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A Novel Three-Head Ultrasonic System for Distance Measurements Based on the Correlation Method

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A novel double-emitter ultrasonic system for distance measurements based on the correlation method is presented. The proposed distance measurement method may be particularly useful in difficult conditions, e.g. for media parameters undergoing fast changes or in cases when obstacles and mechanical interference produce false reflections. The system is a development of a previously studied single-head idea. The present article covers a comparison of the two systems in terms of efficiency and precision. Experimental research described in this paper indicated that adding the second head improved the measurement exactness – standard deviation decreased by 40%. The correlation method is also described in detail, also giving the criterion for the quality of the measurement signal.

Keywords: Ultrasonic measurements, ultrasonic waves, non-destructive testing, distance measurements, cross-correlation.

1. INTRODUCTION

A wide variety of distance measuring systems and devices utilise ultrasound phenomena. An ultrasonic wave can be mechanically generated in a system of a piezoelectric transducer excited by an electrical impulse. The ultrasound wave propagates in a medium and is refracted and reflected on the boundary between media. The wave, which is a superposition of all reflections, returns and is received by a piezoelectric transducer, where it is changed into a low-voltage electrical signal. The analysis of the said electrical signal is the core for ultrasound-based distance measurements.

A widespread classical method used in popular distance measuring devices consists in sending a single impulse ultrasonic wave and measuring the time of flight of its reflection returning to a detector [1]-[8]. However, research have proved that the one-impulse approach is insufficient and does not give satisfying and unequivocal results in cases when the medium parameters are complex or undergo fast changes [9]. The system presented by authors in the earlier article [9] answered the need for a more advanced tool: it emitted a continuous modulated wave signal, instead of a single impulse, and then an analysis of the received continuous superposition of reflections [10] using correlation methods was performed.

Further research of distance measurements using the continuous signal and its correlation-based analysis led the authors to the conclusion that some adjustments might be made to augment the system's efficiency and precision and they are now being presented in this article:

- the system architecture has been developed and a second driving head has been added (see below in sec. 2);
- the new system consisting of two wave generators needed two wave modulators LSFR1 and LSFR2 ([8], [11]), so the needed modulation parameters have been identified and described mathematically, including the continuous-discrete conversion (sections 3 to 6);
- formulas for correlation and criteria for the optimal choice have been proposed to find the identified required modulation parameters (refer to section 5 and 6);
- a set of laboratory tests have been conducted (including also the study described in [9]) to determine and verify experimentally the values of the modulation parameters (section 7);
- assessment of the effectiveness of the phase modulation method with 1 and 2 generators has been done based on the experiment results (section 7), showing a large improvement for a two-head system – standard deviation decreased by 40%.

The system of the correlator with two wave emitters is an asset very useful for materials with fast changing characteristics, due to the continuous signal emission mode. Also, it can be used in situations where measurement results can be destructed or obscured by side reflections, since it allows one to eliminate the influence of such 'false' signals. Side reflection errors can occur if a measurement is performed in a narrow space and the wave does not propagate parallel to this channel. Side reflection errors appear also if there are objects within the area of the conducted measurement whose reflection surfaces are not perpendicular to the ultrasonic beam propagation direction.

The key idea of this article is then to present a new, experimentally verified, proved and working two-head system with continuous wave generation together with criteria allowing to find optimum modulation parameters based on the correlation method. This system is suitable even for high precision sensitive measurements.

2. THE SYSTEM'S ARCHITECTURE

The system which was studied here is shown in Fig. 1. It consisted of the module NEXYS 2 with the device Xilinx Spartan [12] with implemented LSFRs for generation of modulating waves. LSFR1 was assumed as 6-bit, while LSFR2 as 7-bit. There were used three heads BPU-1640IOAH12 (Bestar Electronics Industry Co, Ltd) as the two emitters and the receiver. The analogue-digital converter (ADC) which was used had 50 MHz sampling frequency. The measurement data were sent to a PC using a built-in USB interface for analysis. The use of the PC allowed for gathering measurement data, performing correlations and other calculations, including calculation of standard deviations.

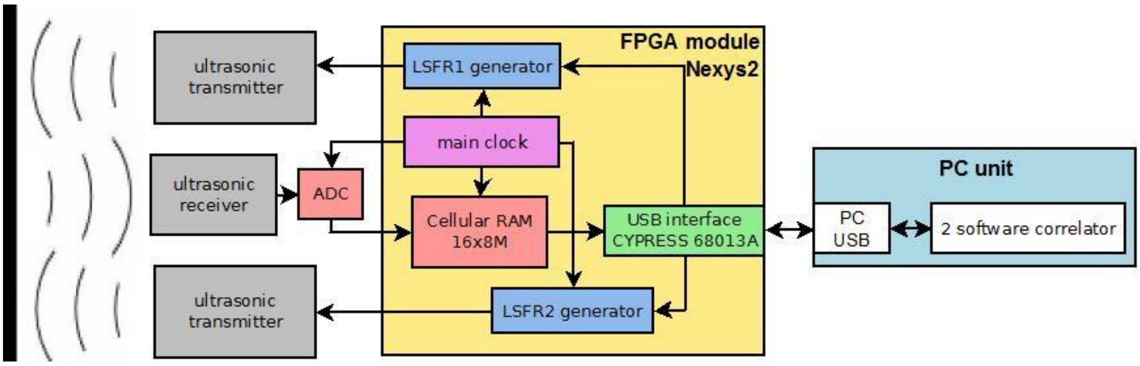

Fig. 1. A block diagram of the studied distance measurement system.

3. MODULATION OF A DRIVING WAVE

A continuous signal generated by an emitter can be continuously modulated in a characteristic way to obtain a unique in time driving wave. Thanks to such a unique modulation, the wave is identified unequivocally among superpositioned signal reflections. In the phase modulator of the carrying wave $f_W(t)$ the signal can be described by the equation:

$$f_W(t) = A_m \cdot \cos\left(2\pi \cdot f_n \cdot t + k_p \cdot KCM(t)\right), \quad (1)$$

where:
A_m – amplitude of the carrying wave,
f_n – frequency of the carrying wave,
k_p – modulation index,
$KCM(t)$ – binary series for modulation of the carrying wave.

In this study $KCM(t)$ was assumed as two modulating registers: 6-bit LSFR1 and 7-bit LSFR2, defined by polynomials *W1*(*x*), *W2*(*x*), respectively for each head (compare eq. (14)). The choice of these polynomials was optimum, based on the minimum cross-correlation criterion (section 5) and the signal quality criterion (section 6). Specific values of the parameters from eq. (1), which were used in this study, are given in the experimental section 7.

4. CORRELATION OF DRIVING AND REFLECTED WAVES

The measurement of the delay of a reflected wave takes place in the system of a software correlator of the modulated signal with the received signal. Assuming that these signals are signals of limited energy, the cross correlation function can be expressed as follows [13]:

$$\phi_{gh}(\tau) = \int_{-\infty}^{\infty} g^*(t) \cdot h(t+\tau)\,dt \quad (2)$$

where:
$h(t)$ – driving signal created by an emitter,
$g(t)$ – signal from a receiver,
$g^*(t)$ – complex function coupled to $g(t)$,
τ – time shift.

For discrete signals *g*(*n*) and *h*(*n*), which are shifted with respect to each other by the number of samples *m*, the discrete form of the cross correlation function [14] determined from (2) reads as follows:

$$\varphi_{gh}(m) = \sum_{n=-\infty}^{\infty} g(n) \cdot h^*(n-m)\,. \quad (3)$$

where:
$h(n)$ – *n*–th sample of the discrete driving signal created by the emitter,
$h^*(n)$ – complex function coupled to $h(n)$,
$g(n)$ – *n*–th sample of the discrete signal from the receiver,
m – discrete shift.

Time of flight of a beam can be determined from relation (4) given below. The time of flight describes the sought distance *l* between the emitter and the medium border for which the reflection coefficient is the largest in this medium. The distance *l* can be calculated by multiplication of sample index *m*. by the ADC sampling period.

$$\left|\phi_{gh}(m_l)\right| \geq \max\left\{\phi_{gh}(1), \phi_{gh}(2), \ldots, \phi_{gh}(\mathrm{L})\right\} \quad (4)$$

where:

L – length of the correlated sequences in samples,

m_l – discrete shift of the function $h(n)$ for which the maximum value of the correlation function $\varphi_{gh}(m)$ was obtained.

5. THE MINIMUM CROSS-CORRELATION CRITERION

For a two-head system, the driving signals are modulated by two different binary series $KCM(t)$. As has been mentioned above, in the present study they were assumed as two modulating registers: 6-bit LSFR1 and 7-bit LSFR2, defined by polynomials $W1(x)$, $W2(x)$, respectively for each head (see eq. (14) in section 7).

One of the criteria for choosing polynomials $W1(x)$ and $W2(x)$ is to choose them in such a way that the sum of values of the cross-correlation [14] of the driving signals modulated by them, $f_{W1}(k)$ and $f_{W2}(k)$ respectively, is minimal (5):

$$\min \sum_{k=0}^{\mathrm{L}} \left[f_{W1}(k) \cdot f_{W2}^{*}(k-m) \right]. \quad (5)$$

6. THE SIGNAL QUALITY CRITERION

The sole minimum cross-correlation criterion is not enough. Hence, it is proposed here to use an additional criterion for determination of the optimum parameters of the modulated signal. The criterion is defined as the maximum ratio of the correlation peak value to background noise:

$$E(W, k_{\mathrm{p}}) = \frac{\varphi_{gh}(m_l)}{\frac{1}{\mathrm{L}} \cdot \left(\sum_{n=0}^{\mathrm{L}} g(n) \cdot h^{*}(n-m) \right)}. \quad (6)$$

The higher the value of the ratio $E(W,k_{\mathrm{p}})$, the better, i.e. the more unequivocally the distance is measured by the system.

In the study presented here, the above criterion was tailored duly to assess efficiency of measurements of a system with one driving signal compared with the proposed innovation of the double-emitter system. In case of the one-emitter system, the denominator in (6) could be assumed straight away as the background noise. However, the double-emitter system required combining cross-correlations for both modulated signals. Thus, four following expressions were substituted in the denominator of formula (6) and results were compared:

- for one driving signal case, the correlation of the signal form the emitter 1 $f_{W1}(k)$ and the signal from the receiver $f_R(k)$ was assumed:

$$\sum_{k=0}^{\mathrm{L}} \left[f_{W1}(k) \cdot f_R^{*}(k-m) \right], \quad (7)$$

- for one driving signal case, the correlation of the signal from the emitter 2 $f_{W2}(k)$ and the signal from the receiver $f_R(k)$ was assumed:

$$\sum_{k=0}^{\mathrm{L}} \left[f_{W2}(k) \cdot f_R^{*}(k-m) \right], \quad (8)$$

- for the double-emitter, one variant to check was assumed as the sum of correlations of individual modulated signals, $f_{W1}(k)$ and $f_{W2}(k)$, with the signal from the receiver $f_R(k)$ respectively, (labeled: Corr(W1) + Corr(W2)):

$$\sum_{k=0}^{\mathrm{L}} \left[f_{W1}(k) \cdot f_R^{*}(k-m) + f_{W2}(k) \cdot f_R^{*}(k-m) \right], \quad (9)$$

- the other variant for the double-emitter was to assume the multiplication of the correlations (labeled: Corr(W1) x Corr(W2)):

$$\sum_{k=0}^{\mathrm{L}} \left[f_{W1}(k) \cdot f_R^{*}(k-m) \cdot f_{W2}(k) \cdot f_R^{*}(k-m) \right]. \quad (10)$$

7. THE EXPERIMENT AND RESULTS

The experiment consisted in measuring a distance to an obstacle using the proposed ultrasound system shown in Fig. 1. First, the built system sent two phase-encoded signals: $f_{W1}(k)$ and $f_{W2}(k)$ separately, as a representation of a single-head system, and then both modulated waves were emitted simultaneously by the two heads. In all cases the reflection signal $f_R(k)$ was recorded. An exemplary plot of signals is shown in Fig. 2.

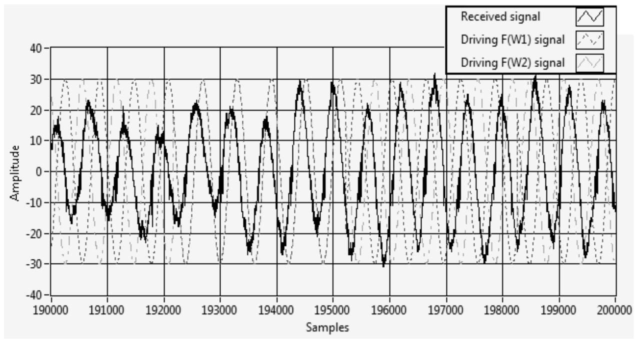

Fig. 2. Driving and received signals for the double driving signal system.

The tests investigated modulation parameters, in search for such a set of them which would provide the most unequivocal measurement results. Parameters describing a modulated signal comprise:

- modulator parameters: A_{m}, f_{n}, k_{p} (compare with eq. (1)),
- parameters of modulating polynomials.

CHOICE OF MODULATOR PARAMETERS

As for the amplitude A_{m}, it was assumed in the experiment as a maximum limited by the voltage of power supply.

The frequency of the carrying wave f_{n} was assumed based on the frequency characteristics of the response of the resonant system of the piezoelectric transducer used in the study, both as the emitter and the receiver, supplied by the transducer producer (compare: Fig. 3 below). It reached the maximum at the resonance frequency $f_{\mathrm{n}} \approx 40$ kHz. Due to symmetrical distribution of zeros and ones of the $KCM(t)$ (according with formula (14) below), the frequency of the carrying wave did not undergo a shift [15]. Thanks to this property of the binary series for modulation, it was possible to assume f_n in the experiment equal to the one from the used device characteristics.

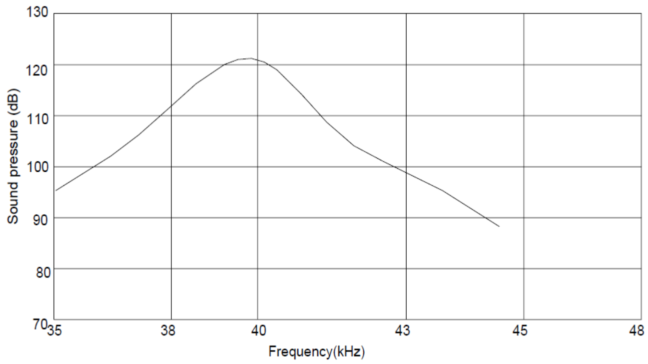

Fig. 3. The frequency characteristics of the BPU-1640IOAH12 transducer. (Source: BeStar Electronics Industry Co., Ltd.)

There were conducted earlier studies [9], in which a set of different modulating polynomials were investigated for the chosen frequency of the carrying wave $f_n = 40$ kHz. Based on those experiments, it was determined, that the optimum modulation index should be assumed as $k_p = 2.13$ rad.

At this point it is worth reminding that in order to preserve maximum of the information in the transmitted signal, the frequency spectrum of a modulated signal should match the frequency characteristics of a used ultrasonic transducer as much as possible [13]. It was then necessary to compare the two characteristics: of the used transducer and the signal modulated with assumed modulator parameters A_m, f_n, k_p. In order to plot the frequency characteristics of the phase modulated signal, the modulated wave formula (1) had to be transformed. First, the following transformation was done:

$$f_W(t) \approx A_m \cdot \cos(2\pi \cdot f_n \cdot t) - k_p \cdot KCM(t) \cdot \sin(2\pi \cdot f_n \cdot t) . \quad (11)$$

Since $KCM(t)$ were assumed as symmetrical, the following equation for the frequency characteristics of the modulated signal [15] was determined from (11):

$$B_T = A_m \cdot \sum_{n=-\infty}^{\infty} J_n(\beta) \cdot \cos\left[2\pi(nf_W + f_n)t\right] \quad (12)$$

where:
f_n is the frequency of the signal of the carrying wave,
$J_n(\beta)$ is the Bessel function, described by the equation:

$$J_n(\beta) = \frac{1}{2\pi} \cdot \int_{-\pi}^{\pi} e^{i[\beta \cdot \sin(\theta - n\theta)]} d\theta \cdot \quad (13)$$

Fig. 4 presents the sought plot of the frequency characteristics of the phase modulated signal determined using the above relations (11) to (13) and for the assumed earlier modulating parameters.

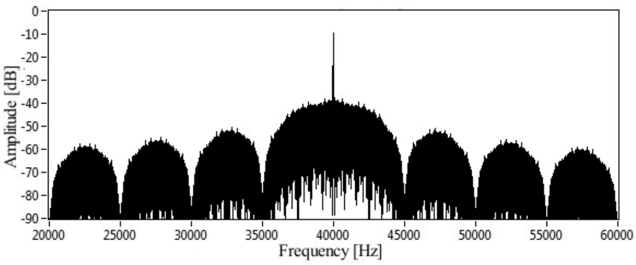

Fig. 4. The frequency characteristics of the phase modulated signal.

The analysis of the characteristics presented in Figs. 3 and 4 led to the conclusion that the phase modulation permitted a transfer of only a part, however, enough of the information contained in the modulated signal [16], taking into account the transmittance of the used ultrasonic transducers. Due to the limited transfer of signal information, further research on adjusting this aspect would improve the system's quality.

CHOICE OF PARAMETERS OF MODULATING POLYNOMIALS

In the study presented in this article, the $KCM(t)$ modulating series were assumed as follows:

$$W1(x) = x^6 + x^4 + 1 , \quad (14)$$
$$W2(x) = x^7 + x^6 + x^3 + x^2 + x^1 .$$

The above polynomials were chosen on the basis of the two criteria defined above: the minimum cross-correlation criterion (section 5) and the signal quality criterion (section 6).

Correlations of signals modulated by polynomials $W1(x)$, $W2(x)$ and also by assumed modulator parameters were performed according to formulae: (5) and (7)-(10). All correlations, for the first criterion, as well as for the second one, were conducted for $m \in \langle 0; \mathrm{L} \rangle$, where L = 500 000. The choice of the length of correlated series is a compromise between the speed of the algorithm defined by the calculation capacity and the selectivity of the resulting data representing the effectiveness of the method.

Results of correlation computations led to determination of the ratio defined in (6). Table 1 presents the ratios $E(W,k_p)$ for four correlation function variants, that is:

- for a single driving signal option from eqs. (7) and (8) – positions 1 and 2 in Table 1
- and also for a double-emitter version from eqs. (9) and (10) – positions 3 and 4 in Table 1.

The greater the value of the $E(W,k_p)$ ratio, the better the efficiency of the investigated distance measurement system. The results in Table 1 show that the system with two driving signals proves to be more advantageous than the single-signal one. Also, it can be inferred that the proposition of the product of correlations is the best suited computational algorithm for the quality criterion to reliably compare and assess the exactness of measurements done by a distance measuring system.

Table 1. The $E(W,k_p)$ ratio for four correlation function variants.

No	Variants of correlation functions in the denominator of eq. (6).	$E(W,k_p)$
1	$\sum_{k=0}^{L}\left[f_{W1}(k)\cdot f_R^*(k-m)\right]$	11.62
2	$\sum_{k=0}^{L}\left[f_{W2}(k)\cdot f_R^*(k-m)\right]$	10.67
3	$\sum_{k=0}^{L}\left[f_{W1}(k)\cdot f_R^*(k-m)+f_{W2}(k)\cdot f_R^*(k-m)\right]$	10.90
4	$\sum_{k=0}^{L}\left[f_{W1}(k)\cdot f_R^*(k-m)\cdot f_{W2}(k)\cdot f_R^*(k-m)\right]$	72.11

A good illustration to this can be found in Fig. 5. The graph shows plots of the sum (solid line) and the product (dashed line) of correlations for the double driving signal system. The product function plot lies below the sum function plot, which means it assures more unequivocal measurements.

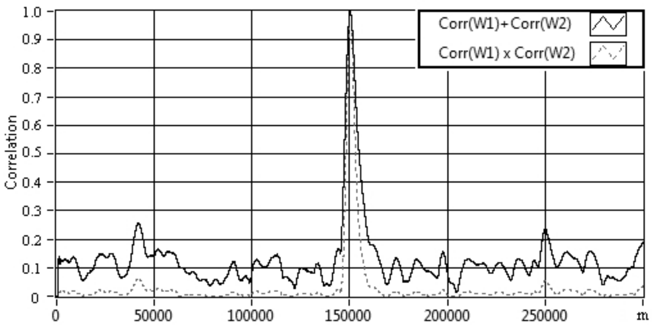

Fig. 5. Sum and product of correlation functions for *m–sample* = 150000.

Calculations conducted in the experiment have shown that plots of correlation functions for the single-signal system ($f_{W1}(k)$ or $f_{W2}(k)$ with the respective $f_R(k)$) almost overlapped with the sum of correlations for the double emitter system, so for the lucidity of the figure they were omitted in Fig. 5.

DISTANCE MEASUREMENT STANDARD DEVIATION

In order to determine the error of the measurement method, there were performed 7 series of measurements for 7 different distances. There was measured a distance to an obstacle located at 100 mm and then with a 100 mm step until 700 mm. For each distance 50 measurements were performed and a standard deviation was determined (Fig. 6).

The conducted laboratory tests confirmed reduction of the standard deviation for the system with two driving signals in comparison to the single-signal one. Both the sum and product of the correlations for two signals showed a 40% reduction [17] in standard deviation with respect to the system with one signal emitted [9], [1]

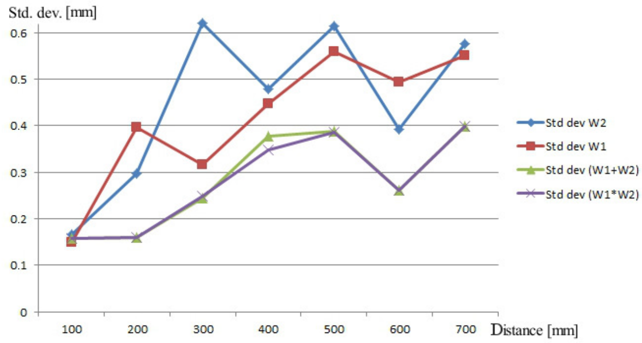

Fig. 6. Standard deviation for correlations of signals driven by $W1(x)$ and $W2(x)$ acting separately and sum and product of correlation signals driven by $W1(x)$ and $W2(x)$ acting simultaneously

8. CONCLUSIONS

The novel single-head system for correlation-based ultrasound distance measurement [9] was adjusted to improve its effectiveness and precision: a two-head system was built.

The studied new system had two wave generators requiring two wave modulators, so the needed modulation parameters were identified A_m, f_n, k_p and their values were assumed optimal, based on conducted experiments and taking into account characteristics of used transducers, as well as other system components.

A lot of attention was devoted to optimal choice of modulating polynomials $W1(x)$, $W2(x)$. Two criteria were assumed: the minimum cross-correlation criterion and the signal quality criterion. The second criterion was studied in four variants in order to tailor its form to the most sensitive indicator of the system precision. Experiments proved that the use of multiplication of cross-correlations indicated best the system with the most unequivocal measurement results.

Effectiveness of the phase modulation method with 1 and 2 generators was assessed, showing a large improvement for a two-head system (standard deviation decreased by 40%).

The proposed distance measurement method may be particularly useful in difficult conditions where obstacles and mechanical interference may produce false reflections. It is desired to conduct further research focused, among other aspects, on preservation of maximum information in the transmitted signal.

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