

# Novel ultrasonic distance measuring system based on correlation method

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**Abstract:** This paper presents an innovative method for measuring the time delay of ultrasonic waves. Pulse methods used in the previous studies was characterized by latency. The method of phase correlation, presented in this article is free from this disadvantages. Due to the phase encoding with the use of Walsh functions the presented method allows to obtain better precision than previous methods. The algorithm to measure delay of the reflected wave with the use of microprocessor ARM Cortex M4 linked to a PC has been worked out and tested. This method uses the signal from the ultrasonic probe to precisely determine the time delay, caused by the propagation in medium, possible. In order to verify the effectiveness of the method a part of the measuring system was implemented in LabVIEW. The presented method proved to be effective, as it is shown in presented simulation results.

**Key words:** ultrasonic measurements, non-destructive testing, delay measurement algorithm, phase correlation

## 1. Introduction

The ultrasound phenomena is widely used to distance measuring by systems and devices. Ultrasonic waves can be mechanically generated in the system with a piezoelectric transducer excited by an electrical impulse. Frequency of the wave generated in such a way is determined by the mechanical resonance of the transducer, which is in turn strongly dependent on the thickness of piezoelectric element. The incoming signal is a superposition of all reflected waves and is detected by a piezoelectric transducer. The signal is then converted to a low-voltage electrical signal. The analysis of this electrical signal is the main point of the presented method of distance measuring. The methods used so far have been limited to the analysis of a single impulse of ultrasonic wave propagation in a medium [3-7, 13-15] which is insufficient and does not give satisfying and unequivocal results when the medium parameters are complex or subject to changes. The method described in the article allows the analysis of time delay of ultrasonic wave with frequency higher than the inverse of the time delay of the wave. The use of ARM processor allows to increase the frequency for continuous phase modulation,

and phase encoding with the use of Walsh functions gives the better resolution of measurement [8].

## 2. Analysis of detected signal

The measurement system presented in the article consists of the microcontroller ARM CORTEX M4, that online modulates the ultrasonic wave and retrieves data from detector [1]. Using the built-in USB interface, the measured data are transferred to a PC for further analysis. The PC enables to collect measured data and allows comparison of different measurement methods as to determine their effectiveness, comparing its parameters such as standard deviation, absolute and relative error.

Frequency response of the resonant piezoelectric transducer has its maximum at the resonant frequency  $\omega_0$  [kHz] (see Fig. 2).

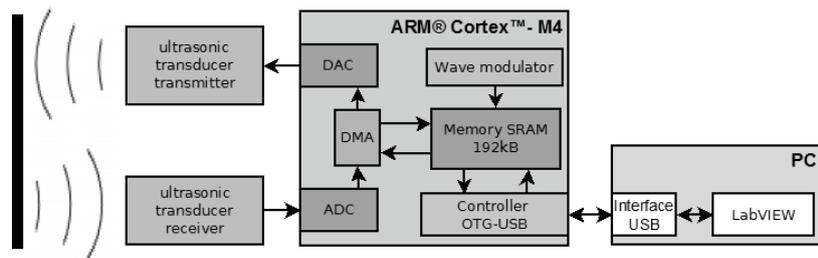


Fig. 1. A block diagram of the module with the ARM Cortex M4 to analyze ultrasonic wave delay

If this system is driven by the resonant frequency we obtain the strongest response of the incoming signal in the detector.

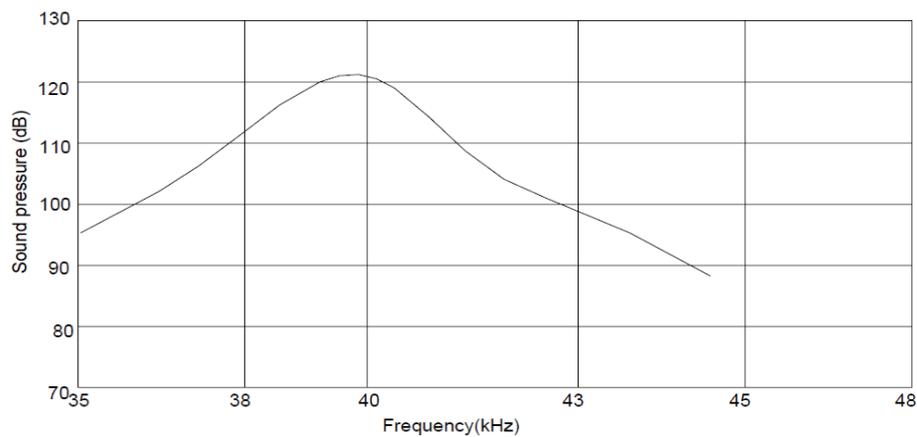


Fig. 2. Frequency characteristics of the transducer BPU-1640IOAH12 (source: Bestar Electronics Industry Co., LTD., LTD)

In the situation when the carrier signal frequency equals the resonance frequency of  $\omega_0$  the transmitter and the signal is modulated with signal  $y_o(t)$  of lower frequency, it is possible to obtain the modulation signal (envelope)  $y_o(t)$  of the received signal [2, 12].

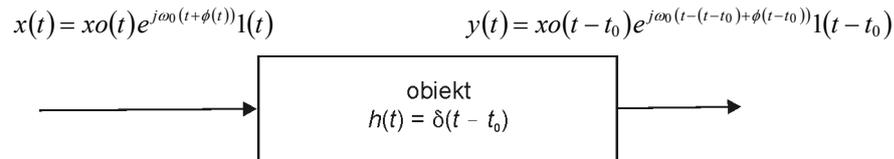


Fig. 3. Transducer response in resonance (convolution type) to the exponential signal which is a product of  $x_o$ -envelope and carrier wave with frequency

The transmitted signal has the frequency of the carrier wave and its phase is modulated by the function  $\phi(t)$ .

Its complex time formula is

$$x(t) = x_o(t) e^{j(-\omega_0 t + \phi(t))} 1(t) = x_m(t) e^{-j\omega_0 t} 1(t). \quad (1)$$

Similarly, the received signal can be described as

$$y(t) = y_o(t-t_0) e^{j(-\omega_0(t-t_0) + \phi(t-t_0))} 1(t-t_0) = y_m(t) e^{-j\omega_0 t} 1(t), \quad (2)$$

where:  $1(t)$  – unit step function,  $\omega_0$  – frequency of the carrier wave,  $\phi(t)$  – phase shift of the wave,  $t_0$  – the time delay of wave,  $x_o(t)$ ,  $y_o(t)$  – envelopes of transmitted and received signals  $x_m(t)$ ,  $y_m(t)$  – modulating signals of transmitted and received waves.

Modulating signals of transmitted and received waves are the complex envelopes of the carrier signal (see Fig. 3).

$$\begin{aligned} x_m(t) &= x_o(t) e^{j\phi(t)} \\ y_m(t) &\approx x_o(t-t_0) e^{j\phi(t-t_0)} 1(t-t_0) = \delta(t-t_0) * x_o(t) e^{-j\phi(t)} 1(t) \end{aligned} \quad (3)$$

where:  $1(t)$  – unit step function, \* – convolution.

After the Fourier transform we obtain

$$\begin{aligned} F(x_o(t)) &= X_o(j\omega) \\ F(x(t)) &= F(x_m(t) e^{-j\omega_0 t}) \approx X_o(j\omega + j\omega_0) e^{j\phi(t)}, \end{aligned} \quad (4)$$

where:  $Y_o$ ,  $X_o$  – transform of modulating signals  $y_o(t)$  and  $x_o(t)$  taking into account that

$$F(\delta(t-t_0)) = e^{-j\omega t_0}$$

and the fact that the change rate of modulating signal is much smaller than this of carrier signal, we obtain the transform of the received-modulating and received-modulated signals

$$F(y_m(t)) = c^{j\phi t_0} X_o(j\omega) c^{j\phi(t)} = Y_m(j\omega) \quad (5)$$

$$F(y(t)) = F(y_m(t) e^{-j\omega_0 t}) \approx c^{-j\omega_0 t_0} X_o(j\omega + j\omega_0) c^{j\phi(t)} = Y_m(j\omega + j\omega_0),$$

Thus, if the transform of modulated signal  $Y_m(j\omega + j\omega_0)$  is shifted in the frequency domain to the left (to lower frequency see Fig. 4) by  $\omega_0$ , i.e.  $\omega \rightarrow \omega - \omega_0$

$$Y_m(j\omega + j\omega_0) \rightarrow Y_m(j\omega) c^{j\omega_0 t_0} \quad (6)$$

we get the transform of the modulating signal with the initial phase altered.

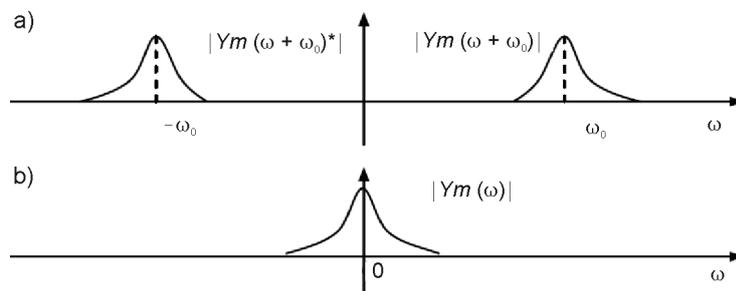


Fig. 4. Frequency offset by  $\omega_0$  to lower signal frequency as to obtain the transform of the modulating signal  $Y_m$  (b) from the modulated signal response (a) ( $Y_m^*$  is the conjugate transform of  $Y_m$ )

Turning back to the complex time signals

$$F^{-1}(Y_m(j\omega) c^{j\omega_0 t_0}) = x_o(t - t_0) e^{j(\phi(t-t_0) + \omega_0 t_0)} 1(t - t_0), \quad (7)$$

we obtain modulating signal whose phase is delayed and changed by a constant factor  $\omega_0 t_0$

$$\phi(t - t_0) + \omega_0 t_0. \quad (8)$$

Assuming that the phase modulating signal  $\phi(t)$  changes slower than the carrier signal [9], we can easily correlate the phase of both signals [10, 11] as to find their relative delay  $t_0$

$$\text{correl}(\phi(t - t_0) + \omega_0 t_0, \phi(t)).$$

An example result of such correlation of phases is shown in Figure 9.

### 3. Distance measuring experiment

Distances were measured by the use of system presented in Figure 1. Original LabVIEW program has been created to calculate, visualize and analyse the measurement data (see Fig. 11).

In order to generate a signal which would have the least number of autocorrelation false peaks, the Walsh function was used to phase encoding. Eight orthogonal base Walsh function are shown in Figure 5.

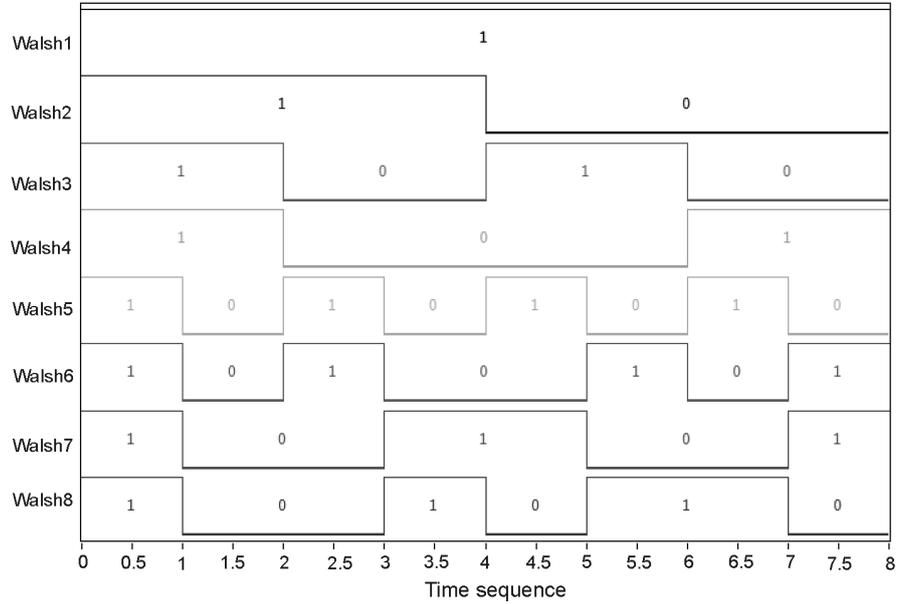


Fig. 5. Waveforms of 8 orthogonal Walsh functions

To reduce interference, the duration of each function was doubled. It has been obtained the following waveforms (Fig. 6)

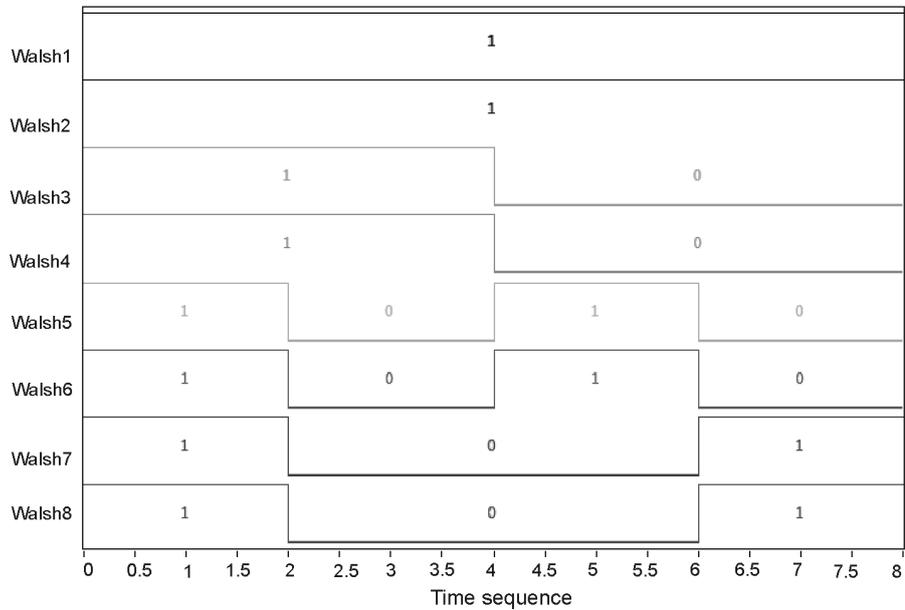


Fig. 6. Walsh functions Waveforms of doubled duration

After its sequential connection and scaling to the range  $(0, \pi)$  the phase function  $\phi(t)$  of the signal was generated (Fig. 7).

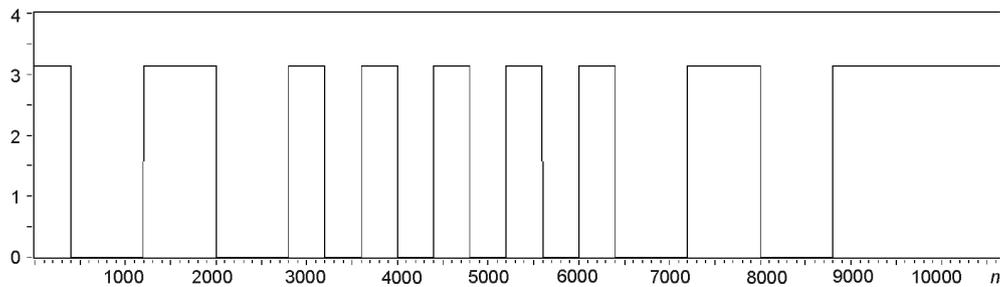


Fig. 7. Phase modulating signal of carrier wave

The phases signals of transmitted and received waves shifted to the range  $(-\pi/2, \pi/2)$  are shown in Figure 8

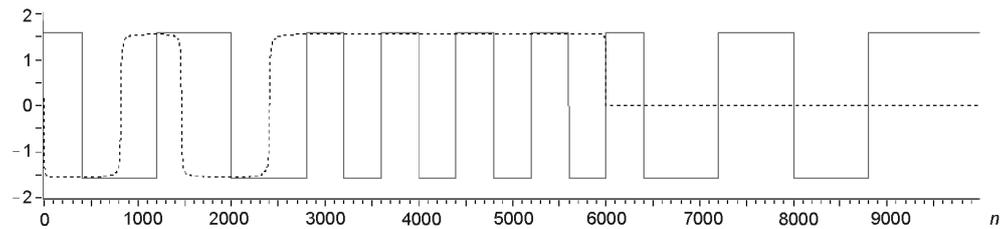


Fig. 8. The phase modulating signals of the transmitted signal (solid line) and the received (dotted line)

The phases of transmitted and received signals have been correlated. The maximum of correlation (Fig. 9) were used to determine the distance  $l$ .

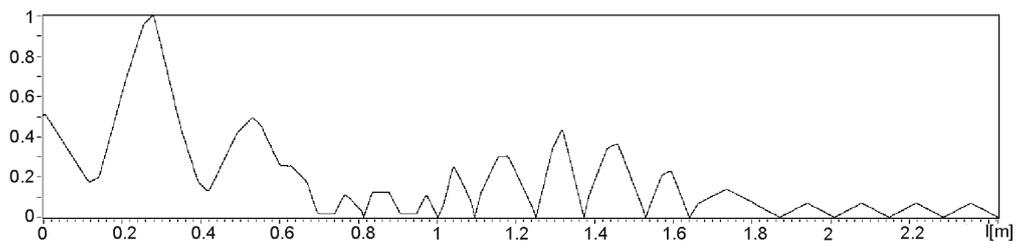


Fig. 9. The result of phase correlation of the transmitted and received signals

For the methods comparison the threshold detector method for distance measuring using signal envelope obtained with Hilbert transform was performed [13].

The deviations of measuring results has normal distribution. For measured distance the average of 50 individual measurements was taken. Assuming that the resolution  $\Delta l$  is defined as a situation of 50% probability that the result belongs to one or the other distance then the resolution equals

$$\Delta l = \frac{2}{3}\sigma,$$

where:  $\sigma$  – standard deviation.

An example of  $\Delta l$  dependence on the measured distance in the range (0.1÷0.9)[m] is shown in the Figure 10.

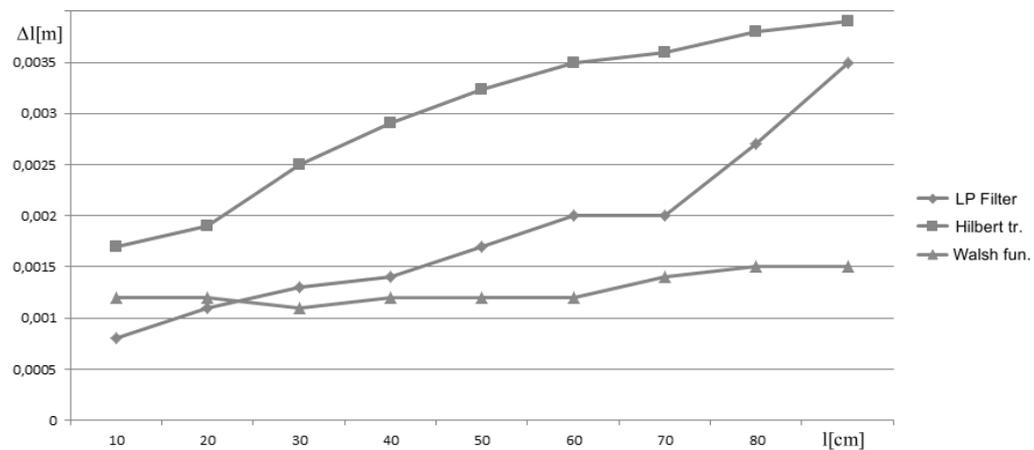


Fig. 10. Distance measurement resolution comparison for various methods

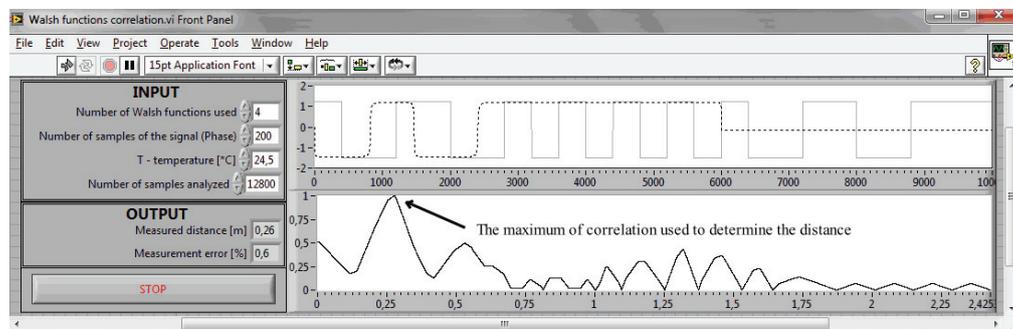


Fig. 11. The front panel of LabVIEW program. Example of phase modulation of transmitted and received signal and their correlation

## 4. Summary

The set of measuring instruments used to the distance determination presented in the article uses the correlation method of the signals transmitted and received. The novelty of the method is based on the use of orthogonal Walsh sequences for correlation to eliminate false local correlation maxima which usually result from the local repetition of sequences encoding the emitted signal phase. In order to determine the effectiveness of the method the measure-

ment errors were compared with the classical threshold methods, where the distance is determined with the threshold value of the signal envelopes. The measurement errors of the threshold methods, in which the envelope of the signal is determined by the low-pass filter and Hilbert transform was added to the presentation of the results as to show the improved efficiency of the new method (see Fig. 11). The experiment showed that the author's method of encoding phase by Walsh functions, allows to get better accuracy, less error dependence on the distance and distortion due to the clearer and sharper correlation peak that gives more accurate and stable results.

## References

- [1] Gądek K., *Methods of analysis of an impulse response wave of a steel anchor fixed in a rock mass*. International Journal of Rock Mechanics and Mining Sciences 43(8): 1288-1292 (2006).
- [2] Riley K., Hobson M., Bence S., *Mathematical Methods for Physics and Engineering*. Cambridge University Press, New York (2006).
- [3] Tsuneda A., Miyazaki Y., *Performance Evaluation of LFSR-Based Spreading Sequences with Negative Auto-correlation Designed by Chaos Theory of Modulo-2 Added Sequences*. IEEE, pp. 141-144 (2009).
- [4] Zhao X., Luo Q., Han B., *A Novel Ultrasonic Ranging System Based on the Self-correlation of Pseudo-random Sequence*. Proceedings of the 2009 IEEE International Conference on Information and Automation, Zhuhai/Macau, pp. 1124-1128 (2009).
- [5] Granja F., Jimenez A.R., *Ultrasound modulation and codification for localization systems, New Acoustics II*. CSIC Biblioteca de Ciencias, pp. 167-186 (2006).
- [6] Qing Xie., Shuyi Cheng, Fangcheng Lü, *Partial Discharge Location in Oil Using Ultrasonic Phased Array*. Przegląd Elektrotechniczny 89(3b) pp. 84-87 (2013).
- [7] Filipowicz Z., *Evidence Representations in Position Fixing*. Przegląd Elektrotechniczny 88(10b): 256-260 (2012).
- [8] Gądek K., Jaraczewski M., *Ultradźwiękowa metoda określania odległości*. Przegląd Elektrotechniczny, 89 (2013), 12 (2013), pp. 142-144 (2012).
- [9] Huang Y.P., Wang J.S., Huang K.N. et al., *Envelope pulsed ultrasonic distance measurement system based upon amplitude modulation and phase modulation*. Rev. Sci. Instrum. 78(6): 065103 (2007).
- [10] Hirata S., Kurosawa M.K., Katagiri T., *Real-time ultrasonic distance measurement for autonomous mobile robots using cross correlation by single-bit signal processing*. Proc. of IEEE Int. Conf. on Robotics and Automation, pp. 3601-3606, Kobe, Japan, May 12-17 (2009).
- [11] Hirata S., Kurosawa M.K., Katagiri T., *Cross-correlation by Singlebit Signal Processing for Ultrasonic Distance Measurement*. IEICE, Trans. Fundamentals E91-A(4): 1031-1037 (2008).
- [12] Huang Y.P., Wang J.S., Huang K.N. et al., *Envelope pulsed ultrasonic distance measurement system based upon amplitude modulation and phase modulation*. Rev. Sci. Instrum. 78(6): 065103-1-065103-8 (2007).
- [13] Li W., Chen Q., Wu J., *Double threshold ultrasonic distance measurement technique and its application*. [Journal Article] Rev. Sci. Instrum. 85(4) (2014).
- [14] Yang M., Hill S.L., Gray J.O., *A multifrequency AM-based ultrasonic system for accuracy distance measurement*. IEEE Trans. Instrum. Meas. 43(6): 861-866 (1994).
- [15] Huang C.F., Young M.S., Li Y.C., *Multiple-frequency continuous wave ultrasonic system for accurate distance measurement*. Rev. Sci. Instrum. 70(2): 1452-1458 (1999).