monitoring and alarm devices.

References