VPS VIBRATIONS IN PHYSICAL SYSTEMS

DOI: 10.21008/j.0860-6897.2021.1.15
Vibrations in Physical Systems, 32(1):2021115, 2021

A Method of Precise Pulse Onset Determination Using the Akaike Information Criterion for Ultrasound Transmission Tomography

Piotr PRUCHNICKI[1,2], Krzysztof J. OPIELIŃSKI[1,2]

Corresponding author: Krzysztof J. OPIELIŃSKI, email: krzysztof.opielinski@pwr.edu.pl

[1] Department of Acoustics, Multimedia and Signal Processing, Faculty of Electronics, Wrocław University of Science and Technology, Wybrzeże Wyspiańskiego 27, 50-370 Wrocław, Poland
[2] DRAMIŃSKI S.A., Owocowa 17, 10-860 Olsztyn, Poland

Abstract Information criteria used in statistics for model selection can be used to accurately determine pulse transition times in transmission methods. The most popular information criteria are the Akaike Information Criterion (AIC) and the Bayesian Schwartz Criterion (BIC). These criteria are considered the most reliable tests of model type and structure and are computationally simple. In this paper, an algorithm developed according to the AIC criterion is used to determine the transition time from transmission tomography measurements acquired with a multi-element ultrasonic ring array, which is the scanning element of the novel prototype of ultrasound tomography device for detecting and estimating the malignancy of female breast cancer *in vivo*. As a result, a new algorithm was developed to precise search for the onset of the recorded receiving pulse. The algorithm was tested in an aqueous environment using elementary pairs of transmitting and receiving ultrasonic transducers of a tomographic ring array.

Keywords: Akaike Information Criteria (AIC), pulse wave, transmission method, ultrasound tomography

1. Introduction

Information criteria used in statistics for model selection can be used to accurately determine the transition time in transmission methods [1]. The most popular information criteria are the Akaike Information Criterion (AIC) and the Bayesian Schwartz Information Criterion (BIC) also denoted as SC, SBC, SIC. The AIC and BIC criteria are described by general formulas respectively:

$$AIC = -\frac{2 \cdot \log\big(V(\theta)\big)}{N} + \frac{2K}{N}, \tag{1}$$

$$BIC = -\frac{2 \cdot \log\big(V(\theta)\big)}{N} + \frac{K \cdot \log(N)}{N}, \tag{2}$$

where $V(\theta)$ - the reliability function for the estimated vector of parameters, K - the number of model parameters, and N denotes the number of observations. The first component of equations (1) and (2) represents the fit of the model to the measurement data (tends to decrease as the number of parameters increases), the second component takes into account the requirement for the model economy (represents a kind of penalty proportional to the number of parameters). The value of AIC and BIC indices as a function of model structure parameters reaches a minimum for correct (or close to correct) model structure. The AIC and BIC criteria are considered the most reliable tests of model type and structure. They do not require a data set for verification, but are applied directly to the data set for estimation; they are also computationally simple. The difference between the AIC and BIC criteria is the different weighting of the quality of fit and the simplicity of the model. The second element of the sum in the information criteria formulas measures the simplicity of the model. In both cases, this element increases as the number of parameters increases, and this increase is greater the smaller the number of observations. This definition of information criteria is related to the fact that model simplicity is particularly important for models estimated on small samples. Although asymptotically both criteria will select the true model as the correct model, in small samples their indications may differ significantly.

2. AIC algorithm

In this paper, an algorithm developed according to the AIC criterion [2] was used to determine the transition time from tomographic transmission measurements acquired with a multi-element ultrasonic ring array, which is the scanning element of a novel prototype of the ultrasound tomography diagnostic device for the detection and estimation of female breast cancer malignancy *in vivo* [3,4]. This algorithm was modified, improved, and adapted to the measurement needs accordingly. The measurement window in which the receiving signal was recorded contains N samples, which can be denoted by the indices i = 1, 2, ..., N. This window is then divided into two sections (sub-windows) with a floating split sample number k = 2, 3, ..., N-1, such that section No. 1 named $S(1,k)$ contains the initial samples i = 1, 2, ..., k from the main window, and section No. 2 named $S(k+1,N)$ contains the remaining samples i = k+1, 2, ..., N from the main window. The $AIC(k)$ index values for k = 2, 3, ..., N-1 are then calculated using the formula:

$$AIC(k) = k \cdot \log\left[\mathbf{var}\left(S(1,k)\right)\right] + (N-k-1) \cdot \log\left[\mathbf{var}\left(S(k+1,N)\right)\right], \tag{3}$$

where **var** operator denotes a variance of the form:

$$\mathbf{var}\left(S(k+1,N)\right) = \sigma^2_{N-k-1} = \frac{1}{N-k-1}\sum_{l=k+1}^{N}\left(S(l,l) - \bar{S}\right)^2, \tag{4}$$

where $\bar{S}$ is the mean value of the samples. In the $S(1,k)$ window, the mean value is calculated using the formula:

$$\bar{S} = \sum_{i=1}^{k} \frac{samples(i)}{k}. \tag{5}$$

In the $S(k+1,N)$ window, the average value is calculated using the formula:

$$\bar{S} = \sum_{i=k+1}^{N} \frac{samples(i)}{N-k}, \tag{6}$$

The transit time of the ultrasonic pulse is determined for the sample from the window for which the value of $AIC(k)$ reaches a minimum.

The algorithm can be further extended to more accurately determine the transition time in the case of a soft minimum $AIC(k)$. To do so, count the AIC_i indices for samples i = 1, 2, ..., n in a narrow window around the sample for which the pulse transition time was determined. Then count the differences $\Delta_i = AIC_i - AIC_{min}$ for each i = 1, 2, ..., n (AIC_{min} – the previously determined index value) and weights:

$$W_i = \frac{e^{\left(-\frac{\Delta_i}{2}\right)}}{\sum_{r=1}^{n} e^{\left(-\frac{\Delta_r}{2}\right)}}. \tag{7}$$

Finally, the transit time of the ultrasonic pulse is calculated using the formula:

$$t_{TOF} = \sum_{i=1}^{n} W_i \cdot t_i, \tag{8}$$

where t_i is the transition time for samples i = 1, 2, ..., n, respectively.

3. Results of measurements and calculations

The validation of the AIC algorithm was done using transmission time measurements of ultrasonic pulses recorded with a 1024-element ultrasonic ring array, which is the scanning element of a novel prototype of the ultrasonic tomography diagnostic device for the detection and estimation of female breast cancer malignancy *in vivo* [3-5]. The algorithm was tested in an aqueous environment using elementary pairs of piezoceramic transmitting and receiving ultrasonic transducers of a tomographic ring array [6]. Figs. 1-3 show examples of the application of the AIC criterion to determine the transit time of a 2 MHz ultrasonic pulse in water, in the area of the ultrasonic ring array. The gray curve plotted on the graphs illustrates the values of $AIC(k)$ indices (acc. Eq. (3)).

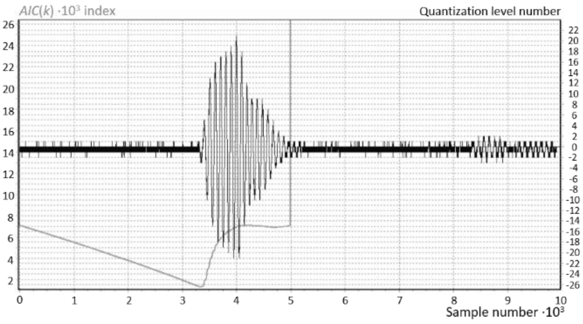

Fig. 1. Received pulse after passing through the water between a pair of opposite transmitting and receiving transducers of the ultrasonic ring array recorded over a measurement window of 10 000 samples.

(a) (b)

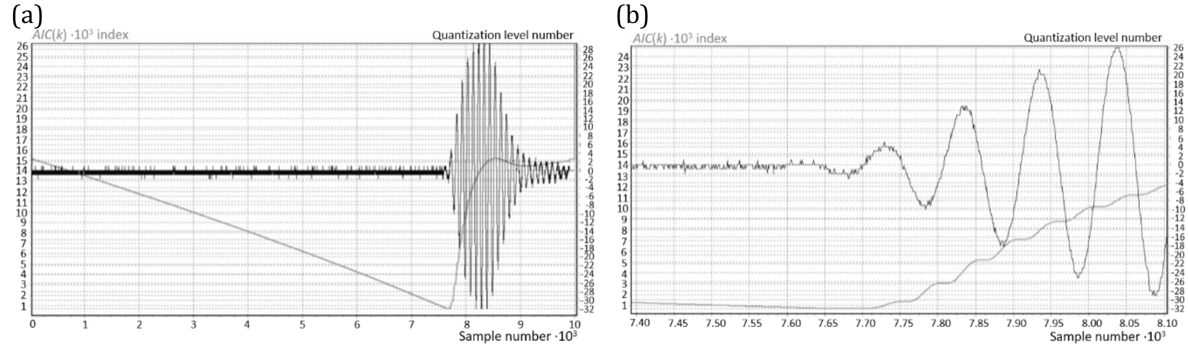

Fig. 2. Received pulse after passing through the water between a pair of transmitting and receiving transducers of the ultrasonic ring array recorded in a measurement window of 10 000 samples (a) and enlarged view in a window of 700 samples (b).

(a) (b)

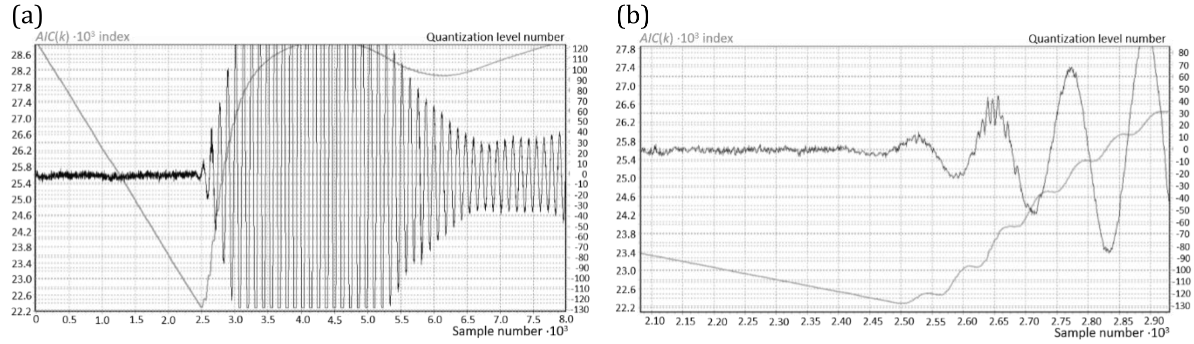

Fig. 3. Received pulse after passing through the water between a pair of transmitting and receiving transducers of the ultrasonic ring array recorded in a measurement window of 8 000 samples (a) and enlarged view, in a window of 700 samples (b).

Tests showed that the algorithm in most cases accurately determines the first zero crossings, at the beginning of the received pulse (Fig. 2b, Fig. 3b). Significant errors in the measurement of the transition time using the AIC criterion appear in the case of determining the $AIC(k)$ indices in the window, in which, in addition to the receiving pulse, there are also reflected pulses (Fig. 4) and in the case of large windows. Too wide calculation of AIC indices has also another disadvantage **-** long calculation time.

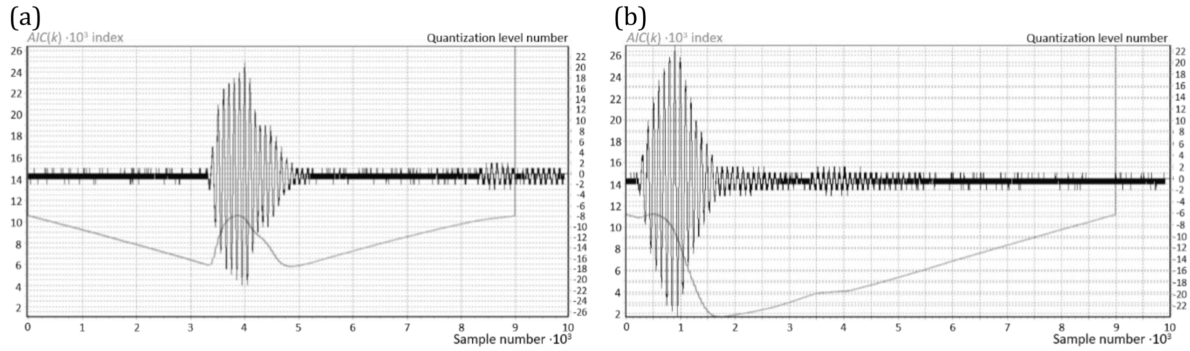

Fig. 4. Received pulse after passing through the water between a pair of transmitting and receiving transducers of the ultrasonic ring array recorded in a measurement window of 10 000 samples with subsequent lateral or multiple reflections: a) pulse at 1/3 of the measurement window, b) pulse at the beginning of the measurement window.

In the case shown in Fig. 4a, two similar minima of the $AIC(k)$ value appear, with the smallest value being the minimum at the location of the end of the useful received pulse, resulting in the pulse transit time being determined with a large error comparable to the duration of the received pulse. In the case shown in Fig. 4b, due to the position of the useful received pulse at the beginning of the detection window, the error is similar, except that only one minimum of $AIC(k)$ at the end of the received pulse is relevant. Shifting the detection window so that there is more "empty space" in front of the useful received pulse causes the first, relevant $AIC(k)$ minimum corresponding to the beginning of the received signal to be more pronounced (Fig. 5).

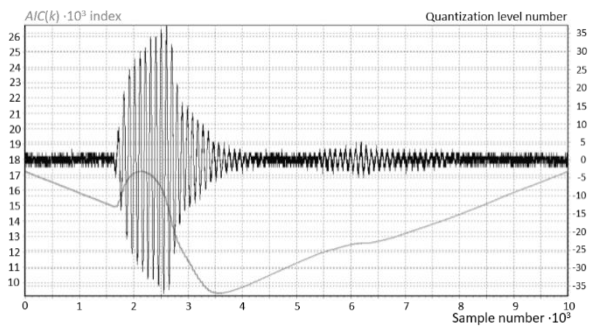

Fig. 5. Results of $AIC(k)$ index calculations when the detection window of the receiving pulse (after passing through the water between a pair of transmitting and receiving transducers of the ultrasonic ring array recorded in a measurement window of 10 000 samples) is shifted to increase the window to pulse onset interval.

As can be seen, the use of a too wide detection window covering with excess the receiving pulse is a source of significant errors in this method, as well as too small samples between the beginning of the window and the beginning of the pulse. The main way to eliminate the measurement errors should be the selection of appropriate ranges for determining the values of $AIC(k)$ indices. Fig. 6 shows $AIC(k)$ values for different sizes of the detection window with a sufficiently large number of samples from the beginning of the window to the beginning of the pulse. As can be seen, choosing even a very narrow range of calculation of $AIC(k)$ index does not cause errors in the detection of the beginning of the pulse, provided that this beginning is inside the calculation range.

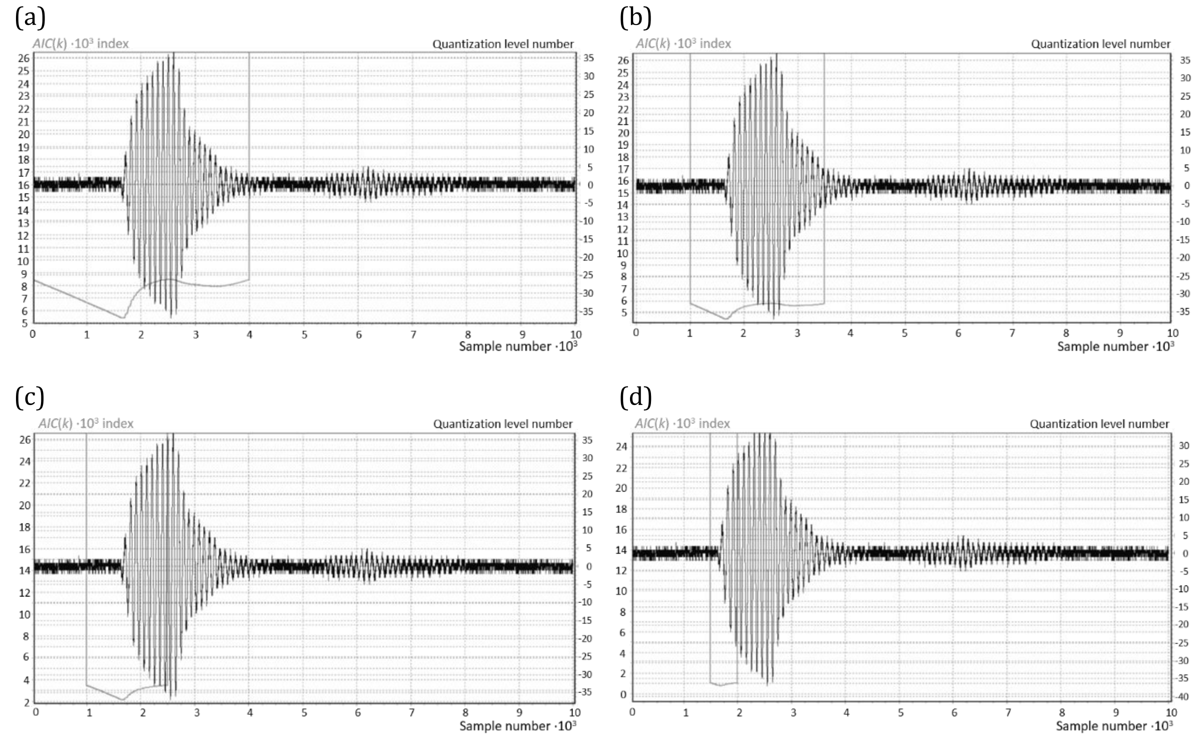

Fig. 6. The results of $AIC(k)$ index calculations when limiting the size of the received pulse detection window adopted for the calculation: a) 4 000, b) 2 500, c) 1 500, d) 500 samples.

4. Summary and conclusion

As a result of the experiments, a special algorithm was developed to find the beginning of the recorded received pulse in successive steps:

1) the maximum of the received signal is searched,
2) the range of determination of $AIC(k)$ index in a limited window from 2 500 samples before the found maximum to the maximum is determined,
3) minimum of obtained function $AIC(k)$ is searched - it is the first approximation of the beginning of pulse (in the case shown in Fig. 7a it is sample number 3395),
4) again the range of $AIC(k)$ is determined in the window from -400 to +400 samples around the determined beginning,
5) the minimum of the obtained function $AIC(k)$ is searched again - this is the beginning of the pulse (in the case shown in Fig. 7b it is sample number 3385).

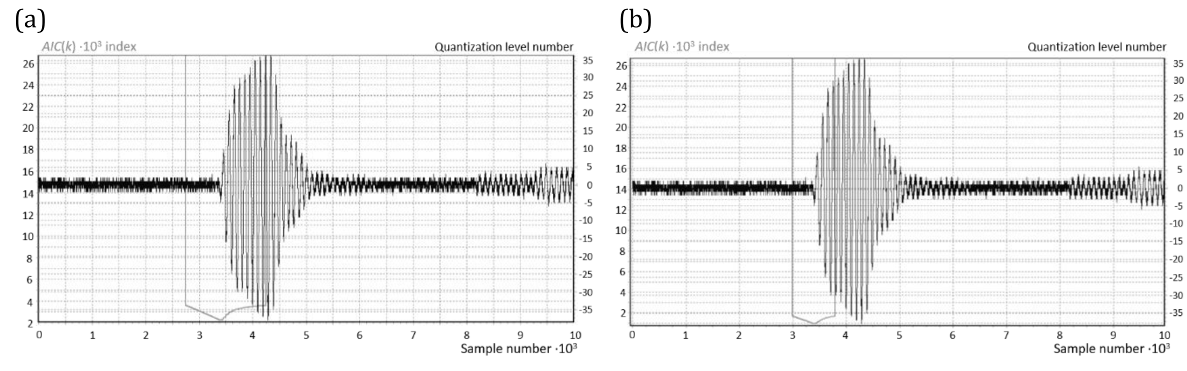

Fig. 7. Results of $AIC(k)$ index computation in each step of the developed algorithm for finding the beginning of the recorded receiving pulse: a) first approximation, b) final detection.

The pulse transit time between a pair of transmitting and receiving transducers of the ultrasonic ring array is determined by multiplying the sample number obtained from the minimum $AIC(k)$ index by the sampling period (4 ns) with correction for the detection window onset delay and the signal generation delay supplying the transmitting transducer.

It is possible to apply additional weighting of the $AIC(k)$ function around the minimum found (in the area of 100 samples), which allows determining the beginning of the pulse with the accuracy below one sample. In the presented case we get 3389.22. Such spread results from the specific shape of the $AIC(k)$ curve around the minimum (Fig. 8), which is very flat. In this situation, the use of weighting gives the most precise results.

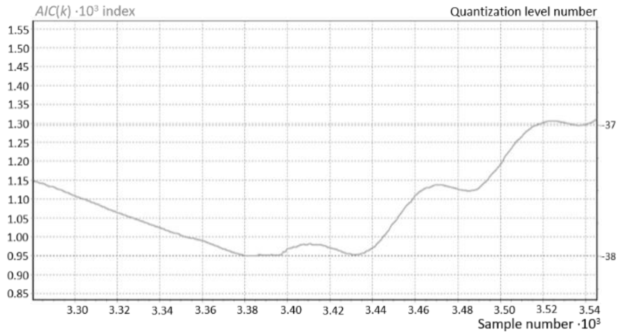

Fig. 8. $AIC(k)$ curve from Fig. 7b under magnification.

Acknowledgments

The paper has been prepared based on the results of industrial and development works carried out in the project POIR.01.01.01-00-1595/15, entitled: "*Development of a prototype multimodal ultrasound tomography scanner for breast diagnostics*", co-financed by the European Union from the European Regional Development Fund (Sub-measure 1.1.1 Industrial research and development works carried out by enterprises, Operational Program Intelligent Development 2014-2020), as part of the grant awarded by the National Centre for Research and Development to DRAMIŃSKI S.A. company.

References

1. H. Akaike. A new look at the statistical model identification, IEEE Transactions on Automatic Control, 19(6):716–723, 1974. DOI: 10.1109/TAC.1974.1100705
2. C. Li, L. Huang, N. Duric, et al. An improved automatic time-of-flight picker for medical ultrasound tomography, Ultrasonics, 49(1):61-72, 2009. DOI: 10.1016/j.ultras.2008.05.005
3. K.J. Opieliński, P. Pruchnicki, P. Szymanowski, et al. Multimodal ultrasound computer-assisted tomography: An approach to the recognition of breast lesions. Computerized Medical Imaging and Graphics, 65:102-114, 2018. DOI: 10.1016/j.compmedimag.2017.06.009
4. T. Milewski, M. Michalak, A. Wiktorowicz, et al. Hybrid Ultrasound Tomography Scanner - a Novel Instrument Designed to Examine Breast as a Breast Cancer Screening Method. Biomedical Journal of Scientific & Technical Research, 14(4):1-5, 2019. DOI: 10.26717/BJSTR.2019.14.002594
5. T. Gudra, K.J. Opielinski. The ultrasonic probe for the investigating of internal object structure by ultrasound transmission tomography. Ultrasonics, 44:e679–e683, 2006. DOI: 10.1016/j.ultras.2006.05.126
6. K.J. Opieliński, M. Celmer, R. Bolejko. Crosstalk Effect in Medical Ultrasound Tomography Imaging. Acoustics 2018 proceedings of joint conference, 1-6, IEEE, 2018. DOI: 10.1109/ACOUSTICS.2018.8502426