ULTRASOUND METHOD OF MULTI-LAYER MATERIAL THICKNESS MEASUREMENT

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ABSTRACT. The new multi-layer materials are widely used in air-space industry. We present the new method of multi-layer material thickness measurement, which is based on the digital Hilbert transformation and the signal unwrapped phase analysis. The results indicate that a phase unwrapping of a signal from transducer is able to detect the phase jumps, which are produced by the eho signal superposition during ultrasound nondestructive examination of a multi-layer material.

INTRODUCTION

The problem of a material thickness measurement belongs to number of conventional problems of ultrasonic nondestructive examination [1]. The solution of this problem is based on usage of a pulse-echo method, which guesses definition of ultrasonic signal delay propagation τ through the testing object (TO). If the rate c of ultrasonic wave propagation in TO is known and the wave is propagated in two directions between the TO walls, the delay is connected uniquely to depth h by an equation $h = 0.5c\tau$.

The value of τ is customary estimated on time frame between both of a probing signal envelope and an echo signal envelop (or between two echo signal envelops), which are determined by an amplitude detector. In this case thickness measurement is possible if the condition $\tau > \tau_s$ is satisfied, where τ_s is transducer signal duration. If the indicated condition is defaulted, it is impossible to measure material thickness using the amplitude detector because of signal superposition.

In figure 1 it is shown the scheme of the reflected ultrasonic beams formation during multi-layer the TO a thickness measurement. In this figure the TO consist of two layers. If all layers have the different acoustic properties each border of a layer gives its own reflected pulse. All reflected signals $u_{ec}(t)$ and a probing signal $u_{pr}(t)$ make a signal from transducer as shown in figure 2. The signal $u(t)$ is received by measurement equipment. The definition of the layer thickness can be executed according to the formulas:

$$h_1 = 0,5c_1(\tau_1 - \tau_d), \quad h_2 = 0,5c_2\tau_2, \tag{1}$$

wheare c_1, c_2 are the ultrasonic longitudinal waves velocity in the layers 1 and 2 accordingly, τ_d is propagation delay in a delay line.
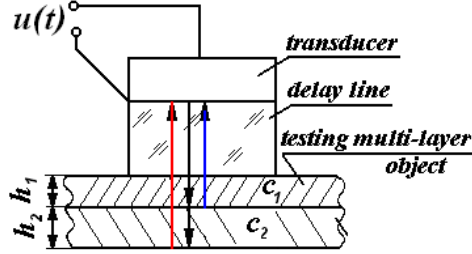

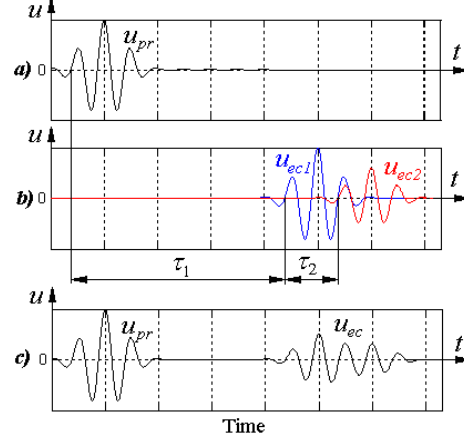FIGURE 1. The schematic diagram of ultrasonic multi-layer material thickness measurement

FIGURE 2. (a) probing signal, (b) echo signal, (c) signal from transducer

The general reflected signal $u_{ec}(t)$ consists of the sum of echo signals $u_{ec1}(t)$ and $u_{ec2}(t)$ which can not be separate by amplitude analysis. So the envelop analysis allows to detect only delay τ_1. On the other hand the echo signals have identical frequency, so it does not allow applying frequency methods for their separation.

At the same time feasibilities of a signal phase analysis for this problem solution are not studied up to the end. The purpose of this report consists in the research of ultrasonic echo signal phase structure and uses their features for multi-layer material thickness measurement.

THEORRETICAL BACKGROUND

The main idea of the proposed method of multi-layer material thickness measurement [2] is based on the analysis of a signal unwrap phase. There are a lot of industrial and medical applications that use phase unwrapping. Examples of such applications are interferometric synthetic-aperture radar [3], optical interferometry, magnetic resonance imaging, finger pattern analysis, tomography and others [4].

In case of ultrasonic thickness measurement a wrapped phase $\varphi(t)$ of a signal from transducer $u(t)$ can be obtained by its Hilbert transform [5].

$$\tilde{u}(t) = \frac{1}{\pi} PV \int_0^\infty \frac{u(\tau)}{\tau - t} d\tau \tag{2}$$

where PV stands for "principal value". Using both of these signals $u(t)$ and $\tilde{u}(t)$, it is possible to comput the envelop and the wrapped phase $\varphi(t)$. The signal envelop is determined as:

$$U(t) = \sqrt{u^2(t) + \breve{u}^2(t)}. \tag{3}$$

When $\varphi(t)$ is limited on the interval $[0, \ 2\pi)$, it can be computed according to the formula [6]:

$$\varphi(t) = arctg\frac{\breve{u}(t)}{u(t)} + \frac{\pi}{2}\{2 - [sign(\breve{u}(t))] \cdot [1 + sign(u(t))]\}, \tag{4}$$

where $sign(\cdot)$ is a signum function.

For the continuous function $u(t)$ the unwrapped phase is a continuous function of the argument t. It can be obtained from a wrapped phase which is determined through Hilbert transform [3]. If $u(t)$ is a harmonic funtion $u(t) = U\cos(2\pi ft + \varphi_0)$, the unwrapped phase is a linear function of time $\Phi(t) = 2\pi ft + \varphi_0$, while the wrapped phase corresponds to the sawtooth funtion $\varphi(t) = (2\pi ft + \varphi_0)(\text{mod}\,2\pi)$. The phase jumps of $\varphi(t)$ are equal 2π.

It is known, that an initial phase φ_Σ of two harmonic signals sum with the identical frequency $u_\Sigma(t) = u_1(t) + u_2(t)$, where $u_1(t) = U_1\sin(2\pi ft + \varphi_1)$ and $u_2(t) = U_2\sin(2\pi ft + \varphi_2)$, $\varphi_1, \varphi_2 \in [0, \ 2\pi)$ is equal to

$$\varphi_\Sigma = arctg\frac{U_1\sin\varphi_1 + U_2\sin\varphi_2}{U_1\cos\varphi_1 + U_2\cos\varphi_2}. \tag{5}$$

If the harmonic signal $u_2(t)$, $t \in [t_1, \infty)$ adds to another harmonic signal $u_2(t)$, $t \in (-\infty, \ \infty)$ phase jump in the moment t_1 will be equal to $\Delta\varphi = \varphi_\Sigma - \varphi_2$.

Thus, in case of superposition of the echo signals during ultrasonic multi-layer material thickness measurement the wrapped phase will contain phase jump of two kinds, witch can be separated on their value. The first kind of jump has a value of 2π and can be used for phase unwrapping

$$\Phi(t) = \varphi(t) + 2\pi \cdot S[\varphi(t)], \tag{6}$$

where $S[\varphi(t)]$ is a step function, $S[\varphi(t)] \in N$.

The second kind of phase jump has a valuer in interval $(-0.5\pi, \ 0.5\pi)$ and can be detected from unwrapped phase difference

$$\delta\Phi(t) = \Phi(t) - 2\pi ft, \tag{7}$$

The position of a second kind of phase jump in time allows determining the delay τ_2 and computing the material thickness h_2 according to (1).

RESULTS OF SIMULATION

The tendered method was tested on a model of two-layer structure the TO as shown in the figure 1. As a probing signal we used the radio-frequency pulse

$$u_{pr}(t) = e^{-at^2} \cos 2\pi f t, \quad t \in [0, T_s], \tag{8}$$

where a is a parameter, which controls of a radio pulse length. This pulse has a gaussian envelop. There are reflections from a border of each layer of the TO during signal propagation through it. The echo signals are introduced by following model after the first reflection:

$$u_{ec1}(t) = k_{eac1}(t)e^{-at^2} \cos(2\pi f(t - \tau_1)), \; u_{ec2}(t) = k_{eac2}(t)e^{-at^2} \cos(2\pi f(t - \tau_1 - \tau_2)), \tag{9}$$

where k_{eac} is a factor of electro acoustic transform.

Signal from transducer (disregarding of measure channel noise) is introduced by sum of the probing signal (8) and the echo signals (9)

$$u(t) = u_{pr}(t) + u_{ec1}(t) + u_{ec2}(t). \tag{10}$$

During simulation the following signal parameters are used: $a= 35000$ s^{-2}, $T_s = 0.18$ s, $f=100$ Hz, $\tau_1 = 0.08$ s, $\tau_2 = 0.024$ s, $k_{eac1} = 0.5$, $k_{eac2} = 0.3$, sampling rate equal to 10^{-4}s. The results of simulation are shown on the figure 3.
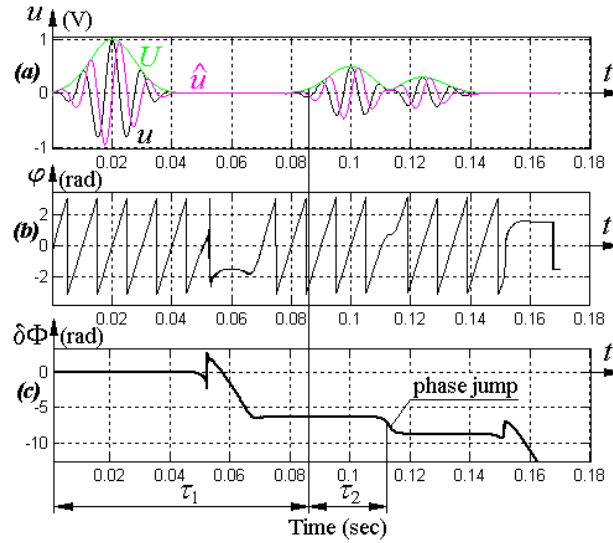

FIGURE 3. (a) time domain functions $u(t)$, $\hat{u}(t)$ and the envelope $U(t)$,
(b) wrapped phase of the function $u(t)$, (c) phase difference $\delta\Phi(t)$ computed according to (7)

In this case the phase jump is equel to value $\delta\varphi = \delta\Phi(t = 0.12s) - \delta\Phi(t = 0.11s) \approx 2.3$ rad as it is shown on the figure 3(c). Such phase jump can be reliably detected. It allows to determine delay τ_2 and to compute value of depth h_2 (1).

The calculation of phase jump for for different parameters of the echo signals was executed with the purpose of a phase sensitivity relation definition from the amplitudes and phases ratio of the echo of signals. The obtained two dimensional functions $\delta\varphi(k, \theta)$ for a case of a harmonic signals superposition is shown on the figure 4. The arguments of this

function are the amplitude ratio $k = k_{eac2}/k_{eac1}$ and the angular phase difference $\theta = 2\pi f \tau_2$, $\tau_2 \in \left[0.1, \; 1\right]$.
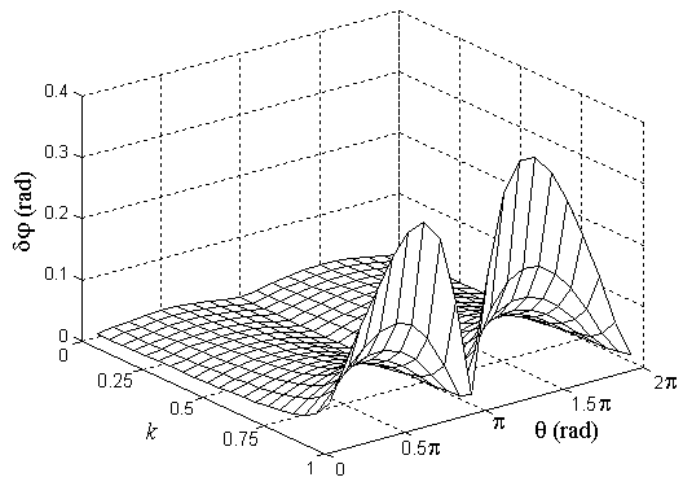

FIGURE 4. Calculated result of the influence of the k and θ on the phase difference sensitivity

Figure 4 shows that this method provides satisfactory sensitivity as a whole, but it also demonstrates that the sensitivity reaches minimums in points $\theta = \left\{0, \; \pi, \; 2\pi\right\}$. It is possible to avoid measurement in minimum sensitivity points at the expense of a frequency drift in a small range.

EXPERIMENTAL SETUP

Schematic of the experimental setup is shown on the figure 5. The figure 6 gives a common view of the experimental setup with probe placed on the testing object.
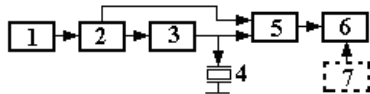

FIGURE 5. Structural diagram of the experimental setup: 1- sineshaped oscillator, 2- radio- frequency pulse signal conditioner, 3 - power amplifier, 4 – superposed transducer, 5 – digital oscilloscope, 6 – PC, 7 – software
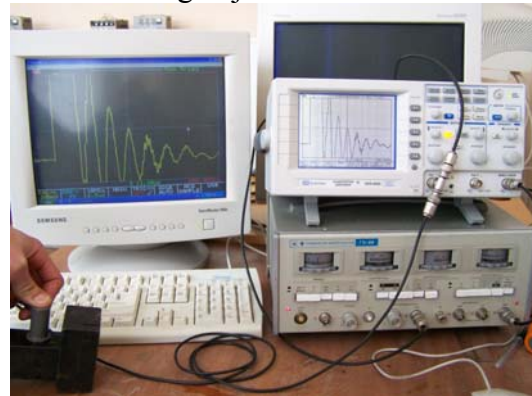
FIGURE 6. Common view of the experimental setup

The sineshaped oscillator 1 generates a continuous harmonic signal with frequency f, which goes on the radiofrequency pulse signal conditioner 2. The signal from the power amplifier 3 goes to the superposed transducer 4 and the digital oscilloscope (GDS-840S) 5, which samplings the probing signal and transmits the result to PC 6. The system operation was tested for the thin metallical sheets thickness measurement.

CONCLUSIONS AND FUTURE WORK

The new method of multi-layer structure ultrasonic testing is reviewed. The method is based on application of Hilbert transform and signal phase unwrapping analysis. Hilbert transform gives possibility to find the unwrapped phase of a signal. When echo signals coincide, the unwrapped phase of a signal is distorted. The moment of its distortion corresponds to a phase jump. The time definition of a phase jump gives a chance to estimate time delay and find the material thickness.

The analysis of the sensitivity method is conducted. The points of sensitivity maxima and minima are detected and the way to avoid zones with minimum sensitivity is indicated.

In the near future the experimental research of this method will be proceeded with wide band ultrasonic transducer. More experimental and modelling work will be accomplished on real multi-layer material structure to provide a comprehensive study of unwrap phase for ultrasound nondestructive examination.

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