ANALYSIS OF ULTRASOUND SIGNAL ON REFLECTION FROM A SHARP CORNER SURFACE

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Abstract
The article deals with the analysis of ultrasonic signal amplitudes when the reflecting surface changes from the planar case to the sharp corner case. The distance between the transmitter and the reflecting surface was varied in steps in the interval 100 mm ÷ 215 mm. Statistically significant differences between the planar reflection and the reflection from the corner surface were demonstrated in the case of the ultrasound signal amplitudes at each distance as well as in the cases of the maximum components of the frequency analysis of the ultrasound signal. The statistically non-significant difference between the amplitude of the ultrasound signal and the amplitude of the simulated transfer function gives an indication of the universal description of the ultrasound signal on complex variable modelling in the case of reflection from a planar and corner surface.

Key words: *distance, measurement, transfer function, ultrasound amplitude, ultrasound reflection.*

INTRODUCTION

The measurement of position has fundamental place in the industry. Not only accuracy and scale but also the economics of the measurement system are addressed. Ultrasonic waves are widely used for object distance measurement, distance measurement in robots, robot (vehicle) navigation and so on in industrial applications (*Naba et al., 2015*). A typical system for distance measurement using ultrasound includes ultrasonic transducers for generating and sensing ultrasonic pulses, a microcontroller for controlling the measurement system, a temperature compensation for the accuracy of the measured distance, and a unit for processing the measured data (*Qiu et al., 2022*). The basic distance measurement method is the impulse method. Measurement systems using correlation for distance measurement, the generated ultrasonic signal is compared with the reflected ultrasonic signal from the object. The maximum of the correlation function over time gives a more accurate time indication for distance measurements relative to the impulse method. Compared to the impulse method, the correlation method requires a higher number of iterations of cross-correlations by convolution (*Hirata et al., 2008*). The authors (*Vogt et al., 2014*) report the application of ultrasonic water flow measurement. They note that the use of the correlation method improves the accuracy of flow measurement in turbulent flow media. In (*Blasina et al., 2017*), the authors subjected ultrasonic reflections from steel rods to correlation at specific times to which it was exposed to external heat. The method is used in monitoring temperature characteristics in food production. The measurement of the position of an object can also be obtained by integrating two ultrasonic sensors and identifying the position vector by triangulation. In applying the triangulation method, the authors (*Moreira et al., 2019*) used the standard deviation to quantify the deviations between the actual and the measured position vector. The authors (*Martínez et al., 2004*) used a nonlinear regression method to estimate the shape of the reflection surface between the planar case and the sharp edge. The aim of this article is the frequency analysis of an ultrasonic signal reflected from a sharp corner, representing a simulated edge in space. The results are compared with the reflection of the ultrasonic signal from a planar surface with unchanged characteristics.

MATERIALS AND METHODS

Measurement system

The animal positional identification logging system (*Lendelová et al., 2017*) was used as the measurement system. The block diagram of the measurement system is shown in Fig. 1. A 400ST160 piezoelectric transmitter was used as the source of ultrasonic impulses. The transmitter had a resonant frequency of 40 kHz ± 1 kHz according to (*Pro-Wave, 2005*). A 400SR160 piezoelectric sensor was used for ultrasonic reflection sensing. The electrical signal from the ultrasonic transducer was amplified with an operational amplifier with an input impedance of 1 kΩ and a gain of 25 dB. One transmitter and one ultrasonic impulse sensor were used.

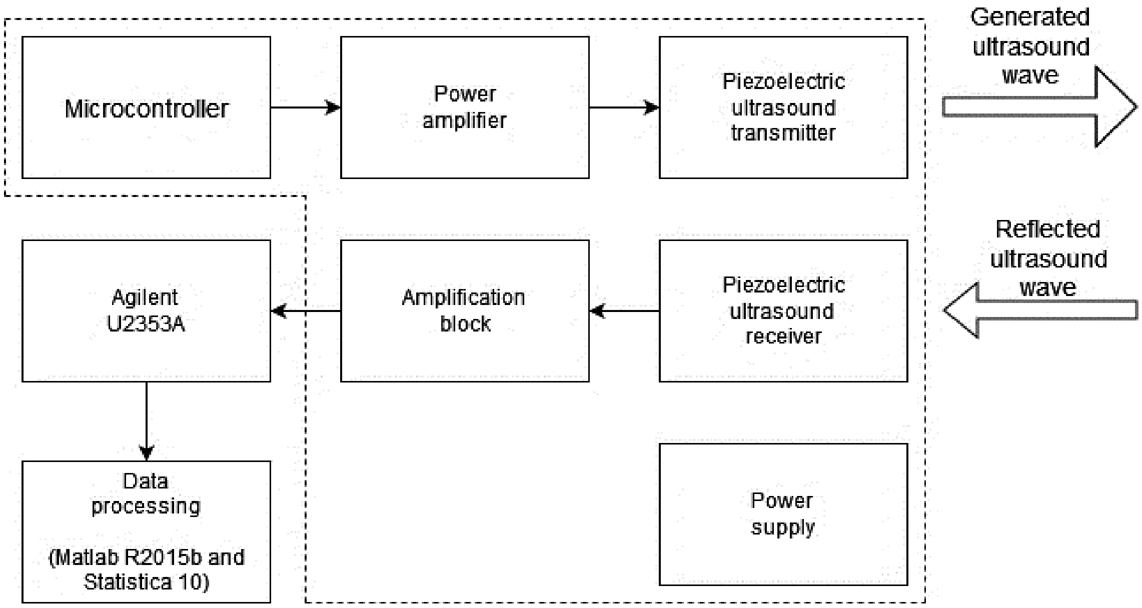

Fig. 1 Block diagram of measurement system

The electrical signal was measured with an Agilent U2353A data logger in differential mode of the analog inputs. The sampling frequency was determined 200 kHz heuristically. Selected characteristics of the datalogger used are shown in Tab. 1.

Tab. 1 Selected characteristics of U2353A dataloger (*Keysight, 2021*)

Parameter	**Value**
Resolution, bit	16
Number of analog channels, -	16
Input impedance, GΩ / pF	1 / 100
Uncertainty of measure, μV (at selected range: a) ± 10 V, b) ± 5 V, c) ± 2,5 V, d) ± 1,25 V)	± 305.2 a)
	± 152.6 b)
	± 76.3 c)
	± 38.2 d)
Sampling, MSa · s^{-1}	max. 1
Offset error, mV	± 1
Gain error, mV	± 2
System noise, mV	1
Slew rate, V · $(\mu s)^{-1}$	19

Agilent Measurement manager 1.2 software was used to acquire the measured signals. An electrical signal with an effective value of 3 mV was interpreted as noise. We cleaned the measured sample from the noise defined in this way, taking into respect the amplitude of the acquired signal in the Matlab environment.

Conditions of experiment

As a reflective surface we used a metal profile of ‘L’ shape with a thickness of 1.5 mm. The surfaces which were perpendicular to each other have the dimensions 230 mm x 110 mm. The reflecting normal was exposed to ultrasonic impulses in the planar case (Fig. 2, a) and in the corner case (Fig. 2, b). During the experiment, we changed the geometrical conditions of the measurement, namely: the distance between the transmitter and the reflecting surface was changed stepwise in the interval 100 mm to 215 mm. For the corner case, the transmit vector guide made a mid-angle with the reflection corner (45°). The ultrasound transducer and receiver were positioned at the geometric centre in the X-axis direction (Fig. 2).

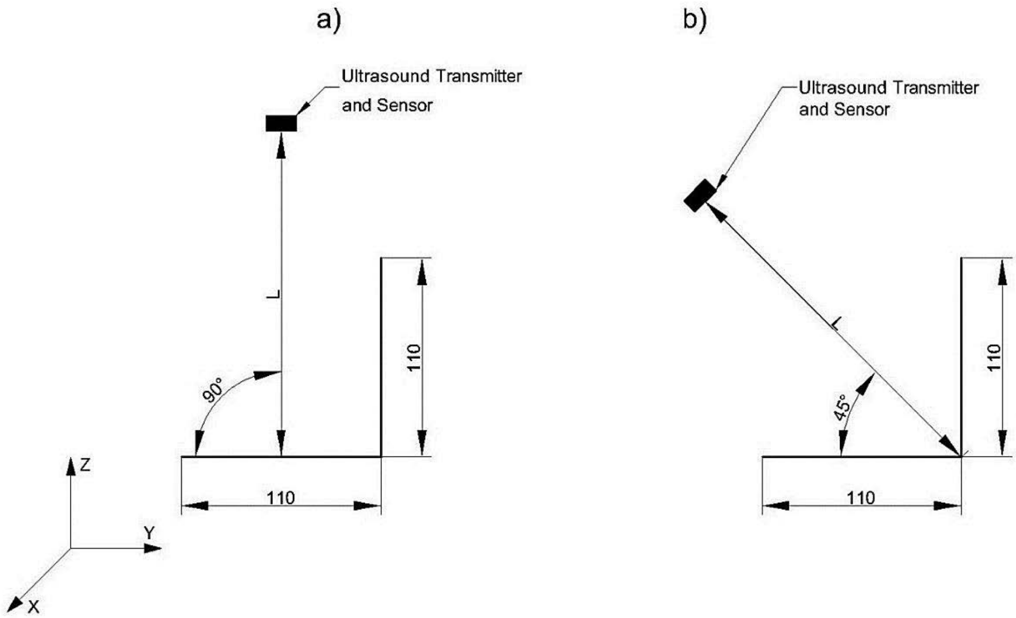

Fig. 2 Measurement geometric conditions (all length dimensions are in millimetres)

Data processing and used software

For statistical processing of observed data, STATISTICA 10 software was used. Results are presented as mean ± standard deviation. Statistically significant differences ($p \leq 0.05$) were obtained by Sidak's test in one-factor analysis of variance at the significance level of $\alpha = 0.05$. The normality of the measured data was verified by the Shapiro-Wilk test at a significance level of $\alpha = 0.05$. The experimental measurement was performed 4 times at a given distance *L*. Frequency analysis of the measured samples from the ultrasound sensor and modelling in the complex variable were performed by Discrete Fourier Transform in Matlab R2015b environment. The maximum frequency component was chosen as the quantifier of the frequency analysis result. We determined the correlation between the selected parameters by Pearson's correlation coefficient *r*.

RESULTS AND DISCUSSION

Analysis of ultrasound signal amplitudes

The statistical evaluation of the mean amplitudes of the ultrasonic signals at given distances *L* is presented in Fig. 3. The correlation between the average amplitudes and the distance *L* shows a nonlinear characteristic in the planar case with a coefficient of $r = -0.595$. The normality of the measured amplitudes was verified in favour of the Normal probability distribution with a maximum coefficient of variation which equal to 2.239 % for the condition $L = 200$ mm. In the corner case, the measured data showed statistically significant similarity to the Normal probability distribution with a maximum coefficient of variation of 2.393 % at the $L = 215$ mm condition. The correlation between the average ultrasound signal amplitudes and the distance *L* shows a non-linear characteristic in the corner case with a coefficient of correlation $r = -0.640$. By Sidak's test of statistically significant difference, we obtained statistically significant differences between the amplitudes of similar dimensions ($p \leq 0.05$). The nonlinearity of the signal amplitude with distance is consistent with the authors (*Martínez et al., 2004*), who modelled the amplitude function of ultrasound on distance with the exponential regression equation.

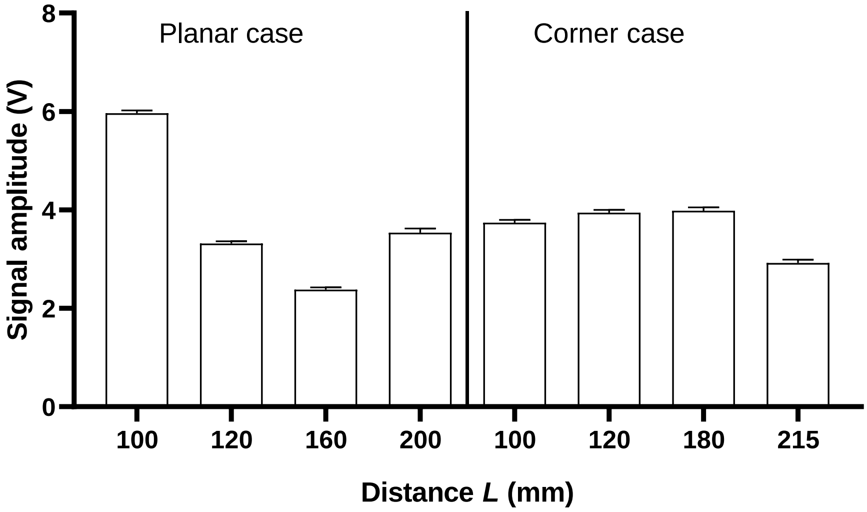

Fig. 3 Statistical evaluation of ultrasound signal amplitudes

Analysis of ultrasound signal frequency spectra

A statistical evaluation of the mean amplitudes of the ultrasound signal spectra at given distances *L* is shown on Fig. 4. By identifying the maximum amplitude component of the signal spectra at the ultrasound sensor, we determined the maximum frequency component, which was in the interval 40.039 kHz ÷ 40.625 kHz for both planar and corner cases. The normality of the identified spectra amplitudes was verified in favour of the Normal Probability Distribution for all measured samples with a maximum coefficient of variation of 2.746 % for the L = 200 mm condition. The correlation between the average spectral amplitudes of the ultrasound signal and the distance *L* shows a nonlinear characteristic with a coefficient r = **-** 0.635 on the planar case and a nonlinear characteristic with a coefficient r = **-** 0.195 on the corner case. By Sidak's test of statistically significant difference, we obtained statistically significant differences between the amplitudes of the spectra of similar dimensions ($p \leq 0.05$).

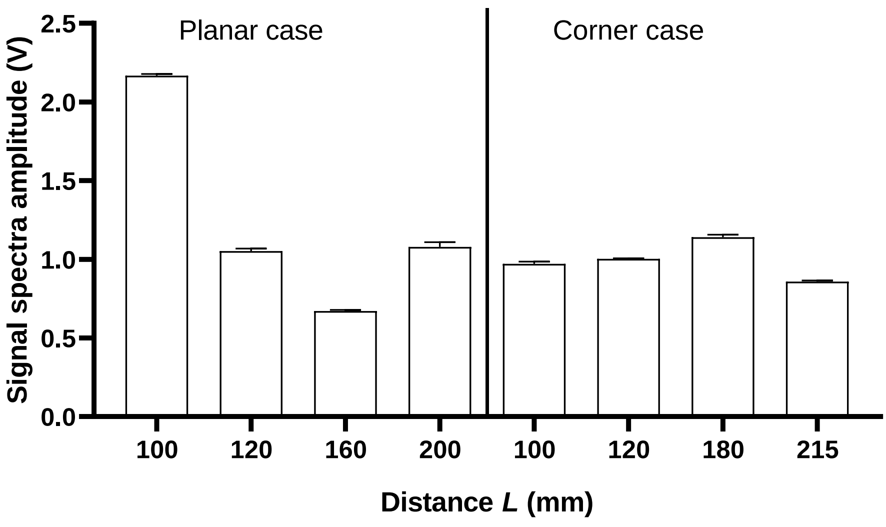

Fig. 4 Statistical evaluation of ultrasound frequency component amplitudes from signal spectra

Analysis of ultrasound signal by modelling on complex variable

By modelling the transfer functions of the measured ultrasound signals with maximum amplitudes of voltage on ultrasound sensor, we obtained third-order dynamic systems. The coefficient of determination was up to 85.86 % for the planar case and up to 83.99 % for the corner case.

Tab. 2 Poles and zeros of modelled dynamic systems

Parameter		Value
Poles, -	Planar case	- 1564 - 2249 ± i 3721
	Corner case	- 1196 - 1395 ± i 3885
Zeros, -	Planar case	8943 ± i 8997
	Corner case	6383 ± i 6368

The settlement time of the complex function shows an increase of 25.40 % in the corner case compared to the planar case. The increase indicates longer duration transient phenomenon in the case of reflection from a non-planar surface. The statistically significant difference between the transfer function amplitude and the experimental amplitudes was statistically significant ($p \leq 0.05$) in the planar case and statistically insignificant ($p > 0.05$) in the corner case. By comparing the chosen level of statistical significance and identified statistically significant differences, we can obtain similar distance measurement deviations, as the authors (*Moreira et al., 2019*) when interpreting the ultrasound signal amplitude at the level of threshold by voltage. Based on the amplitude of the ultrasound signal, we can correlate the dependence between the shape of the reflecting surface and the distance between the transmitter and the reflecting surface, which is nonlinear (*Yata et al., 2000*). The increase in transient phenomena for the corner case correlates with the multiple reflection from sharp edges as has been the result of the authors (*Martínez et al., 2004*). The authors (*Chen & Chou, 2008*) used the triangulation method to identify the corner reflective surface. Evaluating the influence of additional reflections on the frequency domain of the signal gives a direction to classify the acquired signal as time-varying, which will be reflected in quantifying the impulse duration over time as an n-th order dynamic system. It can be stated that according to the authors (*Qiu et al., 2022*), when cross-correlation is used to increase the accuracy of the distance measurement, at the same time, the computation duration requirements increase significantly due to the possibility of the presence of higher frequency significantly. The decrease in ultrasound signal amplitude in the corner case can be compared with the article (*Yata et al., 2000*), where the authors present a power function for the ultrasound amplitude as a function of the characteristics and distance from the reflecting surface.

CONCLUSIONS

The evaluation of correlation between the distance between object and the amplitude of ultrasonic signal is indicating a strong nonlinear dependence. The statistically significant difference between the planar reflection case of the ultrasound pulse versus the corner case suggest a possible correlation between the reflection case and the signal amplitude. Frequency analysis of the ultrasound signal showed identically statistically significant differences between the planar case and the corner case. The correlation between the amplitudes of the ultrasound signal spectra showed a poor nonlinear dependence to distance vector. In terms of transient effects, modelling the ultrasonic pulse is more guided by a complex model versus regression model.

ACKNOWLEDGMENT

The article was realized with the support of the project of Ministry of Education, Science, Research and Sport of the Slovak Republic: KEGA 006SPU-4/2021 Implementation of technology of Industry 4.0 in education process in study program ‘Control Systems in Production Engineering’.

REFERENCES

1. Blasina, F., Perez, N., Budelli, E., Lema, P., Kiri Ing, R., & Negreira, C. (2017). Development of a multiple-scattering acoustic sensor for process monitoring: Application to monitoring milk coagulation. 2017 IEEE International Instrumentation and Measurement Technology Conference. DOI: 10.1109/i2mtc.2017.7969965.
2. Hirata, S., Kurosawa, M. K., & Katagiri, T. (2008). Cross-Correlation by Single-bit Signal Processing for Ultrasonic Distance Measurement. IEICE Transactions on Fundamentals of Electronics, Communications and Computer Sciences. DOI: 10.1093/ietfec/e91-a.4.1031.
3. Chen, B. Ch. & Chou, J. (2008). A corner differentiation algorithm by a single sonar sensor for mobile robots. Asian Journal of Control. DOI: 10.1002/asjc.42.
4. Keysight. (2021). Keysight U2300A Series USB Multifunction Data Acquisition Devices. © Keysight Technologies.
5. Lendelová, J., Cviklovič, V., Olejár, M., & Pogran, Š. (2017). Animal position identification logging system. SK patent 288467.
6. Martínez, M., Benet, G., Blanes, F., Simó, J., Pérez, P., & Poza, J. (2004). Wall/corner classification. A new ultrasonic amplitude-based approach. IFAC Proceedings Volumes. DOI: 10.1016/s1474-6670(17)32054-2.
7. Moreira, T., Lima, J., Costa, P., & Cunha, M. (2019a). Low Cost Binaural System Based on the Echolocation. Advances in Intelligent Systems and Computing. DOI: 10.1007/978-3-030-36150-1_6.
8. Moreira, T., Lima, J., Costa, P., & Cunha, M. (2019b). Low-cost Sonar based on the Echolocation. Proceedings of the 16th International Conference on Informatics in Control, Automation and Robotics. DOI: 10.5220/0008119108180825.
9. Naba, A., Khoironi, M. F., & Santjojo, D. D. H. (2015). Low cost but accurate ultrasonic distance measurement using combined method of threshold-correlation. 2015 International Conference on Quality in Research. DOI: 10.1109/qir.2015.7374887.
10. Pro-Wave. (2005). Air Ultrasonic Ceramic Transducers: 400ST/R160. © Pro-Wave Electronic corp.
11. Qiu, Z., Lu, Y., & Qiu, Z. (2022). Review of Ultrasonic Ranging Methods and Their Current Challenges. Micromachines. DOI: 10.3390/mi13040520.
12. Vogt, M., Gevers, M., & Musch, T. (2014). Evaluation of transducer configurations for ultrasound cross-correlation flowmeters. 2014 IEEE International Instrumentation and Measurement Technology Conference Proceedings. DOI: 10.1109/i2mtc.2014.6860519.
13. Yata, T., Ohya, A., & Yuta, S. (2000). Use of amplitude of echo for environment recognition by mobile robots. Proceedings. 2000 IEEE/RSJ International Conference on Intelligent Robots and Systems. DOI: 10.1109/iros.2000.893198.

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