Sonic Gas Analysis

Matthew V. Golden, Robert M. Keolian and Steven L. Garrett

Graduate Program in Acoustics and Applied Research Laboratory
The Pennsylvania State University, P. O. Box 30, State College, PA 16804

Abstract: The precision-to-cost ratio for frequency-time measurements exceeds that for voltage-current measurements by more than an order-of-magnitude. This advantage suggests that resonant acoustic determination of sound speed in gas mixtures might now be a viable alternative to thermal conductivity measurements for detection of gaseous contaminants in air. We describe a novel and economical resonator design and transducer configuration which suppresses unwanted modes, reduces sensitivity to pressure changes, provides rapid response times, rejects environmental noise and produces signals which are inexpensive to acquire and process automatically.

INTRODUCTION

The speed of sound, \( a \), in an ideal gas is given by \( a^2 = \gamma RT/M \). The polytropic coefficient, \( \gamma \), is the ratio of the heat capacity at constant pressure to the heat capacity at constant volume (\( 1 \leq \gamma \leq 5/3 \)). \( R = 8.314471 \pm 0.000014 \) J/mole-K, is the Universal Gas Constant (1). \( T \) is the absolute (Kelvin) temperature and \( M \) is the molecular weight of the gas. In a gas mixture containing two species of different molecular weights, \( M_1 \) and \( M_2 \), the mean molecular weight of the mixture is \( M_{\text{mean}} = xM_1 + (1-x)M_2 \). \( x \) is the molar concentration (partial pressure fraction) of the first species. A similar molar weighting of heat capacities estimates the mean value of \( \gamma_{\text{mean}} \) for the mixture. The sound speed in the mixture, \( a_{\text{mix}} \), is very nearly given by \( a_{\text{mix}}^2 = \gamma_{\text{mean}}RT/M_{\text{mean}} \). Measurement of sound speed is therefore sufficient to determine the relative concentration of a binary or pseudo-binary (one contaminant in a mixture of stable constitution such as air) gas mixture, if the temperature is known.

Whistles were used to determine the presence of hydrogen and/or methane in mines before the turn of the century in Germany (2). Since the early 20th century, the measurement of gas thermal conductivity using a hot-wire technique has been the method of choice for non-specific detection of contaminating gases in air. The change from sound speed measurement to thermal conductivity measurement was motivated by the popularity of the Wheatstone bridge circuit for precision measurement (3). Advances in electronics suggest that acoustic gas analysis might now provide better performance at lower cost.

RESONATOR DESIGN FEATURES

The resonator shown in Fig. 1 below is essentially two identical open-open resonators of rectangular cross-section which are driven at opposite phases in their half-wavelength mode by a single double-acting (dipole) electrodynamic speaker mounted on the common wall. The speaker is mounted at the pressure anti-node for any odd-integer mode. By symmetry, the speaker does not couple to the even-integer modes.

FIGURE 1. Assembled (right) and disassembled (left) views of the open-open resonator. The AD592 IC temperature sensor is mounted in the lid. The dipole loudspeaker is mounted at the center of the divider and electret microphones, facing into opposite cavities are placed on the divider at either side of the loudspeaker.
Two electret microphones are placed facing in opposite directions on the common wall. They are located at the pressure node of the third mode. Both sides of their diaphragms are vented to the resonator so the microphones are driven by the fundamental mode in a push-pull fashion. Their outputs are subtracted electronically so that the sensitivity to the fundamental mode is four times greater than that of a single pressure sensor, while low frequency far-field extraneous noise which enters from the open ends of the resonator is canceled. The sound speed is nearly pressure independent (4) and the front-back venting of the mikes and speaker prevent trapping of gas in back volumes and makes the system immune to rapid pressurization or evacuation.

The transducer locations guarantee strong coupling to the fundamental mode and suppression of the second, third and forth modes. This prevents mode-hopping of the electronics, if there are large changes in sound speed due to temperature changes or the detection of gaseous contaminants (5).

The resonator configuration also has a rapid response time. The resonance frequency of the fundamental mode is determined by the adiabatic compressibility (potential energy) of the gas near the center of the resonator and by the density of the gas (kinetic energy) near the ends of the divider. Contaminants enter the resonator from the open ends. Since the range of molecular weights is much greater than the range of polytropic coefficients, this geometry will respond more quickly to the presence of contaminants.

FREQUENCY TRACKING AND TEMPERATURE COMPENSATION ELECTRONICS

Over the past decade there have also been tremendous reductions in the price/performance ratio for a variety of off-the-shelf analog electronic integrated circuits including temperature sensors, four-quadrant multipliers, op-amps, frequency-to-voltage converters, and voltage-controlled oscillators. We exploit these improvements by tracking the resonant frequency of the resonator using a phase-locked-loop. The signal which energizes the driver is multiplied by the difference signal from the two dipolar microphones. That product is passed through an op-amp integrator with a time constant of approximately one second. The integrator output provides an ‘error signal’ which is used to maintain the frequency of the voltage-controlled oscillator at the fundamental resonator frequency as the sound speed varies due to the changes in temperature and gas mixture concentration. The integrator also is useful in reducing the effects of both incoherent and impulsive background noises which “leak through” imperfect cancellation by the microphone signal subtraction circuitry.

The availability of inexpensive and accurate temperature sensors allows electronic compensation for the changes in gas temperature (6). This eliminates the need for complex and power-hungry temperature stabilization systems used in the thermal conductivity sensors. In the current embodiment of our analog signal processing electronics, the temperature of the gas in the resonator is measured by an AD592 integrated circuit (IC) temperature sensor that one microampere per degree Kelvin. The temperature signal is scaled and subtracted from the output of a frequency-to-voltage converter to provide an analog signal which is proportional to the deviation of the mean molecular weight of the gas mixture from some preset standard (uncontaminated) value.

We suspect that a mixed analog-digital signal processing circuit might further improve performance and reduce cost by exploiting the frequency information from the resonator more directly.

ACKNOWLEDGMENTS

This work is supported by the Office of Naval Research.

REFERENCES