New apparatus for speed of sound measurement in gases

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Abstrakt

V práci je popsán návrh dalšího prototypu aparatury pro měření rychlosti zvuku v plynech. Měřící aparatura se skládá ze tří základních částí: měřící trubice, měřící elektroniky a systému pro sběr dat (DAQ). Všechny tyto základní komponenty byly vyrobeny a odzkoušeny v laboratořích ústavu fyziky. Rychlost zvuku v měřící trubici, která je naplněna zkoumaným plynem, se určuje pomocí měření doby, po kterou se šíří ultrazvukový signál z jednoho konce trubice na druhý. Měřící trubice je osazena vysoce přesným tlakovým senzorem Keller a šesti teplotními senzory (4x NTC a 2x Pt1000). Všechny naměřené hodnoty se zpracovávají DAQ systémem a ukládají se do PC (Personal Computer).

Klíčová slova

Rychlost zvuku, měřící aparatura, plynový analyzátor, kalibrace, měření tlaku, teplotní senzory

1. Introduction

The sonar gas analyzer is a device used for the speed of sound measurement at given temperature and pressure in selected pure gas or gaseous mixture. Since the equation for calculating the speed of sound can be relatively easily derived from the various equations of state, the speed of sound in gases is an important property in the field of thermodynamics. For example the certain coefficients of the equation of state can be obtained through fitting the set of speed of sound data measured at different temperatures and pressures. Furthermore the acoustic coefficients of virial equation of state in acoustic form can be completely derived from the measured speed of sound data. Another field where the speed of sound plays an important role is the gas dynamic, the Mach's number definition contains the speed of sound and it has broad use for instance in nozzle design. Nowadays the most precise method of speed of sound measurement is realized by the spherical resonator and less precise by the cylindrical resonator, however both methods require expensive instrumentation. The measurement methods based on sonar principle can provide precision sufficient for most applications and don't require expensive instrumentation. The further development of sonar gas analyzer, which has been carried out at the Department of Physic at Faculty of Mechanical Engineering, is described in this paper. The new prototype of sonar gas analyzer is under development and it will provide number of improvements over the previous device.

2. Principle of sonar gas analyzer

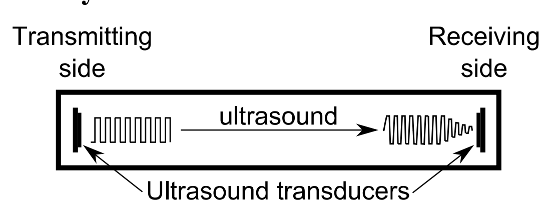

Fig. 1. *Sonar gas analyzer tube principle.*

The speed of sound is measured inside the sonar gas analyzer tube, which is filled with the analyzed gas. The ultrasound transducers are firmly attached at ~~the~~ both ends of sonar tube facing each other, see Fig. 1. One transducer transmits short burst of ultrasound pulses while the other transducer functions as a receiver. At the moment when the first ultrasound pulse is being transmitted a timer is started. The timer is stopped when the first ultrasound pulse is received at the other end of sonar tube. The number of fast-clock ticks counted by the timer represents the ultrasound transition time, so the speed of sound in the analyzed gas equals to the distance between transducers divided by adequate transition time. In order to obtain the proper transition time, the gas inside the sonar gas analyzer tube has to be still (without any residual flow) and the temperature and the pressure inside the sonar gas analyzer tube have to be uniform and stable. The sonar gas analyzer tube has to be leak tight and well insulated to secure these conditions. It is crucial to use very sensitive ultrasound transducers otherwise the response to the received ultrasound signal is slow and it takes considerable long time before the electrical signal from the excited receiving ultrasound transducer is strong enough to trigger the connected circuits. One could also notice the similarities between the sonar gas analyzer and sonar flow meter. In the sonar flow meter the flow rate is proportional to the difference between upstream and downstream ultrasound transition time. With a little effort the sonar gas analyzer electronics can be modified in such a way that ultrasound is transmitted alternatively in both directions resulting in the device ability to work also as a flow meter. Additional modifications of the tube geometry would be necessary to ensure smooth streamlined flow between the ultrasound transducers.

3. Design of the sonar gas analyzer tube

The sonar gas analyzer tube is made of stainless steel so that it is chemically and corrosion resistant. Its body consists of three main parts: two flanges and the central tube (see Fig. 2). The length of the central tube is 350 mm and its internal diameter is 44.3 mm, thickness of the tube is 2 mm. The flanges are standard UHV (Ultra High Vacuum) with copper gasket as sealing.

Fig. 2 *Central tube and one flange*

A number of threads are machined in both flanges: four blind M3 threads on the inner sides of the flanges, three threads for the bulkhead fittings and one thread for nine-pin electric connector which connects the transducers and temperature sensors inside the tube to the sonar electronics and DAQ (Data Acquisition) system. The electric connectors have rubber o-ring sealing and can withstand pressures up to 20 bar, the bulkhead fittings are sealed by copper gaskets. One holder made of aluminum in which the ultrasound transducers are accommodated is attached to each flange via the M3 threads. In order to be able to measure the speed of sound at temperatures different from the room temperature, two copper tube coils are placed inside the sonar gas analyzer tube, see Fig. 3. The inputs and outputs of these coils pass through the bulkhead fittings mentioned above so that the coils can be connected to chiller or any other supply of liquid having a stable temperature. The third and last bulkhead fitting on each flange is used as a connecting port for the measured gas, pressure sensor or vacuum pump.

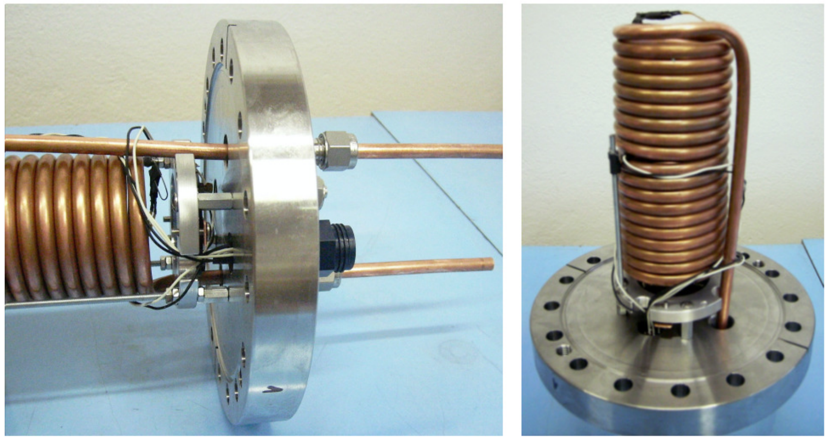

Fig. 3 Fully instrumented flange

4. An improved sonar gas analyzer electronics

The aim was to develop more versatile electronics providing higher precision of measurement then the traditionally used one. The sonar gas electronics generates the signal by which the transmitting ultrasound transducer is excited, measures the ultrasound transition time, detects received ultrasound and sends the measured values to PC (Personal Computer). Since the capacitive ultrasound transducers are used our electronics also provides a high voltage bias necessary for transducers operation. The capacitive transducers consist of a metal plate and thin gold membrane. When the high voltage bias is applied an electrostatic force deflects the membrane from the metal plate allowing it to oscillate freely once the exciting signal is added to the bias voltage. The industrial DC/DC (Direct Current/Direct Current) convertor with output adjustable from 0V up to 500V is used as a high voltage bias source. The PC can be connected to the sonar electronics via USB (Universal Serial Bus) or RS232 (Serial Port). Basic scheme of the electronics is introduced in the Fig. 4.

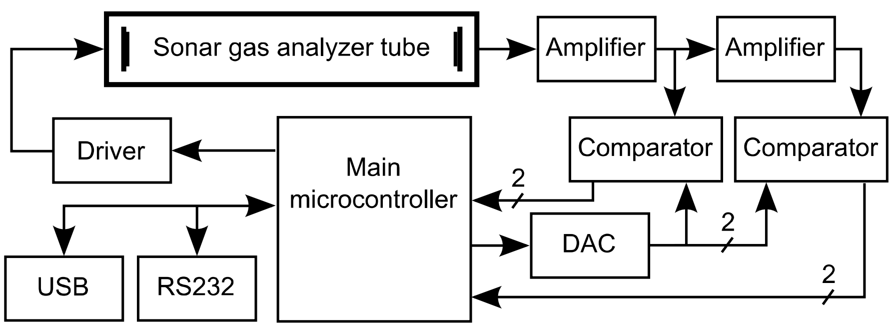

Fig. 4. *Block scheme of sonar gas analyzer electronics*

The transmitting ultrasound transducer is connected to the driver circuit. When idle, the transducer is biased by high voltage provided by DC/DC convertor. The transducer is periodically driven to 0V during the ultrasound transmitting. The 50 kHz TTL signal for the driver block is generated in the main microcontroller, usually eight pulses are transmitted. The detail of the driver circuit is shown in the Fig. 5. The capacitor C8 is charged from high voltage source through the resistor R7. When the log. 0 is present on DRIVER signal leaving the transistor T2 open (idle state) the voltage on the transducer equals the high voltage on the capacitor C8 and the transducer is biased. Once the log.1 is present on the DRIVER signal the transistor T2 closes and connects the transducer to the ground while discharging the capacitor C8 through the resistor R6. These periodic changes of the electric tension on the transducer excite its membrane and hereby the ultrasound is emitted.

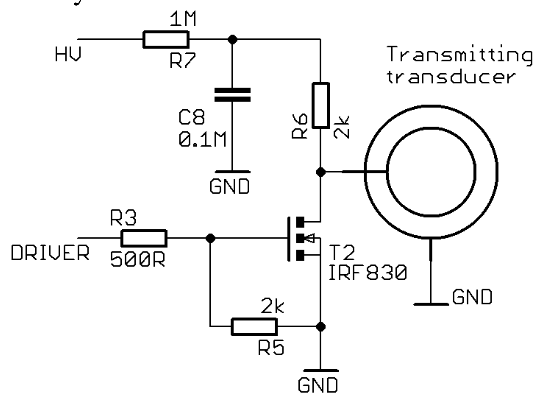

***Fig. 5.** Detail of driver circuit with ultrasound transducer*

Once passing the distance between the transducers, the ultrasound is converted into the electrical signal by the second transducer and this signal passes to the dual stage high speed amplifier which is depicted in Fig. 6. The receiving transducer is biased through the resistor R2 and this bias is eliminated by mica coupling capacitor C5 at the input of the amplifier. The diode D2 provides some level of protection in the event of high voltage presence at the amplifier input. The first stage of amplifier is set to high gain since the signal amplitude after the coupling capacitor is tens of millivolts. The amplification factor of the second stage is to two in order to obtain better shape of the signal and steeper slope of signals edges. Both operational amplifiers are equipped with capacitors close to the power pins as recommended in the data sheets. Output signals from first and second stage are then compared in the Comparator blocks with two threshold levels generated by dual channel DAC (Digital to Analog Convertor).

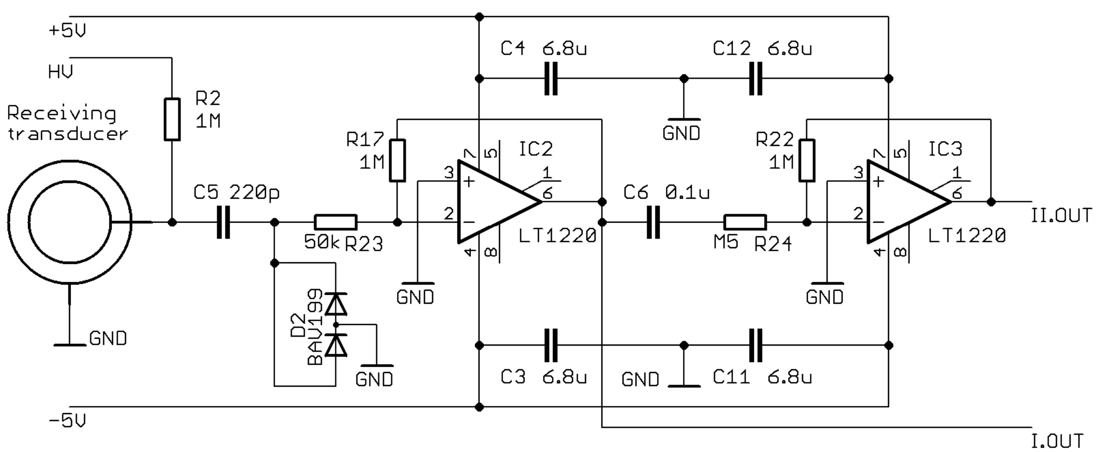

***Fig. 6.** Detail of high sped dual stage amplifier*

The digital values representing the threshold levels are sent from PC to the main microcontroller and they are written to DAC via SPI (Serial Peripheral Interface). The 16bit timer running at 20MHz inside the main microcontroller measures the ultrasound transition time. The timer is started at the moment when the first edge of square-wave driving signal is being generated. Two transition times are then measured. The first one is measured when the received signal crosses the lower threshold for the first time and the second one is measured when the second and higher threshold is crossed. The crossing of the thresholds is detected by Comparator circuits. The resulting transition time is calculated as an average of these two transition times. An example of received ultrasound signal after amplification and principle of first edge detection are shown in the Fig. 7.

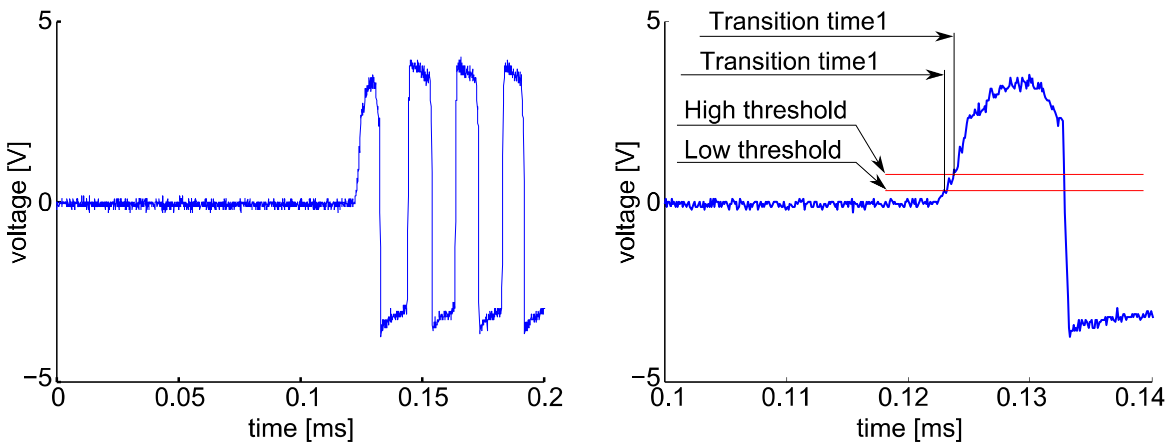

Fig. 7. *Received ultrasound signal after amplification and principle of first edge detection*

The measurement cycle begins after the instruction from PC is received. The valid threshold levels have to be set prior to the beginning of the cycle. The status of the sonar electronics is indicated by five LEDs (Light-Emitting Diode) during the operation. Two green LEDs indicate the traffic via USB. The red LED indicates that there is no reception of ultrasound signal - this can happen when there is vacuum in the sonar gas analyzer tube or the connectors on flanges are disconnected. The last two LEDs indicate the start and the end of measurement cycle. The populated PCB (Printed Circuit Board) of the sonar gas analyzer electronics is shown in the Fig. 8.

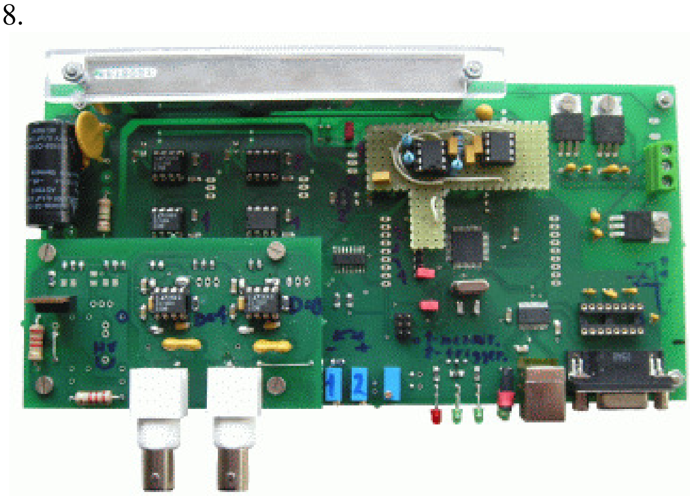

Fig. 8. *Sonar gas analyzer electronics*

The communication protocol between PC and the sonar gas analyzer electronics comprises seven messages. Four command messages are sent from PC: “Reset”, “Echo”, “Start measurement” and “Set threshold levels”, the other three messages are sent to PC as an answer to command messages: “Reset OK”, “Echo” and “Measured transition times”.

5. Description of the full set up for speed of sound measurement

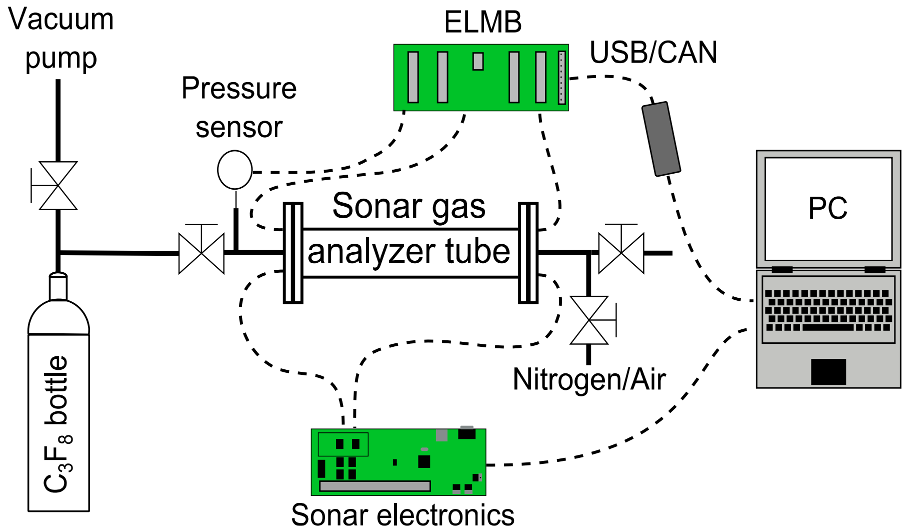

Fig. 9. *Overview of speed of sound measurement facility*

Whole set up for speed of sound measurement is composed of following parts (see Fig.7):

- sonar gas analyzer tube
- sonar gas analyzer electronics
- DAQ system with ELMB for temperature and pressure sensors readout
- computer/laptop
- vacuum pump

The ELMB (Embedded Local Monitor Board) was chosen as a DAQ system, since it has been widely used at our Department of Applied Physics. The ELMB offers readout of up to 64 analog channels, each of them can be configured for any kind of temperature or pressure sensor and ELMB itself is connected to superior PC via CAN (Controlled Area Network) bus and USB to CAN convertor. The GUI (Graphic User Interface) allowing to plot, store and export data acquired by ELMB was also developed at the Department of Applied Physics. Four NTC (Negative Temperature Coefficient) and two Pt1000 temperature sensors are installed inside the sonar gas analyzer tube, allowing to measure temperature along whole length of the ultrasound path. The precise Keller pressure transducer (0-15bar) with (0-10) V output was chosen for the pressure monitoring. The gas inputs of the sonar gas analyzer tube are equipped with needle valves in order to be able to set the gas pressure precisely. The internal volume has to be evacuated before the sonar gas analyzer tube is filled with the investigated gas or vapor. For that purpose the gas input is shared with a vacuum pump which can be separated by a ball valve on one side of the sonar tube.

6. Summary of prototype improvements

- The internal volume of the sonar gas analyzer tube was reduced from approximately 4 liters to 0.6 liters This helps to reduce the amount of gas consumed for measurements and thus reduce the sample cost.
- Two copper tube coils are placed inside the sonar gas analyzer tube and its inputs and outputs pass through the bulkhead fittings in the flanges. This arrangement should help

to control the temperature of the analyzed gas better when the cooling fluid circulates through these coils.

- The sonar gas analyzer electronics uses dual stage amplifier instead of single stage one and two instead of only one threshold level. Threshold levels can be set from the PC thanks to dual channel DAC implemented in sonar gas analyzer electronics. It is also possible to trigger on both positive and negative polarity of the received ultrasound signal.

7. Results of commissioning measurements

The calibration of the sonar gas analyzer has to be carried out before the real measurements of speed of sound. The precise distance between ultrasound transducers membranes is obtained as a result of this calibration. The knowledge of the correct distance is necessary since the speed of sound is calculated as the distance divided by the measured transition time. Behavior of the selected gas for the calibration should be close to the ideal gas model so the speed of sound in the reference gas at certain pressure and temperature can be precisely calculated. The NIST (National Institute of Standards and Technology) REFPROP software tool was used for speed of sound calculations. For nitrogen and used ranges of temperature and pressure, the uncertainty of the calculated speed of sound value is within 0.005%. The verified distance equals the calculated speed of sound divided by the measured transition time. For the calibration and all subsequent measurements the bias voltage was set to 300V and the threshold levels were set to 174mV and 192mV. Data from our calibration carried out in nitrogen are shown in Table 1.

Table 1. – *Calibration in nitrogen*

Transition time	Temperature	Pressure	Calculated speed of sound	Verified distance
[ms]	[K]	[bar_a]	[m/s]	[m]
0.781208	296.08	1.071	350.85	274.087
0.781200	296.07	1.185	350.86	274.092
0.781125	296.06	1.291	350.87	274.073
0.780821	296.26	1.415	351.01	274.076
0.780621	296.25	1.714	351.05	274.037
0.780633	296.25	1.801	351.06	274.049
0.780596	296.25	1.906	351.08	274.052
0.780500	296.23	2.095	351.10	274.034
0.780433	296.23	2.201	351.11	274.018
0.780371	296.22	2.396	351.14	274.019
0.780259	296.22	2.589	351.17	274.003
0.780125	296.24	2.685	351.19	273.972

The average verified distances equals 274.043 mm with a standard deviation of 0.029 mm. For the subsequent measurements in other gases the measured speed of sound was calculated as the calibrated distance divided by the measured transition time. The speed of sound measured in C_3F_8 vapor is shown in the Table 2 and Fig. 10. The C_3F_8 is used as a refrigerant in evaporative cooling circuits for high tech electronics, its boiling point at 1 bar_a is 236K (-37°C) while its critical pressure and temperature are 71.8°C and 26.4 bar_a respectively. The NIST REFPROP was used for calculation of speed of sound at certain temperature and pressure, the uncertainty pronounced to the calculated values is 1%.

Table 2. *– Measurement of speed of sound in C_3F_8*

Temperature	Pressure	Calculated speed of sound	Measured speed of sound	Absolute difference	Relative difference
[K]	[bar_a]	[m/s]	[m/s]	[m/s]	[%]
296.72	1.046	115.67	115.68	0.01	0.01
296.69	1.114	115.51	115.53	0.02	0.02
296.67	1.227	115.23	115.27	0.04	0.04
296.65	1.299	115.06	115.10	0.04	0.04
296.62	1.394	114.83	114.88	0.05	0.04
296.57	1.517	114.53	114.57	0.04	0.04
296.46	1.715	114.02	114.08	0.06	0.05
296.39	1.815	113.76	113.83	0.07	0.06
296.38	1.889	113.57	113.64	0.07	0.06
296.22	2.002	113.25	113.33	0.08	0.07
296.13	2.180	112.80	112.87	0.07	0.07
296.06	2.355	112.36	112.43	0.07	0.06
296.04	2.409	112.22	112.29	0.07	0.06
296.01	2.453	112.11	112.18	0.07	0.06
295.98	2.544	111.88	111.94	0.06	0.06
295.96	2.663	111.59	111.64	0.05	0.04

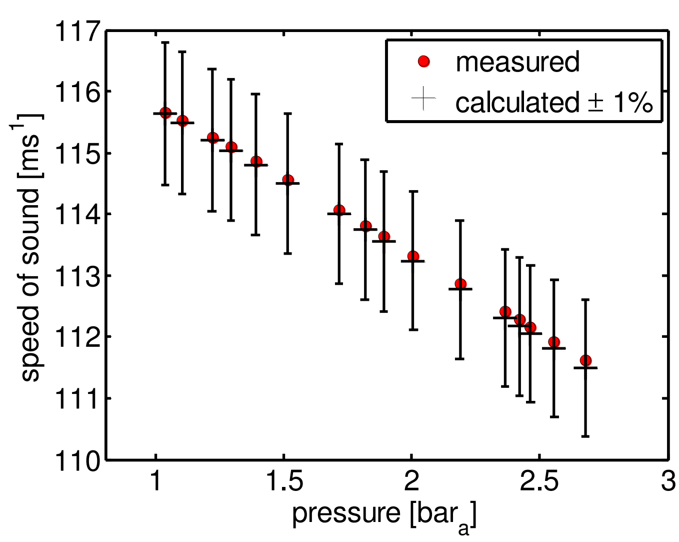

Fig. 10. *Measurement of speed of sound in C_3F_8*

8. Conclusions

Although based on relatively simple principle, the sonar gas analyzer proved itself to be a sensitive and versatile device. In comparison to other principles of laboratory speed of sound measurement such as spherical resonators, the sonar gas analyzer provides lower precision of measurement, however it can provide valuable thermodynamic data in short time and at a fraction of costs of a high precision method such as spherical or cylinder resonator. The range of operational pressures is basically limited by the type of used ultrasound transducers; feed through and by the construction of the sonar gas analyzer tube. The operational range of our capacitive ultrasound transducers was found to be the absolute pressure from 1 to 5 bar_a. The average error between the measured speed of sound (in nitrogen or in C_3F_8) and predicted speed of sound (by NIST REFPROP) within the range of pressures at room temperature was smaller than 0.1 $m.s^{-1}$. These measurements proved that it is possible to calibrate the device using well known gas such as nitrogen and then perform measurements in different gases with different molecular mass.

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