

The Use of Phase-Shift Keyed Signals to Increase Thickness Measurement Accuracy of Large-Sized Products Made of Polymeric Composite Materials

Vladimir K. Kachanov, Igor V. Sokolov, Alexey A. Sinitsyn* and Maksim B. Fedorov

National Research University, Moscow Power Engineering Institute, Electrical Engineering Faculty, Moscow,



Russian Federation; c.i.n@mail.ru

Abstract

It is shown that to improve the accuracy of Ultrasonic (US) thickness measurements of the large-sized products made of polymeric composite materials it is required to use Phase-Shift Keyed (PSK) Signals, known from Radio Engineering, and to determine echo signal time delay by the maximum of compressed PSK pulse. In order to improve the measurement accuracy US PSK Huffman encoding signals (M-signals) should be used in the continuous repetition mode, providing simultaneously high measurement accuracy and the greatest possible control sensitivity for a given period of repetition of probing pulses.

Keywords: Phase-Shift Keyed Signals, Polymeric Composite Materials, Measurement Accuracy, Ultrasonic Thickness Measurement

1. Introduction

While carrying out Ultrasonic (US) echo-pulse Defectoscopy of large-sized products made of Polymeric Composite Materials (PCM) two conflicting problems have to be solved simultaneously – to provide high sensitivity and high resolution capability (or high accuracy of the product thickness measurement when measuring product thickness by US methods). The requirement for high sensitivity is determined by an abnormally large frequency-dependent attenuation of US Oscillations (USO) in the product, and therefore the received echo signal A_2 US attenuates considerably and may become comparable with the white noise level (noise of US flaw detector receiving path)¹:

$$A_2 = A_1 e^{-\delta(f)X} \quad (1)$$

Where A_1 - amplitude of the US probing signal, $\delta(f)$ - attenuation rate, X - product thickness.

Dependence $\delta(f)$ for the PCM is such that in order to

increase the control sensitivity it is required to reduce the probing signal frequency, however this increases the length of USO, resulting in reduced accuracy of determination of echo signal time delay. Thus, when choosing a probing signal frequency during US testing of PCM products it is necessary to seek a compromise between the requirements of high accuracy of measurements and high sensitivity of testing.² However, it often turns out that the required high measurement accuracy of echo signal is possible to provide only at such frequencies when the echo signals are masked (and distorted) by white noise – the receiving path noise of the equipment inlet. In this case, solutions, known from radar broadband, relating to of the error minimization in measuring time delay of echo signal distorted by white noise should be used.

2. Method

The problem of determining the exact echo signal time delay in the presence of white noise is a statistical one;

* Author for correspondence

therefore the statistical methods are required to solve this problem. The theory of radio engineering signals indicates that the minimized value of measurement error dispersion for echo signal time delay can be written as follows:³

$$\sigma_{t_{\min}}^2 = [(2E/N_0)\Pi^2]^{-1},$$

Where $2E/N_0$ - the maximum possible signal/noise ratio at the output of the Optimal Filter (OF) for this signal; Π - efficient width of the signal spectrum.

This implies that the US echo signal extraction from white noise (which is realized by RP) and the use of maximum broadband signal make a necessary condition for minimizing the error $\sigma_{t_{\min}}^2$. Moreover, the use a simple unmodulated short (and therefore broadband) signal without optimal filtering is an insufficient condition, since it does not meet the requirement to ensure a high value of the signal/noise ratio. At the same time the use of broadband Complex-Modulated (CM) signals followed by optimal filtration allows fulfilling these two conditions.⁴

Figure 1a shows one of the most widespread CM signals – a Phase-Shift Keyed (PSK) signal with duration T_s , having carrier frequency modulated by binary Barker code with the base $B = T_s \Delta f_s = 13$. Figure 1b shows video code corresponding to this signal which consists of $B = 13$ elementary video pulses with duration T_3 . Barker video code repeats the form of the signal the Auto Correlation Function (ACF) at the output of its optimal filter (Figure 1c), having one main lobe with duration $T_{\text{сж}} = T_s/B = 13T_3/B = T_3$ and amplitude exceeding the amplitude of side lobes by $B = 13$ times. In this case it is said that Barker PSK signal with base $B = 13$ is somewhat ‘compressed’ in time by 13 times at its optimal filter output.

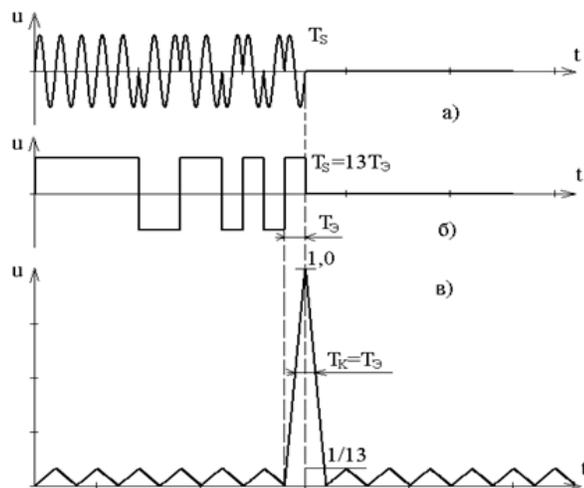


Figure 1. Barker PSK signal B=13.

Analyzing the shape of the PSK signal at the OF output, it is seen that its time delay should be measured by ACF maximum. In this case it is desirable to carry out measurement by video pulse peak, and it is necessary to ensure synchronous detection of US PSK echo signal for this purpose.⁵

Another condition for improving the measurement accuracy is the need to use US CM signals with the utmost energy $E = U^2 T_s$ (with extremely large base) to ensure the highest possible signal/noise ratio. Thus, when using PSK signals with base $B \approx 100$, PSK signal energy will increase by $T_s/T_3 = B \approx 100$ times compared to the elementary pulse energy with duration T_3 . Amplitude of the compressed echo signal after the optimal processing will also increase by $B \approx 100$ times. If the echo signal is below white noise level, then by means of optimal filtering the signal/noise ratio will increase by $\sqrt{100} \approx 10$ times, and measurement error of echo signal time delay (1) will decrease by $B \approx 100$ times. This property of PSK signals with a large base allows providing the required testing sensitivity rather increasing its energy than by reducing the frequency of probing signal.

Thus, use of PSK signals with large base solves several problems at once: both high testing sensitivity at sufficiently high frequency of the probing signal and high measurement accuracy of echo signal time delay are provided simultaneously.

3. Results and Discussion

Complex-modulated signals were initially used in radiolocation, and starting from the mid 1970-s onward they were increasingly applied in US flaw detection both in Russia⁶, and abroad.⁷⁻⁹ However, CM signals are still used, as a rule, only for research; their industrial application is limited by the fact that so far there is no mass-production of US testing equipment, which uses CM signals and carries out their processing.

The multifunctional Measuring System (MS) developed in MPEI enables to apply simple and CM signals, including Linear Frequency Modulated (LFM) signals), split-signals, Barker phase-shift keyed signals, Golay signals, Huffman signals, etc. The MS has special features enabling to change the CM signal frequency in the course of testing, to select the signal code, to change its base by means of changing duration of elementary pulse T_3 . The measuring system allows carrying out almost any radio engineering processing of US echo signals, operating

in single and multi-channel modes (including US phased antenna arrays).¹⁰ Selection of CM probing signal type, adjustment of its parameters and implementation of numerous radio engineering processing operations with echo signals is made by the operator using the appropriate setup control panel (Figure 2).

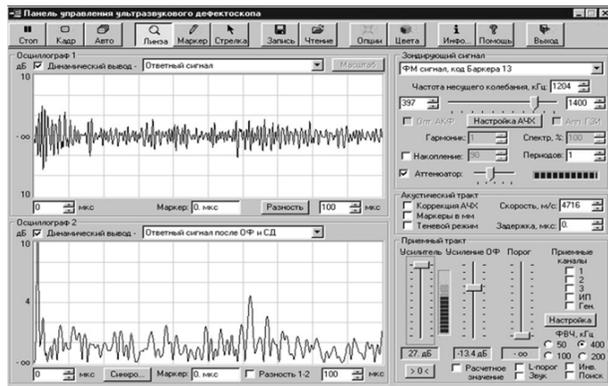


Figure 2. US PSK signal against the background of white noise, ($S/N \approx 1/3$) without processing (top) and after optimal filtering and synchronous detection (bottom).

The Upper Oscillogram on the MS control panel shows the result of PCM product thickness measurement with high level of USO attenuation using Barker PSK signal $B = 13$. Echo signal from the product bottom is masked by white noise (at the MS input S/N ratio $\approx 1/3$). The lower Oscillogram shows echo signal after OF and synchronous detection, demonstrating that the amplitude of compressed US PSK echo signal exceeds slightly the level of white noise, and the level of side lobes is so high that it does not allow uniquely determining echo signal time delay.

To evaluate permissible measurement error of echo signal time delay, distortions of Barker US PSK echo signal with base $B=13$ were simulated at various values of white noise (Figure 3). Figure 3a demonstrates ACF of Barker PSK signal after synchronous detector with absence of white noise. Figure 3b shows 13-bit Barker PSK signal masked by white noise at the OF input. Figures 3c, 3d, 3e show compressed PSK signals after optimal filter and synchronous detector at various values of white noise. It is seen that due to the presence of high level of noise which distorts the signal, the side lobe level increases and the main maximum is distorted. At the S/N ratio = $1/3$ the shape of the compressed signal at the OF output is strongly distorted, however, it still allows recording the

ACF maximum of PSK echo signal (Figure 3e). In this case the simulation shows that the position shift of PSK signal maximum after OF and SD does not exceed 0.02 of the duration of the main maximum at S/N ratio = $1/3$. Thus, it can be argued that at the relatively low level of white noise the signal measurement accuracy is sufficiently high.

At the same time with increasing input noise 13-bit Barker PSK signal may be masked so much that the measurement error will increase unacceptably. In this case, to improve the accuracy of measurement the signal base should be increased.

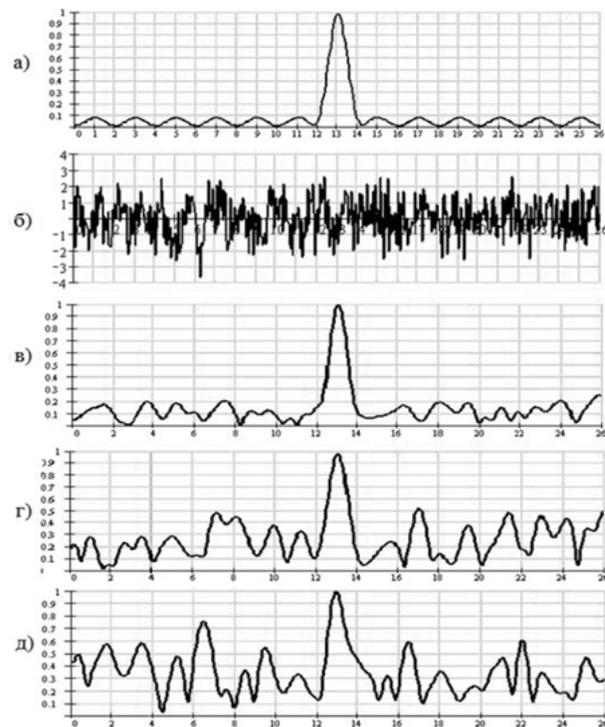


Figure 3. Extraction of 13-bit Barker PSK signal from white noise: a) PSK signal after OF and SD ; b) PSK masked by white noise; PSK signal after OF and SD with S/N input ratio: $S/N = 1$ (c); $S/N = 1/2$ (d); $S/N=1/3$ (e).

Unfortunately, Barker PSK signals have maximum base $B=13$. At the similar correlation of amplitudes of the main maximum and side lobes of the autocorrelation function Huffman PSK signals (M -signals) possess larger base ($B=M= 15, 31, 63, 127$, etc.) in the continuous repetition mode with duration $T_c = MT_s$. If the repetition period of probing pulses T_n equals to the duration of the M -signal $T_n = T_c = MT_s$ and to the period oscilloscope sweep T_p , then using the M -signal continuously a unique mode is formed, when a continuous signal is emitted into

the tested product, which is typical for shadow testing method, and the test results on the oscilloscope display match US echo-pulse control. Since the testing sensitivity is determined by the probing signal energy, in the case under consideration (when the probing signal is emitted continuously during the period $T_n = T_p$), the highest possible sensitivity of US echo-control is provided at the given $U_1(t)$ and T_n , determined by the probing signal energy $E = U_1(t)^2 T_c = U_1(t)^2 T_n$.

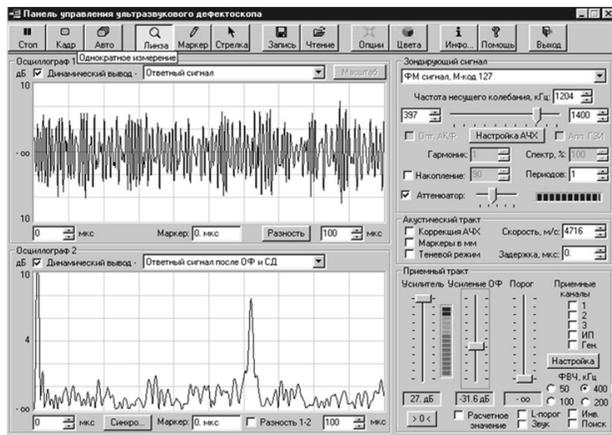


Figure 4. PSK M-signal with base $B=127$ in the continuous repetition mode against the background of white noise (top) and after optimal filtering and synchronous detection (bottom).

The upper window in Figure 4 shows the results of US testing for the extended product made of polymeric composite material by PSK M-signal with base $M=127$ in the conditions of high level of white noise (input signal/noise ratio makes 1/10). “Useful” bottom US signal is located below the white noise level and is not detected. After OF the bottom signal becomes considerably higher than the noise level (lower Oscillogram), and after SD shift of the compressed pulse maximum does not exceed 0.01 of the main maximum duration.

4. Conclusion

Thus, when testing large-sized products made of polymeric composite materials to improve the product thickness measurement accuracy it is required to use complex-modulated signals followed by their processing in the optimal filter and synchronous detector. Application of multifunctional measuring system allows selecting a PSK signal, which is optimal for each definite

product, changing its parameters (modulation code, base, frequency, and duration of the elementary pulse T_s) and, thereby, enables to create optimal conditions for each product while extracting a bottom signal from noise and providing high measurement accuracy for echo signal time delay.

5. Acknowledgments

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