STATISTICAL EVALUATION OF ULTRASONIC SIGNAL DIFFERENCES DEPENDENT ON THE ANGLE OF TILT OF THE REFLECTING SURFACE

Vladimír Madola*, Marián Kišev, Vladimír Cviklovič

Institute of Electrical Engineering, Automation, Informatics and Physics, Faculty of Engineering, Slovak University of Agriculture in Nitra, Tr. A. Hlinku 2, 949 76, Nitra, Slovakia

Abstract

This paper deals with the statistical evaluation of the variation of amplitudes measured on ultrasonic transducers, which were parabolic displaced. The reflecting surface was used metal plate of dimensions 245x220x1 millimetres. The distance of the ultrasonic transmitter from the reflection normal was set conically to 190 mm. The distance of the ultrasonic of the transducers from the reflection normal was 900 mm. At the significance level of α = 0.05, it was shown that there is a statistically significant decrease in absolute amplitude with increasing angle of the reflection normal on the ultrasound transducers. The critical angle was set to be 30°, which supports the chosen angular limit at the -6 dB attenuation band for the ultrasonic transducer used. Significant differences in the amplitudes of the ultrasonic signals give an indication of the direction of tilt of the reflecting surface. The statistically observed differences between the ultrasonic signal amplitudes are more indicative than the attenuation criteria of -3 dB and -6 dB, respectively. The mean values of the signal amplitudes were determined by arithmetic averaging over four repetitions of the experiment. The normality of the distribution of the detected signal amplitudes was verified at a significance level of α = 0.05 by the Shapiro-Wilk test.

Keywords: *ultrasound reflection, ultrasound amplitude, ultrasound echo, acoustic reflection, non-linear regression*

1. INTRODUCTION

Position measurement by indirect methods has an irreplaceable place in automation. The use of ultrasound as an energy carrying medium for distance determination represents a relatively simple and cheap measurement system. In [1], the authors focused on the development of a regression model for the determination of the surface type by the amplitude of the ultrasonic signal. Their model recorded a success rate of (97 ÷ 98) %. It is limited by the type of surfaces, namely flat surface normal and sharp edge. In [2], the authors focused on the quantification of objects by measuring the ultrasonic reflection using the method of decomposition of the received signal in the time domain, namely the signal amplitude, the leading and trailing edge steepness, the delay between reaching the maximum of the function and its onset, and the time differential of the transmission and reception of the pulse. The minimum accuracy of the above approach is 64.4 % in terms of the true object category confidence. The objects that the authors exposed to the ultrasound pulses had a planar, edge, horn, or cylindrical shape. The authors [3] state that in the case of reflections from an inclined plane, it is possible to estimate the angle by modelling the ultrasound pulse with a Gaussian function, with an evaluation of the correlations between the pulse shape and the boundary condition in the geometric direction. The authors used a Polaroid 7000 measurement system on sonar principle. In the case of an angle exceeding 20°, the received pulse was noise-laden and exhibited low amplitude. In contrast, the correlation coefficient was in the vicinity of 0.96 and the accuracy of the angle estimation was in the range of ±1°. According to the authors [4], the estimation of the actual position of the measured object can be determined by the method of intersection ellipses when the deployment of the ultrasonic transducers is known. To determine the moment of detection of the ultrasonic signal, the Hilbert transform was used. The accuracy of this method is in the absolute value of (± 10 ÷ ± 70) mm. In [5], a method of comparing the tangent directive at the leading edge of the ultrasonic pulse was proposed as a quantifier of the pointiness of the object from which the ultrasonic waves are reflected. The authors introduced a 4 % interval in evaluating the amplitude of the ultrasound pulse for comparison with the inflection point. The time course of the ultrasound pulse is subjected to normalization with the peak of the recorded pulse, and individual

progressively at 10 % and 50 % of the global maximum are compared. The authors conclude that the advantage of using this method is for rugged surfaces from which the ultrasound wave is reflected and at the same time does not suit the amplitude aspect of evaluating the nature of the object (point or area). In [6], the authors state the possibility of identifying the shape of the reflecting surface through the impulse characteristics of the ultrasonic transducer. The time model under known geometrical conditions is subjected to correlation with the measured data from the ultrasonic transducer over time. The work [7] states that the ultrasonic pulse amplitude, duration and dominant frequency of the signal spectrum is an indication of the tractability of the mathematical model thus obtained in correlation with the physical properties of the material from which the ultrasonic wave is reflected. In this paper, we focus on the evaluation of a conventional criterion for the attenuation of the electrical signal from ultrasonic transducers. We will compare the standard attenuation of -3 dB logarithmic value with a one-factor analysis of variance of individual measured samples of ultrasonic pulses. A metal standard with dimensions (245x220x1) mm will be used as the reflecting material. The ultrasonic transducers are placed in a parabolic geometry. The subject of geometrical variation is the angle of inclination of the reflecting normal with respect to the direction of propagation of ultrasonic pulses.

2. MATERIALS AND METHODS

2.1. Measurement system

The 'Animal Position Identification Recording System' was used as the measuring system [9] in the function of controlling the generation of ultrasonic pulses. The device is controlled by a Silabs C8051F410 microcontroller. The ultrasonic signal is generated by a piezoelectric ultrasonic transducer SensComp 40LT16. According to the specifications [8], it has a directional characteristic of ± 27.5° for an attenuation criterion of -6 dB. The resonant frequency is 40 kHz ± 1 kHz. The ultrasonic signal was amplified by the piezoelectric transducer SensComp 40LR16. The electrical signal from the piezoelectric transducer was amplified to a logarithmic level of 25 dB. The amplification element used was an operational amplifier in a cascaded inverting circuit. The frequency bandwidth of the amplification circuit was 3MHz. The block diagram of the measurement system is shown on Fig. 1.

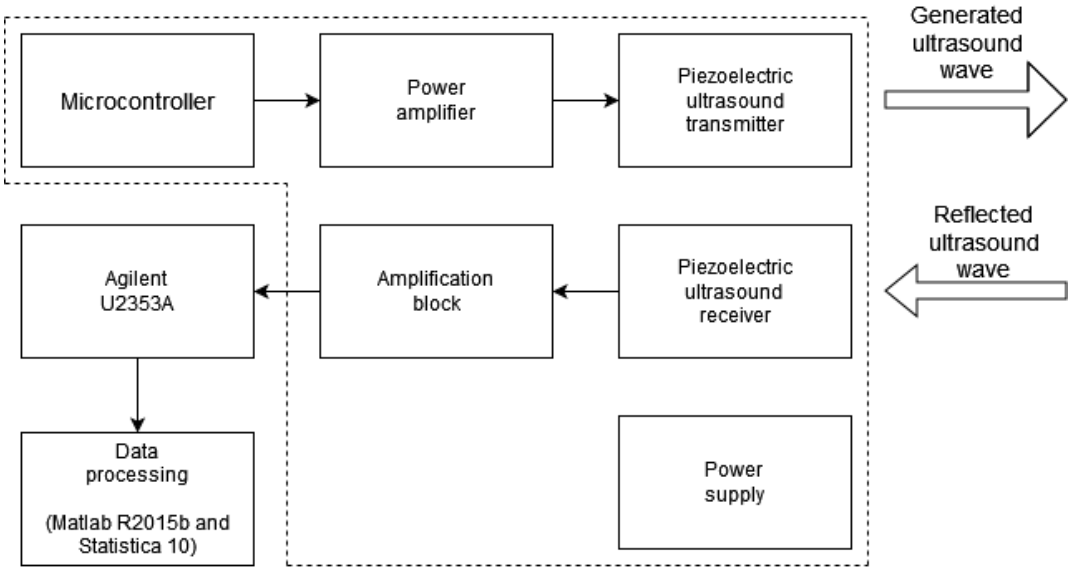

Fig. 1. Block diagram of measurement system

For the time capture of the reflected ultrasound pulses we used the Agilent U2353A data logger. Selected characteristics of the used data logger are shown in Table 1. We used five analogue channels for

simultaneous measurement of all ultrasonic transducers. The sampling frequency was set to 200 kHz. The recording length was set heuristically to a value of 1000 milliseconds.

Parameter	**Value**
Resolution [bit]	16
Number of analogue channels [-]	16
Input impedance [GΩ / pF]	1 / 100
Uncertainty of measure [µV] (at selected range: * ± 10V, ** ± 5V, *** ± 2,5 V, **** ± 1,25 V)	± 305,2 *
	± 152,6 **
	± 76,3 ***
	± 38,15 ****
Sampling [MSa/s]	max. 1

Table 1. Selected characteristics of Agilent U2353A device [10]

The measured data were then filtered of the electrical noise that had preceded the ultrasound pulse. The criterion for selecting the useful part of the acquired data was the threshold voltage, determined heuristically to be 3 millivolts. The length of the useful signal was variable, and the length criterion was the overall shape of the captured ultrasound impulse after the onset of stray echoes.

2.2. Measurement conditions

We chose a metallic normal of planar dimensions 245 mm x 220 mm as the object to be exposed to the ultrasonic pulses. The thickness of the material was 1 mm. The material of the normal was steel, coated with an anti-corrosion coating. It can be stated that the surface is solid and geometrically straight. Ultrasonic pulses were transmitted to the subject normal in the coaxial direction with respect to the scanning axis of the reflected ultrasonic pulses. The experimental conditions on the ultrasound pulse generation side are depicted on Fig. 2.

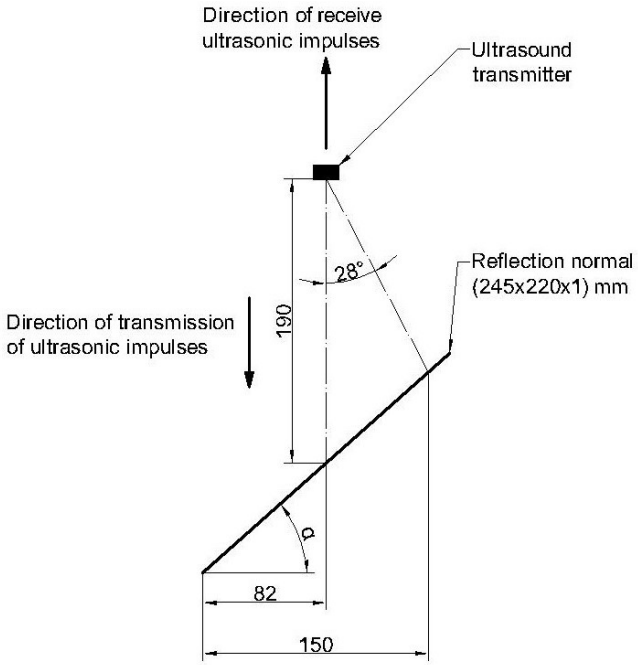

Fig. 2. Experimental conditions on the ultrasonic impulse generation side

The subject of the variation of the geometrical conditions was the angle of inclination of the reflection normal (α-symbol on Fig. 2). The values of the angular vector were changed in steps of 0°; 22.5°; 25°; 27°; 30° and 36°. When the angle of inclination was changed, the distance of the ultrasonic transmitter from the normal was corrected to a constant value of 190 mm. Five SensComp 40LR16 piezoelectric transducers were used to sense the reflected ultrasound pulses. The placement of the ultrasound transducers was implemented in a parabolic layout. The geometrical conditions of the ultrasonic transducers deployment are depicted on Fig. 3.

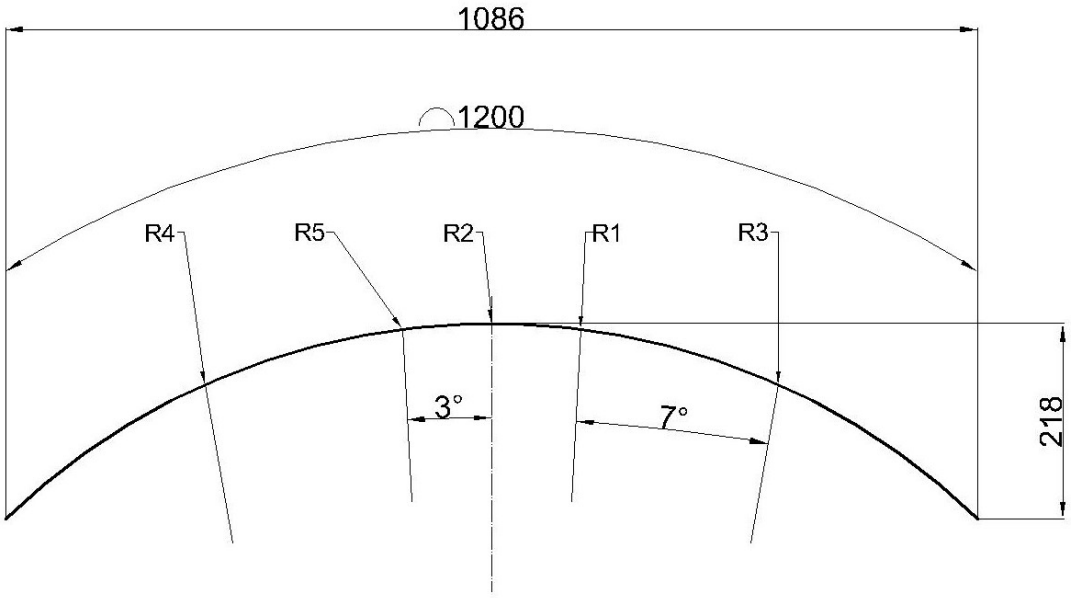

Fig. 3. Distribution of ultrasonic sensors in the experiment

The angular vectors marked on Fig. 3 are related to the distance of the deployment peak (sensor R2) from the reflection normal. The distance was set to a value of 900 mm.

2.3. Statistical analysis

The amplitude of the ultrasound pulse (U_{max}) was chosen as the statistical parameter. The results are interpreted as arithmetic mean ± standard error of the arithmetic mean (SE). To determine statistically significant differences, a one-factor analysis of variance was used with a Tukey's Post - Hoc test for significance of difference at the 0.05 level of significance. Statistically significant differences will be considered to be those for which the condition for the parameter p plotted on the Tukey's Post - Hoc test is reached: $p \leq 0.05$. Statistical analysis was performed when the experiment was repeated four times. The normality of the distribution of the measured data was verified by the Shapiro-Wilk test at a significance level of $\alpha = 0.05$. The electrical difference criterion was set to the conventional attenuation value of -3 dB (70.8%) when analysing the global maximum of the signal over time.

2.4. Used software

Communication between the PC and the Agilent U2353A data logger was provided by Agilent Measurement Manager 1.2 software. Signal processing was performed in Matlab R2015b environment. Statistically, the obtained data were processed in Statistica 10 environment. The firmware development of the microcontroller was carried out in the Keil µVision 5 environment. [11, 12]

3. RESULTS

Average amplitude of ultrasonic impulses and standard error of arithmetic mean was calculated (Fig. 4). From the results we have focused on the statistically significant differences of the individual ultrasound transducers when the angle of tilt of the reflecting surface was varied incrementally. As a criterion for the basic classification of the average amplitudes, we used a standard attenuation of -3 dB. To compare the goodness of fit of the chosen attenuation criterion, we excluded those mean amplitudes that did not fit a given attenuation in the angular direction of succession.

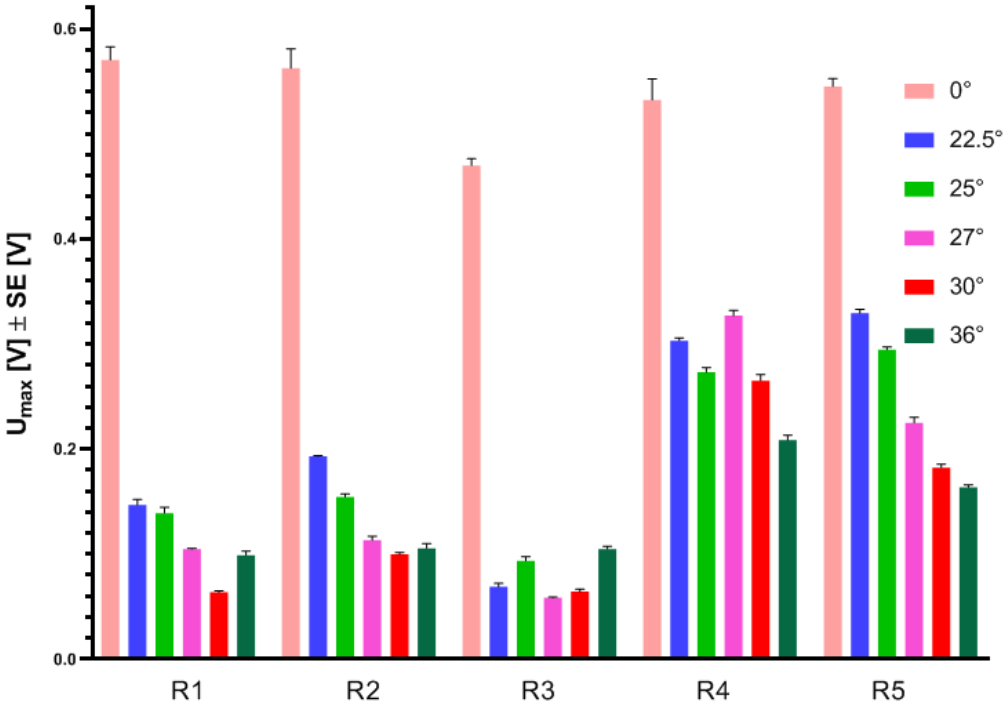

Fig. 4. Statistical evaluation of amplitudes of ultrasonic impulses in the experiment

The variability of the statistical sets did not overcome the value of the coefficient of variation $V_k \leq 2.851$ % in the case of sensor R3 at the tilt of the reflection normal at an angle $\alpha = 22.5°$. The empirical distribution of the measured data was demonstrated at the 0.05 significance level in favour of the Normal distribution for all statistical sets except for sensor R4 at a normal tilt angle of 0°, sensor R2 at a normal tilt angle of 27° and sensor R3 at a normal tilt angle of 36°. In the case of failure to detect empirical distributions according to the Normal Probability Distribution, we used the Kruskal-Wallis test for significance of differences at unchanged significance levels. The results from the analysis of variance compared with the logarithmic gain are shown in Table 2.

Sensor	α_1 [°]	α_2 [°]	Gain [dB]	p-value
R1	25	22.5	-0.473	> 0.05
R2	25	22.5	-1.949	< 0.05
R3	25	22.5	2.664	< 0.05
R4	25	22.5	-0.907	< 0.05
R5	25	22.5	-0.963	< 0.05

Table 2. Comparison first angle pair with non-significant logarithmic gain value

It can be concluded that the first angular pair (25° vs. 22.5°) demonstrates the insufficiency of the electrical attenuation criterion for statistical significance of the amplitude difference. The absolute difference of the coefficients of variation between the statistics was in the interval 2.32% ÷ 2.33%. From the given results, it can be concluded that the distribution of random errors in the statistical sets is statistically significantly closer to each other. The condition of statistical insignificance of the difference is satisfied in the case of sensor R1.

Sensor	α_1 [°]	α_2 [°]	Gain [dB]	p-value
R1	27	25	-2.458	< 0.05
R2	27	25	-2.687	< 0.05
R4	27	25	1.566	< 0.05
R5	27	25	-2.334	< 0.05

Table 3. Comparison second angle pair with non-significant logarithmic gain value

In the case of the second angle pair (27° vs. 25°), all differences show significant differences in Tukey's test. The absolute difference of the coefficients of variation between the statistics was in the interval 1.62% ÷ 2.33%. In respect of the values of the coefficients of variation, the data on sensors R1 and R3 showed the highest values. From the direction of the axis in the normal of the reflecting surface, it can be concluded that the variability of the measured amplitudes is inversely dependent on the minority sensors in terms of the direction of change of the tilt angle α.

Sensor	α_1 [°]	α_2 [°]	Gain [dB]	p-value
R2	30	27	-1.086	< 0.05
R3	30	27	0.832	> 0.05
R4	30	27	-1.822	< 0.05
R5	30	27	-1.824	< 0.05

Table 4. Comparison third angle pair with non-significant logarithmic gain value

In the case of the third angle pair (30° vs. 27°), sensor R3 shows that the difference is insignificant. The absolute difference of the coefficients of variation between the statistics was in the interval 1.10 % ÷ 2.00 %. The value of the coefficients of variation (V_k) was the highest in the case of sensor R3 (30°), when V_k = 2.50 %. For the next angular vector, the coefficient of variation was highest for sensor R2 (27°), when V_k = 2.15 %.

Sensor	α_1 [°]	α_2 [°]	Gain [dB]	p-value
R1	36	30	3.831	< 0.05
R2	36	30	0.484	> 0.05
R3	36	30	4.271	< 0.05
R4	36	30	-2.091	< 0.05
R5	36	30	-0.950	< 0.05

Table 5. Comparison fourth angle pair with non-significant and significant logarithmic gain value

In the case of the fourth angle pair (36° vs. 30°), sensor R2 shows the satisfaction of the condition of insignificance of the difference. The absolute difference of the coefficients of variation between the statistical data was in the interval 1.61 % ÷ 1.66 %. The direction of propagation of variability in statistical indices shows the character of growth of variability of a statistical index with increasing deviation from a given ultrasonic transducer. When evaluating the sensor R2, which represents the peak of the receiving geometrical layout, a local extreme occurs at a tilt angle of α = 30°. Quantitatively, the coefficient of variation was 37% lower with respect to the maximum value obtained at a tilt angle α = 36°. Analyzing the critical values of the logarithmic gain, it can be concluded that the statistical criterion of non-significance of the difference is met for sensors R1 (25° vs. 22.5°), R3 (30° vs. 27°) and R2 (36° vs. 30°). We consider the maximum absolute value, i.e. -0.832 dB (90.87%), as the critical value of the logarithmic attenuation. By modifying the critical logarithmic attenuation level, the next-neighbor attenuation equal to the dependent variable per pass time is satisfactory from a signal point of view.

The average amplitudes of the ultrasound signals at each transducer were subjected to a nonlinear regression with respect to the angle of inclination of the reflecting surface α. Respecting the literature [1], an exponential function of the form (Eq. 1) was derived.

$$\bar{U}(\alpha) = k \cdot e^{-m \cdot \alpha} \quad (1)$$

where: $\bar{U}$ – value of signal amplitude at set tilt angle [V], k – correction factor [-], m – tilt angle factor ratio [-] and α – tilt angle of reflection surface [°].

The values of the coefficients of function (Eq. 1) for each ultrasonic transducer are given in Table 6, together with the coefficients of determination R^2.

Sensor	k [-]	m [-]	R^2 [%]
R1	0.531	0.0568	88.32
R2	0.547	0.0512	94.50
R3	0.470	0.0620	66.81
R4	0.539	0.0244	92.52
R5	0.590	0.0340	90.54

Table 6. Coefficients of exponential function of non-linear regression

The Pearson correlation coefficient reached a value of 0.82 in the critical case (sensor R3) indicating a significantly close functional dependence according to the functional prescription of function (Eq. 1). A graphical representation of the nonlinear regression functions is shown on Fig. 5.

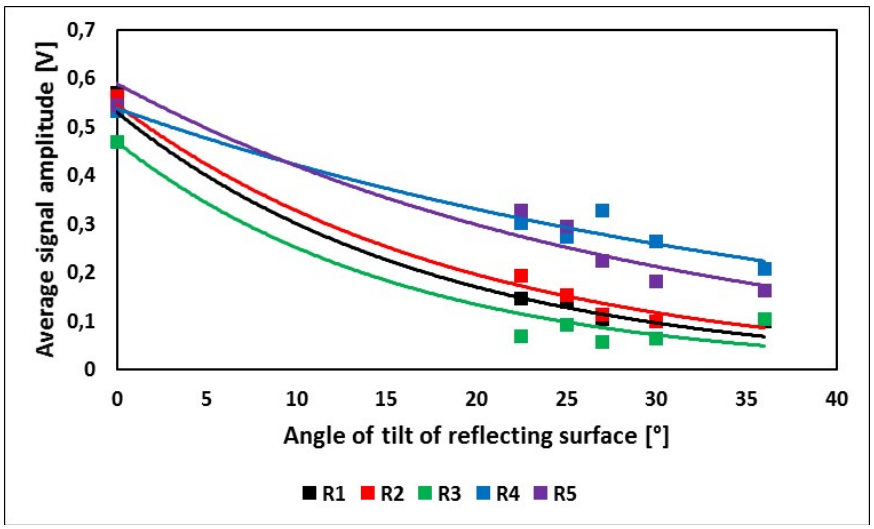

Fig. 5. Nonlinear regression functions related to ultrasonic sensors

With the exception of sensor R3, the individual regression functions in means of the Pearson correlation coefficient are at a high level of closeness. Up to a slope angle $\alpha < 30°$, the coefficient of variation values for sensor R3 were the highest of any of the individual statistical sets.

The variability as shown is not only an indication of the possible presence of random measurement error but also of the dispersion of the ultrasound signal as the tilt angle of the reflecting surface varies over time.

4. DISCUSSION

The results show the sufficiency of the modified significance level for the logarithmic gain attenuation. By neglecting the conventional attenuation values, the significance of Tukey's Post-Hoc test for evaluating the significance of amplitude differences on ultrasonic transducers was demonstrated. By analysing the significance of the difference of individual amplitudes on the transducers while maintaining the nearness of the angular vectors, the value of sufficient attenuation was demonstrated to be 9.13% of the initial value against the conventional value of 29.21% of the initial value. By nonlinear regression, we confirmed the trend of the amplitudes at the ultrasonic transducers as a function of the angle of tilt of the reflecting surface. The Pearson correlation coefficient reached a value of 0.82, which

can be interpreted as a significantly close functional correlation according to the exponential function. The value of the critical logarithmic damping found by us can be used in modelling complex functions obtained from impulse responses according to the literature [1, 3] as a possible quantification index in the evaluation of functional characteristics in time or in the plane of a complex variable.

5. CONCLUSIONS

The presented work deals with the definition of the critical value of logarithmic attenuation for statistical significance of signal amplitude difference from ultrasonic transducers. An ultrasonic measurement system at a conventional frequency of 40 kHz was used. In the next stage of our work, we will focus on the correlations between the angular vector of the geometry of the ultrasonic transducer deployment, the length of the ultrasonic pulse propagation trajectory versus the signal amplitude of the ultrasonic pulse. The tilt angle of the reflecting surface will also be subject to variation. The results of the work can be helpful in the choice of the methodology for the evaluation of the significance of the difference in the variation of the ultrasonic transducer signal. With appropriate modification of the name of the methodology used, the computational approach is applicable to the dependence of other quantities in terms of their dependent variable.

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