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Feasibility study of application of ultrasonic method for precise measurement of the long distances in air

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Abstract

The ultrasonic devices for distance measurement in air are simple in exploitation and their price in most cases is one of the smallest. However, high-precision measurements are affected by deviation of parameters of the surrounding medium, like temperature, relative humidity, CO_2 concentration and other parameters. Changes in air temperature by ±1°C cause deviation of ultrasound velocity by ±0.59 m/s. Such deviation gives the source of the distance measurement uncertainty of 0.17%, in the case of measurement of relatively long distance (4 m). The change of relative humidity by 5% gives the source of distance measurement uncertainty of 0.02%. In the case of carbon dioxide CO_2 concentration increases by 1%, ultrasound velocity decreases and it gives source of distance measurement uncertainty of 0.3%. In order to eliminate such factors, the additional calibration channel should be used. Also, the appropriate signal processing technique should be used in order to increase the resolution of time of flight (TOF) measurement. The uncertainty of TOF measurement was ±0.5 ns, which corresponds to the uncertainty of distance measurement ±0.18 mm (with a confidence probability 68%) and ± 0.36 mm (with a confidence probability 95%).

Keywords: distance measurement, ultrasound velocity, time-of-flight, cross-correlation.

Introduction

There are several ways for non-contact distance measurement in air: infrared light emitters and receivers, laser-based systems, eddy current methods and etc. to use. All these methods have their advantages and disadvantages.

The most reliable and inexpensive methods are based on application of ultrasonic waves. These methods are often used in automobiles to detect distance for parking assistance, in mobile robots to detect the obstacles for guidance control and in other distance measuring systems.

Application of ultrasonic methods for precise distance measurements has some restrictions: the speed of sound is very sensitive to deviations of air parameters along the measuring distance. In this article the feasibility study of algorithms for compensation the influence of the air parameters is presented.

Influence of the air parameters to the ultrasonic measurements

The ultrasonic distance measurement in air may be performed by the time-of-flight (TOF) technique, single frequency continuous wave phase shift, two-frequency continuous wave method, combining methods of TOF and phase-shift and etc. [1-9]. Usually, the TOF method based on transmission of ultrasonic waves along the distance being measured is used. The ultrasonic pulse is generated using a piezoelectric transducer (transmitter) and is received at the distance L by other transducer (receiver). The time of flight τ_{TOF} of the transmitted ultrasonic waves is calculated according the equation:

$$\tau_{TOF} = L/c_s, \tag{1}$$

where c_s is the speed of sound in air.

The principal factors affecting the speed of sound are ambient conditions such as temperature, humidity and air turbulence. Other factors include misalignment of transducers and signal detection method [8]. The speed of sound can be expressed in terms of known quantities and is given by [10]:

$$c = \sqrt{\gamma \frac{RT}{\mu}}, \tag{2}$$

where R is the ideal gas constant, T is the absolute temperature (in K), and μ is the average molecular weight of the gas molecules. Here $\gamma = C_P / C_V$, where C_P is the heat capacity of the gas at constant pressure and C_V is the heat capacity of gas at constant volume.

As shown in Eq.2, the speed of sound depends on the temperature and humidity. Since R and μ are the constants, the dependence of speed of sound on temperature is given by:

$$c = c_0 \sqrt{1 + \frac{T}{273.15}}, \tag{3}$$

where c_0=331.45 m/s is the speed of sound in dry air at temperature of 0^oC and atmospheric pressure of 760 mmHg with 0.03mol% of carbon dioxide [10].

In the case of temperature change by 1^0C, the speed of sound changes by 0.57 m/s at atmospheric pressure of 101,325 kPa. The ultrasound velocity increases in the case of rising temperature.

The influence of the air humidity to the speed of sound can be described as [11]:

$$c_h = c \cdot K_h, \tag{4}$$

$$K_h = 1 + h \cdot \begin{pmatrix} 9.66 \cdot 10^{-4} + 7.2 \cdot 10^{-5} \cdot T + 1.8 \cdot 10^{-6} \cdot T^2 + \\ + 7.2 \cdot 10^{-8} \cdot T^3 + 6.5 \cdot 10^{-11} \cdot T^4 \end{pmatrix},$$

where *h* is the air humidity in %. A significant change in air humidity (for example, by 50%) corresponds to a slight change in temperature (by +1°C). Therefore, the influence of air humidity to the speed of sound can be evaluated using the empirical formulas.

The dependence of the speed of sound on the temperature and humidity are presented in Fig.1.

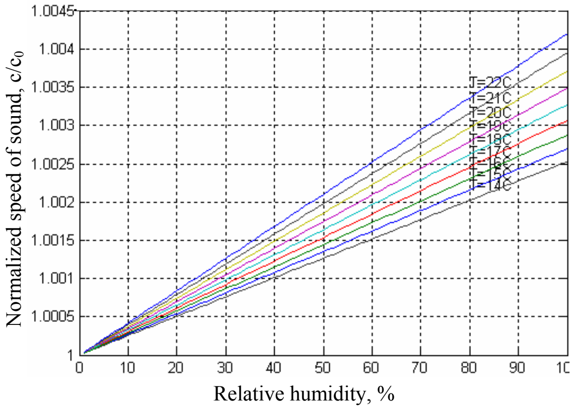

Fig.1. **The dependence of the normalized speed of sound c/c_0 on the temperature T and relative humidity h.**

Another factor is the quantity of the carbon dioxide in air. This factor slightly affects the speed of propagating ultrasonic wave. Most of CO_2 variation does not exceed 0.1%. Therefore, this affects the sound speed variation much less than the temperature change by ±1°C.

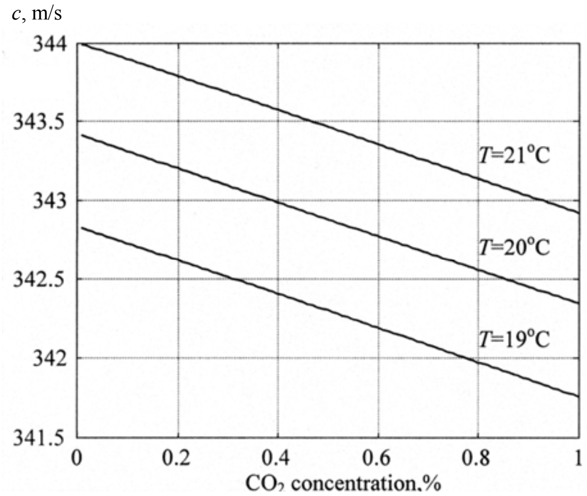

Fig.2. **The dependence of the speed of sound on the CO_2 concentration.**

One of the main factors is the attenuation of ultrasonic waves. The sound attenuation in the air dramatically increases as the frequency increases:

$$a(T,f,h)=\frac{(33+2T)f^2}{2\cdot 10^{12}}\cdot\frac{\left(\dfrac{f^2}{6{,}8\cdot 10^9 h^{1{,}3}}\right)}{1+\left(\dfrac{f}{8{,}5\cdot 10^4 h^{1{,}3}}\right)},\qquad(5)$$

where *f* is the frequency of the ultrasonic waves (Fig.3.).

Higher frequencies (up to 5 MHz) have potentially better resolution, but accordingly to Eq.5 possess essentially higher attenuation. Therefore, lower frequencies (20-100 kHz) have the advantage due to low attenuation and could be used for propagation of long distances in air. Usually, for ultrasonic distance measurement, the ultrasonic transducers having central frequency of 40 kHz are widely used.

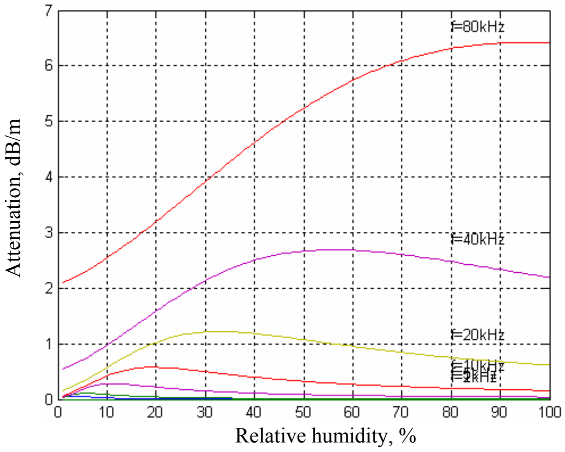

Fig.3. **The dependence of the ultrasound attenuation on the relative humidity and the frequency.**

Problems of the precise ultrasonic distance measurements

In the case of accurate measurements (uncertainty close to ±1 µm) of a relatively long distance (close to 4 m) some restricting facts should be taken into account:

- In order to evaluate the speed of propagating ultrasonic wave, it is not enough to used Eq.4 only. The uncertainty of ultrasound speed estimation should not exceed ±83 mm/s. For example, deviation of temperature of surrounding medium in 0.01°C gives the source of ultrasound speed estimation of 2.4 mm/s;
- the uncertainty of the time of flight measurement of propagating ultrasonic wave should not exceed ±3 ns. Therefore, the stable and reliable detection of received signals should be performed, also the appropriate processing technique should be used;
- in order to compensate the influence of the surrounding medium (deviations of temperature, humidity, CO_2 concentration and etc.) the appropriate calibration (reference) channel with a fixed distance between the transmitter/receiver and the planar reflector should be used.
- After the preliminary calculations it was defined that the optimal distance between the ultrasonic transducer (transmitter/receiver) and the planar reflector should be 1 m. Therefore, there are high requirements for installation of calibration channel: the uncertainty of the 1 m distance measurement using the pulse-echo technique should not exceed ±0.25 µm;

Further, the appropriate experimental investigations concerning the mentioned factors are presented below.

Experimental results

The experimental investigations of the precise distance measurement in air have been performed in the laboratory. The two-channel low-frequency ultrasonic measurement system developed in Ultrasound Institute of Kaunas University of Technology was used (Fig.4). For transmission and reception the commercially available piezoelectric resonant transducers (MURATA) possessing frequency of 40 kHz were used. The transducers are placed face to face with a fixed distance in between (*L*=4154 mm). The ultrasonic transmitter was excited by a pulse of 20 V. The received ultrasonic signals were amplified by the ultrasonic system with 65 dB gain. The control of ultrasonic measurement system and data transfer to PC has been performed via USB 2.0 bus. During the experimental investigations 100 measurements were performed with averaging of 64 signals at each measurement.

a

b

Fig.4. **Images of the used ultrasonic measurement system (a) and air-coupled ultrasonic transducer (b).**

The measured ambient temperature was 22° C, humidity was 80%. These environmental conditions correspond to the theoretical ultrasound velocity in air c=345.715 m/s.

In order to compensate the changes of ultrasound velocity caused by air flow, turbulence, temperature, and humidity the additional measurements were carried out using the second channel of the system (calibration). During the procedure of calibration, the ultrasonic waves reflected by the planar reflector placed at the fixed distance of 1 m were registered and the reference time delay was calculated.

The shape of the ultrasonic signal measured at a fixed distance in the air (*L*=4154 mm) is presented in Fig.5.

At first, the lower sampling frequency of 12.5 MHz was used to digitize the whole signal and to detect the informative part. After that, the selected informative part was digitized with the sampling frequency of 100 MHz.

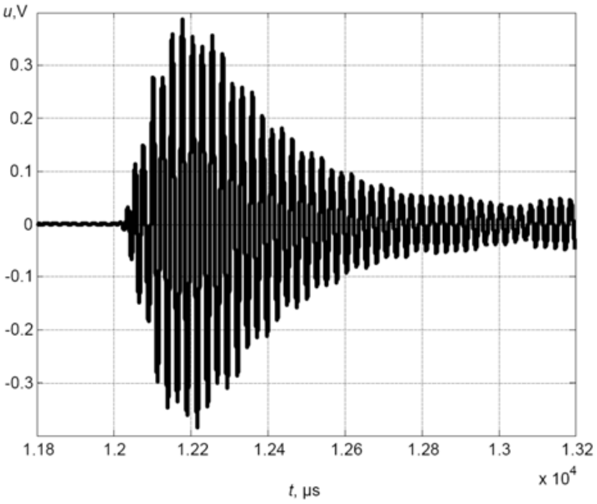

Fig.5. **Waveform of ultrasonic signal at distance of *L*=4154 mm.**

The digital signal processing (digital filters) and correlation processing were used to improve the signal-to-noise ratio. Using the cross-correlation method the delay time of the signal is measured in two steps. The cross-correlation function $y_{cc}(t)$ between the reference signal $u_1(t)$ and the measured signal $u_2(t)$ has been calculated:

$$y_{cc}(\tau) = \frac{1}{T}\int_0^T u_2(t)\cdot u_1(t-\tau)dt\,, \qquad (6)$$

where τ is the delay time between the signals $u_1(t)$ and $u_2(t)$, T is the duration of the rectangularly shaped time window.

The peak position of cross-correlation function corresponding to the difference between the delays time of the signals $u_1(t)$ and $u_2(t)$ is given by:

$$\hat{t}_{cc} = \arg\{\max[y_{cc}(\tau)]\}\,. \qquad (7)$$

Maximal values of the cross-correlation function were revised more precisely by an estimation of the zero-crossing time instant of the cross-correlation function derivative, additionally using the 3rd degree polynomial approximation through 5 neighboring points [12].

Using the above mentioned technique in order to increase resolution of delay time measurement, the achieved uncertainty (standard deviation) of the measured time of flight of ultrasonic wave propagated a long distance (close to 4 m) was ±0.5 ns. This corresponds to the distance measurement uncertainty of ±0.18 μm (with a confidence interval of 68%) and ±0.36 μm (with a confidence interval of 95%).

The histogram of the standard deviation values of the time delay measurements at the fixed distance of 4154 m is presented in Fig.6.

The delay times according to Eq.1 were recalculated into the distance *L*. The histogram of the standard deviation values of the distance measurement is presented in Fig.7.

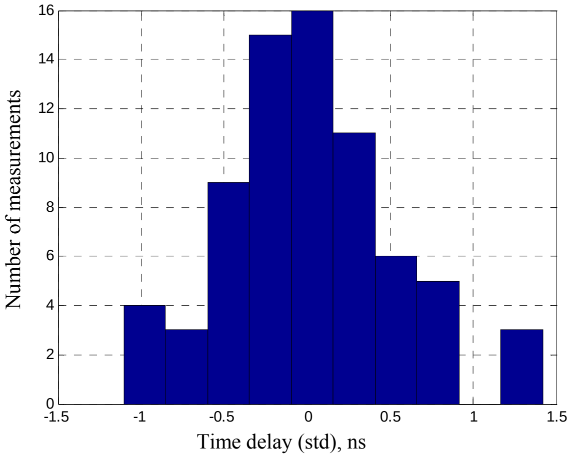

Fig.6. **The histogram of the standard deviations of the time delay measurements at a fixed distance of 4154 mm in the air.**

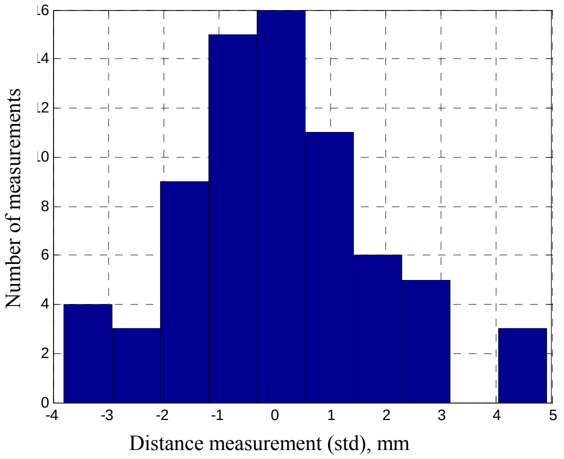

Fig.7. **The histogram of the standard deviations of the distance measurements at a fixed distance of 4154 mm in the air.**

Conclusions

The speed of sound is the main parameter for characterization of air medium in the case of the precise distance measurements. The principal factors affecting the speed of sound are ambient conditions such as temperature, humidity and air turbulence. The article investigates the influence of each factor on the uncertainty of long distance measurements (up to 4 m).

In order to eliminate the sources of uncertainty related to parameters of the surrounding air, the additional calibration channel should be used.

The achieved uncertainty of the time of flight measurement using the interpolation technique was ±0.5 ns, which corresponds to the total distance measurement uncertainty of ±0.18 mm (with a confidence probability of 68%) and ±0.36 mm (with a confidence probability of 95%).

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Ultragarsinio metodo taikymo tiksliesiems didelių atstumų matavimams ore atlikti galimybių studija

Reziumė

Atstumu matuoti ore šiuo metu naudojama daug ir įvairių prietaisų. Iš jų plačiai paplito ultragarsiniai atstumo matuokliai. Šiuos prietaisus nesudėtinga eksploatuoti, o jų kaina daugeliu atvejų yra viena mažiausių. Tačiau atliekant tiksliuosius matavimus susiduriama su tokių prietaisų parametrams turinčiais įtakos veiksniais: matavimų rezultatų neapibrėžtis sąlygoja aplinkos temperatūros, santykinės drėgmės, CO_2 koncentracijos ir kitų parametrų pokyčiai.

Straipsnyje nagrinėjama kiekvieno šių veiksnių įtaka bendrai atstumo matavimo neapibrėžčiai. Oro temperatūrai pakitus ±1°C, ultragarso greitis pakinta ±0,59 m/s, dėl to matuojant 4 m atstumą atsiranda papildoma 0,17 % atstumo matavimo neapibrėžties šaltinio dedamoji. Santykinės drėgmės 5 % pokytis sukelia papildomą 0,02 % atstumo matavimo neapibrėžties šaltinio dedamąją. Anglies dvideginio CO_2 koncentracijai padidėjus 1 %, sumažėja ultragarso greitis ir kartu atsiranda 0.3 % atstumo matavimo neapibrėžties šaltinio dedamoji. Atsižvelgiant į šiuos tyrimus, pateikiamas nagrinėjamų veiksnių įtakos pašalinimo algoritmas. Jis paremtas tuo, kad naudojamas papildomas kalibracinis kanalas dideliam atstumui (iki 4 m) matuoti ore. Naudojant straipsnyje aprašytas skiriamumo padidinimo priemones ultragarsinių signalų suvėlinimo laikui matuoti tikėtinoji suminė neapibrėžtis sumažinta iki ±0,5 ns, o tai atitinka suminę ±0,18 µm (esant 68% pasikliovimo tikimybei) ir ±0,36 µm (esant 95% pasikliovimo tikimybei) atstumo matavimo neapibrėžtį.

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