# IMPROVING THE METHOD OF THE CALIBRATION MULTICHANNEL ULTRASONIC FLAW DETECTORS FOR MEASUREMENTS WITH ANGLE PROBES

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**Summary** In the article an improved method of measurements synchronization which uses the cross correlation function and calibration patterns is presented. The previous version of the method turned out to be not precise enough if angle probes were used during the measurements. Complementing the existing procedures with additional resampling of the signal eliminated in practice the mentioned problems. The presented calibration strategy reduces the time of preparing multi-channel flow detector for the test, allows the correction of spatial placement of the probes and allows to improve the repeatability of the measurements. It also allows to use angle probes and it is suitable for different research methods (echo, shadow or tandem method).

## 1. INTRODUCTION

Calibration of multi-channel ultrasonic flow detector is a very complex process, which consists of many elements as for example setting the measurement parameters [1].

More most often used are: measuring the probe placement (X-, Y-coordinates, angle of incidence) by the sensors that check their placement in the scanner [2], initial calibration of the whole group of probes placed on a stiff runner [2] or calculating the placement of the sensors using calibration patterns [3, 4]. The first solution is used mainly in the systems, where it is possible to move the probes in electric, hydraulic or mechanical way. The second one makes it possible to avoid determining mutual relations among the probes (they are determined in single precalibration of the group). In the third case the correcting parameters are being introduced to the system by the operator based on the measurement diagram [3, 4]. The authors want to show the possibility of determining the spatial relations among the probes based on the analysis of the statistical characteristics of multi-channel measurement of calibration pattern with artificial defects.

In [5,6] the author has presented the method of automatic synchronization of measurements that uses the cross correlation function and calibration patterns with artificial defects, the problem of measurements synchronization is common [7].

Both in [5, 6] and in the presented article the authors will draw attention only to those aspects of calibration related to the automation of measuring process. We will not focus on the calibration of measuring parameters of the ultrasonic flow detector being part of the measuring equipment. We will neither focus on adjusting the parameters to the ultrasound probes, nor the conditions that create the appropriate acoustic link between the measured

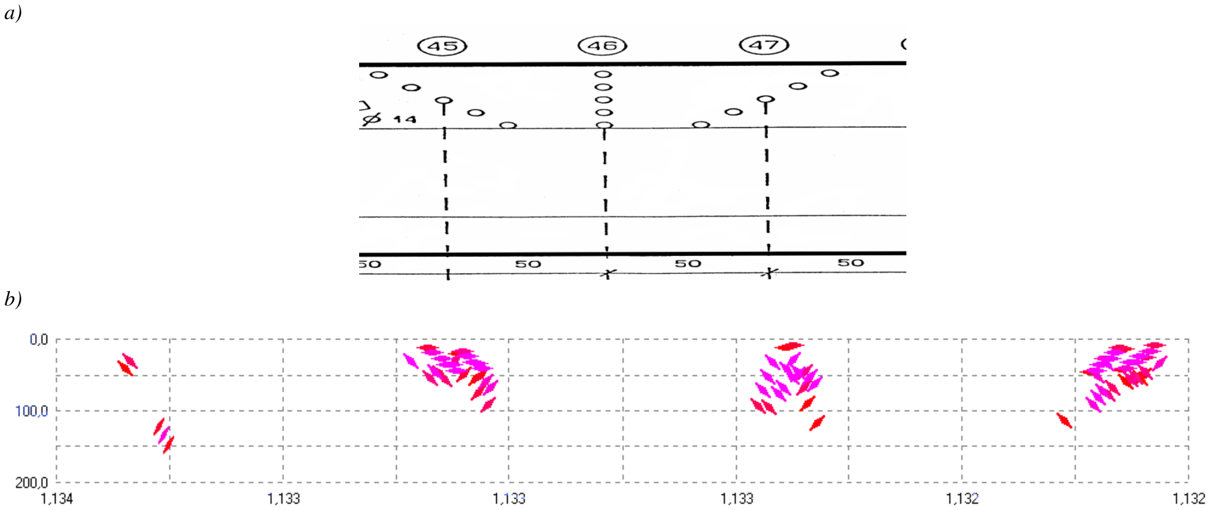


*Fig.1 A diagram of an artificial defect in a rail (a) and reconstruction of its picture based on non-synchronized 8 channel measurements conducted by the ultrasonic flow detector (b). The measurements were made with normal and angle probes. The methods used are echo and tandem*

object and the ultrasound probe. The analysis of those problems can be found in the literature devoted to ultrasound research e.g. [8, 9].

The possible solutions for the first of three common problems in automatic tests can be as follow:

- spatial synchronisation of the measurements (Fig. 1) taken by the particular channels of the ultrasonic flow detector (precise setting of the relative position of the ultrasound probes);
- assuring the repeatability of the measuring results by the right selection of the signal gain for the particular probe and the quality of the acoustic link (so that the defects that have the same reflector have the same repetitive level of the ultrasound echo);
- right choice of measurement timing (so that the measurements taken in the particular channels would not interfere)

The result presented in [5, 6] was not precise enough in case of using angle probes. In spite of using a precise tool as calibration function during setting of spatial placement of the probe the error connected to the measurements type has occurred. The effects of the incorrect calibration are caused by the imperfection of the method are well visible in Fig. 1b. Depending on the angle of the probe the measurements are registered too far or too close to its original placement.

According to what the authors mean the imperfection of the method can be corrected by a slight change of the calibration strategy. But before the details of the changes will be presented we will explain the automation method of the ultrasonic tests and present the primary method of spatial synchronization of the tests.

## 2. AUTOMATION IN ULTRASONIC MEASUREMENTS

A ultrasonic flow detectors use a non-destructive measuring method that is ultrasound testing, which is based on a wave reflection on the border between two layers which are different from each other by velocity of the wave. A mechanic wave produced by a probe is reflected by structure discontinuity and creates echo in the measuring equipment. Characteristic parameters for echo are amplitude and registration time, proportional to the depth of the discontinuity.

If the echo measurement and the registration are repeated in periods while the probe is moving along the measured object, a series of amplitude measurements and echo location are created, that phenomenon is called a signal envelope. The concept of creating measurement series is illustrated in figure 2.

In case of measuring with angle probes the way to make the envelope is similar, but it is necessary to conssider the geometric relationship that comes out from a different wave course (Fig. 5).

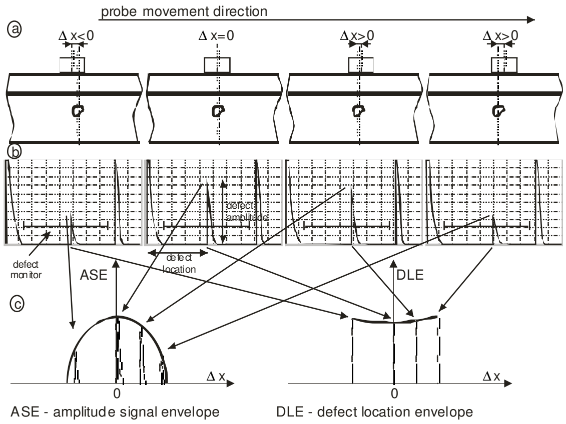


*Fig. 2. Signal envelope construction a) probe movement, b) ultrasonic echoes, c) amplitude and location envelope*

## 3. BASE CALIBRATION METHOD

Signal envelopes constructed on the basis of measurements taken in many ultrasonic flow detector's channels during the tests of the calibration patterns are basis for further deliberation and together with the cross correlation function, defined below, can be helpful to solve the first two of three problems mentioned in the introduction.

In time domain cross correlation of two continuous, stationary processes is defined as (1) [10]

$$R_{xy}(\tau) = \frac{1}{T}\int_0^T x(t)y(t-\tau)dt \tag{1}$$

where:

$T$ - observation time

$x(\cdot)$ - observed signal

$y(\cdot)$ - second signal composed of an information bearing signal $x(\cdot)$ and additive noise

$\tau$ - delay

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$$r_{xy}(t_1,t_2) = \int_{-\infty}^{\infty}\int_{-\infty}^{\infty} x(t_1)y(t_2)f_{X(t_1)Y(t_2)}(x(t_1),y(t_2))dx(t_1)dy(t_2) \tag{2}$$

Equation (2) for the discrete signals with finished length $N$ after replacing time with the sample indexes ($i_1$,$i_2$) and replacing those indexes with the shift between the signals $i=i_1-i_2$ according to (3) becomes (4).

$$r_{xy}(i_1+\tau, i_2+\tau)=r_{xy}(i_1,i_2)=r_{xy}(i_1-i_2)=r_{xy}(i) \quad (3)$$

$$r_{xy}(i)=\frac{1}{N-i}\sum_{m=0}^{N-i-1}x(m)y(m+i) \quad (4)$$

We will now define two discrete signals $y_1(m)$ (5) and $y_2(m)$ (6) consisting of an information bearing signal $x(m)$ and additional noise $n_1(m)$ and $n_2(m)$. As a result of the research we can assume precisely the signals are partially stationary.

$$y_1(m)=x(m)+n_1(m) \quad (5)$$

$$y_2(m)=Ax(m-T_D)+n_2(m) \quad (6)$$

where:

$A$ - amplitude factor

$T_D$ - relative time delay between the first and the second signal.

Situation described by the formulas (5) and (6) is a good representative of the results obtained in two ultrasonic flow detector channels. They should be well correlated with one another, because we detect the same defects in the material using appropriate probe to each channel. However, considering different settings in particular channels and changeable link quality, we can expect the change of the amplitude factor $A$ but spatial layout of the probes causes delays between the measurement signal $T_D$.

Let us continue the deliberation for two channels and we will then generalise the results for larger amount of channels.

Because characteristic (5) is true for the stationary signals the cross correlation between those signals equals

$$r_{y_1y_2}(i)=E[y_1(m)y_2(m+i)] \quad (7)$$

If we substitute y1(m) and y2(m) with formulas (5) and (6) we will get

$$r_{y_1y_2}(i)=E[(x(m)+n_1(m))(Ax(m-T_D+i)+n_2(m+i))] \quad (8)$$

Using the definition of autocorrelation function

$$r_{xx}(i_1,i_2)=E[x(i_1)x(i_2)] \quad (9)$$

and its characteristics for the stationary processes

$$r_{xx}(i_1+\tau,i_2+\tau)=r_{xx}(i_1,i_2)=r_{xx}(i_1-i_2)=r_{xx}(i) \quad (10)$$

we can transform (8) into

$$r_{y_1y_2}(i)=Ar_{xx}(i-T_D)+r_{xn_2}(i)+Ar_{xn_1}(i-T_D)+r_{n_1n_2}(i) \quad (11)$$

Because the signal and the noise are uncorrelated and the wide bandwidth processing the signal lets us assume that the noise has constant power spectral density (PSD), so

$$r_{xn_2}(i)=0 \quad (12)$$

$$r_{xn_1}(i-T_D)=0 \quad (13)$$

$$r_{n_1n_2}(i)=0 \quad (14)$$

We finally get

$$r_{y_1y_2}(i)=Ar_{xx}(i-T_D) \quad (15)$$

As it is shown in figure 3 cross correlation function reaches the maximum for the index equal $T_D$.

If we generalise the result to the other ultrasonic flow detector channels, we can conclude that in order to obtain the relative placement of the ultrasonic flow detector probes in the scanner, cross correlation function of the measurement signals and one chosen reference channel need to be found and we should find the maximum of cross correlation function.

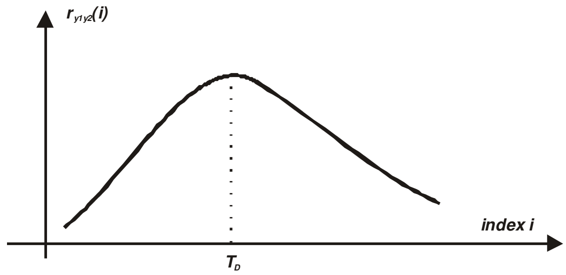


*Fig. 3. The envelope of the cross correlation function of two digital signals delayed to one another [10].*

The obtained indexes of the appropriate maximums will determine the size of the correction that should be made on the scanner placement estimated during the measurement to assure spatial synchronisation of the signals obtained in particular ultrasonic flow detector's channels.

An additive parameter considered during the calibration process can be the knowledge of the relative placement of the defects in the calibration standard. In that situation we can create a kind of reference 'pseudo signal' that contains the information about the real defect location. It can be used as a reference measurement. Cross correlation can be estimated between the measurements taken in the particular channel and the artificially created reference signal.

Figure 4 shows the example measurement results obtained during the test of a reference wheel A-920-28ACO (diameter D=920mm) after the former calibrating the measurement stand using the presented method. It is worth saying that the calibration is correct even though not all the defects are visible in the measurement of the particular ultrasonic flow detector channels.

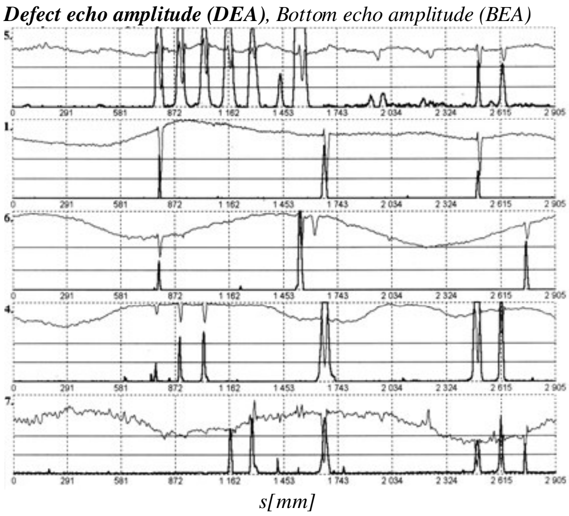


*Fig. 4. The measurement of defect echo amplitude and bottom echo amplitude for the reference wheel A-920-28ACO (diameter D=920mm) obtained after considering the corrections of the probes placement obtained during the calibration of the measurement stand using the correlation method.*

To assure the precision the calibration should be made on the reference that has as many defects as possible and all the defects should be visible for possibly most ultrasound probes.

## 4. PROBLEMS WITH THE ANGLE PROBES

In the example shown in Fig. 4 only the normal probes were used. In case of using angle probes we should remember to revise the determined probe placement with the characteristic for such measurements defect displacement to the sensor $\Delta i$ (Fig. 5).

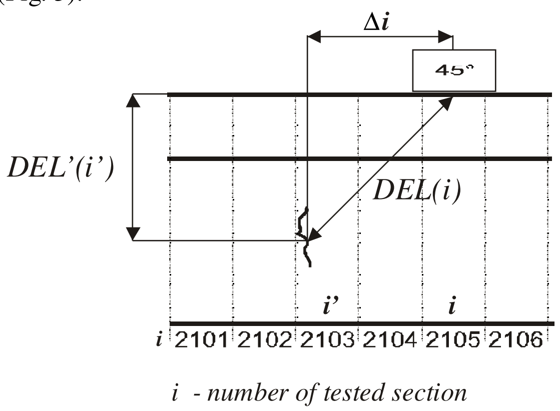


*Fig. 5. Defect and probe displacement in a test of rails in a track with the use of angle probes*

The displacement is dependent on the defect depth (projection of measured defect echo location, DEL) and it should be considered already at the stage of constructing the envelope signal used in calibration process.

Unfortunately in case of angle probes registered defect location depends on the angle of ultrasonic beam (probe parameter) and the depth of the defect placement. it does not match the scanning net (Fig. 6).

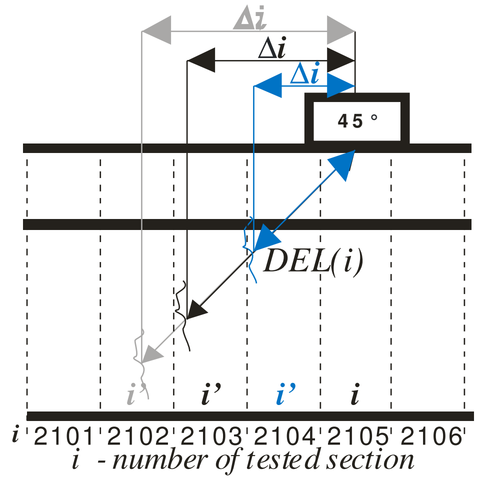


*Fig. 6. Relation between the registered defect location and the depth of the defect placement*

The additional problem is observing different defect edges depending on the direction of the ultrasonic beam. (Fig.7).

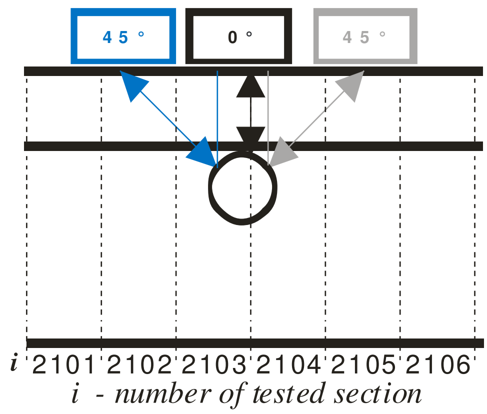


*Fig. 7. The observed defect edge depends on the angle of ultrasonic beam*

## 5. SOLUTION

Both mentioned problems can be solved when the method is slightly corrected.

In the first case we should register data more precisely than the scanning net. Frequency of the sampling signals, that should be treated with the correlation function, have to be higher than original signal frequency. Less precise but still efficient alternative is such as resampling of the signals that the placements of the samples agrees with the scanning net.

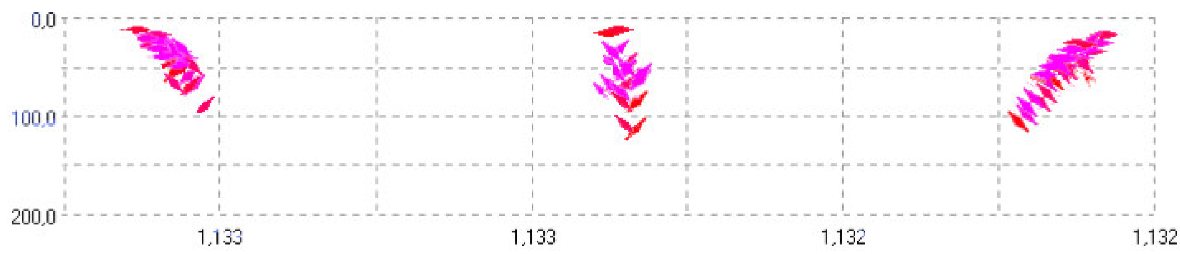


*Fig. 8. The results of the calibration of the multi-channel flow detector with the improved method for the object from the Fig. 1a*

In both cases resampling is necessary, but in case of the first method the signal having a lower frequency (e.g. angle probes that agree with the scanning net) have to be sampled with higher frequency while in case of the alternative method it is necessary to resample the signal with lower frequency to higher frequency so that the placements agree with the original section of the research net. The results of those procedures can be seen in Fig. 8.

The second problem can be solved if we know the shapes of the defects in the calibration patterns. During creating those referential pseudo-signals the specificity of the observation of defects in the appropriate channels in the construction of those signals. It lengthens the time of the calibration which should be conducted separately for each channel and for each referential signal, but the calibration measurements can still be conducted multichannel and the lengthening of the procedure is not significant.

## 6. CONCLUSIONS

The base method proves correct in automatic ultrasonic research in practice. It was used in a few implemented systems that test the quality of the ready products as well as in the railroad testing car used to test railroad [11].

Very good effects were achieved in the systems for submersible research, which provided unchanging conditions for acoustic link. In that case the presented correlation method of calibrating with the use of patterns for ultrasonic measurement stands provides equal conditions for measurement and defect classification for all the tested objects.

Time to prepare the multi channel flow detector for the tests gets shorter if the calibration process of the stand is more simple.

In case of modification suggested by the authors we keep the advantages of the base method, but it becomes more universal. It proves correct now also in the automats with angle probes and for other test methods (echo, shadow). Measurement systems are becoming more flexible and guarantee more precise synchronization of multi-channel measurements.

It is likely that the more precise calibration allows improving functioning of the expert systems for automatic classification of the measurements results [11, 12] and together with other systems as e.g [13] it will contribute to improving of total safety of the exploitation of the tested objects.

Still the disadvantage of the method is that it is necessary to have appropriate and expensive patterns.

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