# Application of the Hilbert-Huang signal processing to ultrasonic nondestructive testing of composite materials

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## Introduction

An important issue in ultrasonic nondestructive testing (NDT) of composite fiber-reinforced materials is the detection of flaw echoes in the presence of structural noise due to scattering of ultrasonic waves and high attenuation of the ultrasonic signal [1]. The named problems show that testing of composite materials requires a special care in signal processing.

For detection and characterization of defects in NDT various signal-processing techniques are already used [1-3]. In all these techniques the signal is analyzed in the time domain, in the frequency domain or in the time-frequency domain. During the last decade time-frequency signal analysis become a popular tool in signal and image processing. Both linear and bilinear transforms have been utilized to describe the ultrasonic signals in the time-frequency plane: Gabor or Short Time Fourier transform (STFT), the Wigner-Ville distribution, the Split Spectrum Processing (SSP) technique, the Wavelet Transform (WT) and other [4-7]. The adoption of any method is determined according to the special field in which the application is made.

The purpose of the present paper is to provide the application of new signal processing method to the defects detection in multi-layered fiber-reinforced plastic pipe. The experimental investigations of plastic pipe sample with artificial defects [8] have showed that detection of holes in a porous layer and under this layer is complicated. To solve this problem Wavelet Transform signal processing method was proposed [9]. Wavelet analysis is still the best available non-stationary data analysis method so far. But in paper [9] it was shown that the standard signal processing procedures of Wavelet Transform can not determine defects in porous intermediate layer. Therefore, for solution of this problem we propose to use a new method for processing of ultrasonic signals called the "Hilbert-Huang method" (HH) [10, 11].

## Hilbert-Huang signal processing

All methods used for time-frequency signal analysis decompose the signal into components and then analyze each of them by standard methods. Signal decomposition can be implemented in many ways. The so-called Hilbert-Huang technique is based on direct extraction of the energy associated with the intrinsic time scales in the signal. This process generates a set of components, called the intrinsic modes functions (IMF) [10].

The Hilbert-Huang method (HH) consist of two steps:

- data "sifting" to generate the intrinsic modes (IMF);
- application of the Hilbert transform to the intrinsic modes.

The algorithm to create IMFs establish with the definitions of local maxima and minima of the time series of the signal $s(t)$. The local maxima $s_{max}(t)$ and minima $s_{min}(t)$ are connected by a cubic spline line to produce respectively upper envelope $u_s(t)$ and lower envelope $l_s(t)$ (Fig.1). Their mean is denoted as $m_1$(t) and is given by:

$$m_1(t) = \frac{u_s(t) + l_s(t)}{2}. \quad (1)$$

The difference between the original signal $s(t)$ and the so-called "running mean" $m_1$(t) is the first component $h_1(t)$:

$$h_1(t) = s(t) - m_1(t). \quad (2)$$

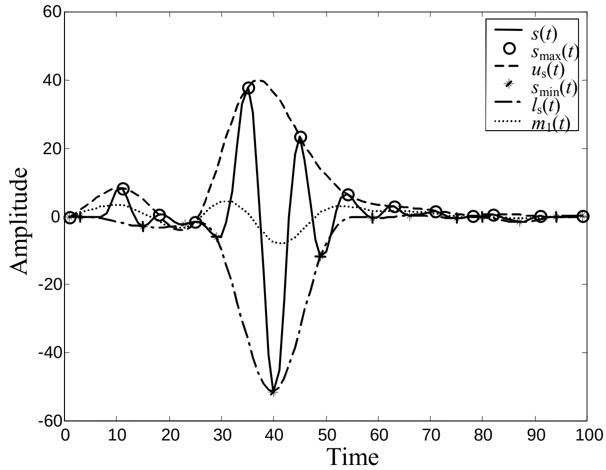



Fig.1. **Illustration of the calculation of the first component $h_1(t)$.**

The sifting process has to be repeated up to $k$ times, as it is required to reduce the extracted signal to an IMF:

$$h_{1k}(t) = h_{1(k-1)}(t) - m_{1k}(t), \quad (3)$$

where subsequent component $h_{1(k-1)}(t)$ is treated as the original signal. The resulting time series is the first IMF: $c_1(t)=h_{1k}(t)$. To check if $h_{1k}(t)$ is an IMF, the following conditions must be fulfilled [11]:

1) the component $h_{1k}(t)$ should not display under-shots or over shots riding on the original signal and producing local extremes without zero crossing;
2) to display symmetry of the upper and lower envelopes with respect to zero;
3) obviously the number of zero crossing and extremes should be the same in both functions.

The criterion for the sifting process to stop can be the size of the standard deviation, computed from the two consecutive sifting results as

$$SD = \frac{1}{m}\sum_{t=0}^{T}\left[\frac{\left|\left(h_{1(k-1)}(t) - h_{1k}(t)\right)\right|^2}{h_{1(k-1)}^2(t)}\right], \qquad (4)$$

where $m$ is the maximum number of the original signal digitising rate cells, $T$ is the total length of the signal. A typical value for $SD$ can be smaller than 0.3.

The first IMF $c_1(t)$ is subtracted from the original signal:

$$r_1(t) = s(t) - c_1(t)\,, \qquad (5)$$

and this difference is called as the residue $r_1$(t). It is treated as the new signal and subjected to the same sifting process.

The process of finding intrinsic modes $c_j$ continues until the final residue $r_n$(t) will be a constant or a monotonic function. Then it is achieved a decomposition of the original signal into $n$-empirical modes and a residue:

$$s(t) = \sum_{j=1}^{n} c_j + r_n\,. \qquad (6)$$

The second step is to apply the Hilbert transform to the decomposed intrinsic modes functions (IMF). Each IMF component has it's Hilbert transform:

$$y_j(t) = \frac{1}{\pi} P\int_{-\infty}^{\infty}\frac{c_j(t')}{t-t'}\,dt'\,, \qquad (7)$$

where $P$ indicates the Cauchy principal value. With this definition the analytic signal is defined as

$$z_j(t) = c_j(t) + iy_j(t) = a(t)e^{i\theta(t)}\,, \qquad (8)$$

in which

$$a_j(t) = \sqrt{c_j^2(t) + y_j^2(t)} \text{ - is the magnitude;} \qquad (9)$$

$$\theta_j(t) = \arctan\left(\frac{y_j(t)}{c_j(t)}\right) \text{ - is the phase.} \qquad (10)$$

To analyse the analytic signal $z_j(t)$ the Hilbert amplitude spectrum $H(\omega,\ t)$ is used. Therefore one can define an instantaneous frequency $\omega_j$ given by:

$$\omega_j(t) = \frac{d\theta_j(t)}{dt}\,. \qquad (11)$$

Thus the original signal can be expressed:

$$s(t) = \mathrm{Re}\left[\sum_{j=1}^{n} a_j(t)\cdot e^{\left(i\int \omega_j(t)dt\right)}\right]. \qquad (12)$$

This equation enables us to represent the amplitude (or the energy) and the instantaneous frequency in a three-dimensional plot. In the Hilbert spectrum we can see the distribution of the signal energy in the time domain. A peak in the Hilbert-Huang spectrum indicates that is highly probable that a wave of that frequency appeared at that particular point in the time interval considered [11].

## Application of Hilbert-Huang method to ultrasonic NDT signal processing

To investigate the possibility of application of the Hilbert-Huang method to multi-layered plastic pipe nondestructive testing, we analyzed two pipe samples with artificial defects. In pipe samples artificial defects – side-drilled holes (SDH) and flat bottom holes (FBH) – at the known position were drilled (Fig.2). The samples used in this investigation were one layer homogeneous pipe sample and three layers inhomogeneous pipe sample with an internal fiberglass layer [8]. As one layer pipe the polypropylene (PP) with 50-60 % chalk pipe (the wall thickness D=7.4 mm) was used. The diameter of all holes was 0.5 mm. The pipe sample with PP layer - fibreglass layer – PP layer was as the three-layered test pipe. The wall thickness of this pipe sample was D=10.8 mm. In the three layers pipe the diameter of holes SDH No.1 and FBH No.4 was 0.5 mm. The diameter of other holes was 1.5 mm. The defects in the test objects are determined by the ultrasonic pulse-echo immersion method. The pipe samples were tested along the coordinates $x$ and $y$. The reflected signals are presented on the graphical screen in form of *A-scans* and *B-scans*.

For ultrasonic signal processing by the Hilbert-Huang method we have used *B-scans* of the described pipe samples. These *B-scans* obtained by scanning of the transducer along the coordinate $x$ are presented in Fig.3. In *B-scan* of the one layer sample (Fig.3, a) it is seen, that all artificial defects at different distances from the front surface were successfully detected. How it is seen from Fig.3, b the artificial defect FBH No.4 in the first layer of the three-layer sample is detected reliably. In the second layer the defect SDH No.2 is detected not reliably and in the third layer defect SDH No.3 is not detected.

For detection of these defects we applied the Hilbert-Huang method. The first step of signal processing is decomposition of the all *A-scans* signals in each *B-scan* into intrinsic oscillation modes or IMFs. Fig.4 displays the decomposition into four IMF of the *A-scans* signals of the one (a) and three (b) layers plastic pipe samples.

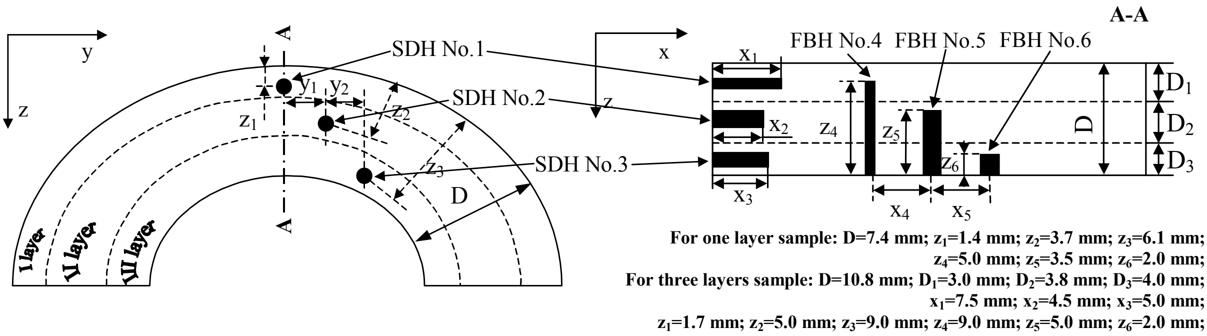
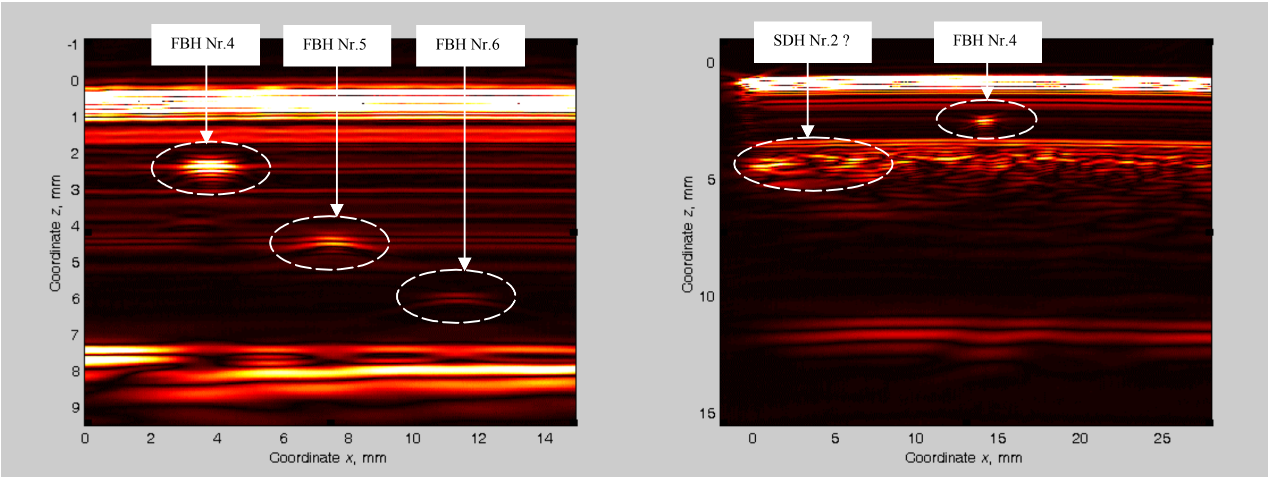


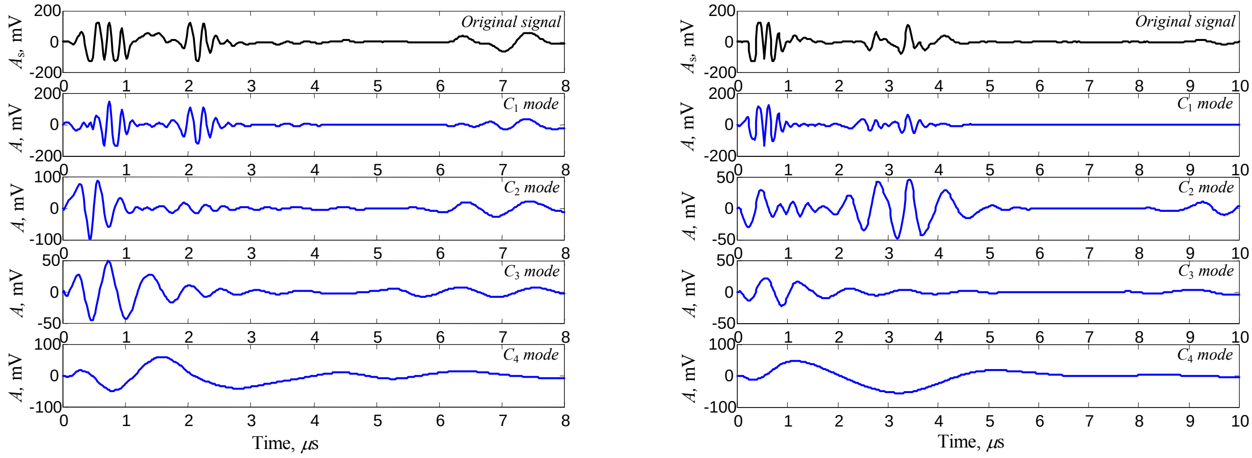

Fig.2. **Artificial defects (SDH and FBH) in plastic pipe samples.**




a b

Fig.3. **B-scans along coordinate *x* with the artificial SBH and FBH defects in one (a) and three (b) layers plastic pipe samples**

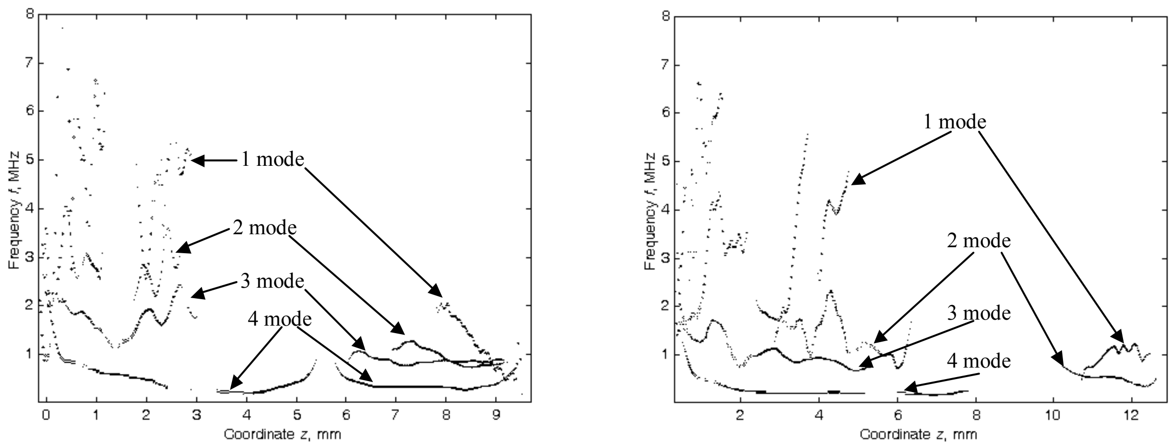
In Fig.4 are represented the *A-scans* signals and four IMF modes of this original signals with artificial defects. The calculation of each mode is stopped when the standard deviation *SD* is smaller than 0.3 (Eq.4). The number of the selected intrinsic modes is based on the criteria how much this mode represent the place of artificial defect in the time domain. It is seen that the first three modes represent the information about the upper and bottom surfaces of the pipe samples or artificial defects.




a b

Fig.4. **Decomposition by the sifting method of the ultrasonic signals of the one (a) and three (b) layers pipe samples into four intrinsic modes**

The next step of the signal analysis was computation of the instantaneous frequency as a function of the time by the Hilbert transform (Eq.7-11). The final presentation of the results is an energy-frequency-time distribution, designated as the Hilbert spectrum [10]. The Hilbert spectra of the four IMF modes of the *A-scans* signals with artificial defects are displayed in Fig.5.

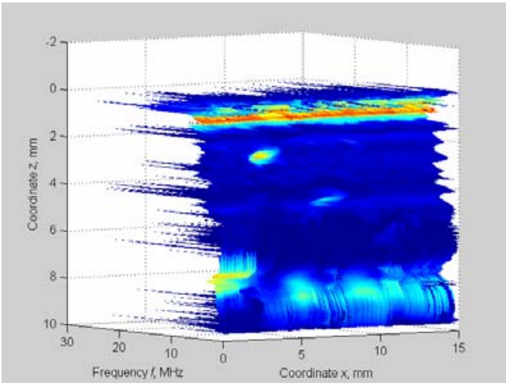



a b

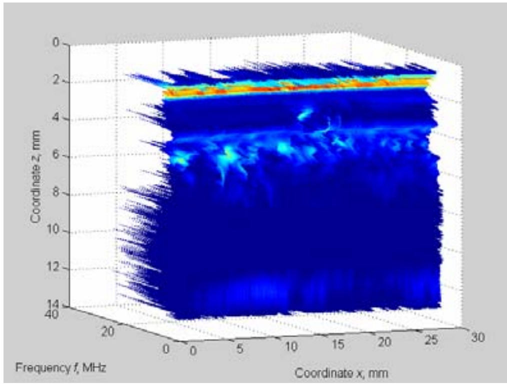
Fig.5. **The Hilbert spectrum for the ultrasonic signals of the one (a) and three (b) layers pipe samples. The signals energy appears in skeleton lines representing each IMF.**

Let us compare the Hilbert spectra of the ultrasonic signals from one (Fig.4a) and three (Fig.4b) layers pipe samples. We can see that the $C_1$, $C_2$ and $C_3$ modes represent the artificial defects distribution in the time scale along the coordinate *z*. The $C_4$ mode is almost monotonic and not informative. Therefore we conclude that we can use the three first modes in the analysis.

To display the Hilbert spectrum distribution along the coordinate *x* we represent the amplitude and the instantaneous frequency as a function of coordinates *x* and *z* in a four-dimensional plot, in which the amplitude is presented as the colour coded maps (Fig.6). In Fig.6 a and b we represent the spatial distributions of the Hilbert spectrum of the first intrinsic modes $C_1$ of the ultrasonic signals of the one (a) and three (b) layers pipe samples with artificial defects.




a

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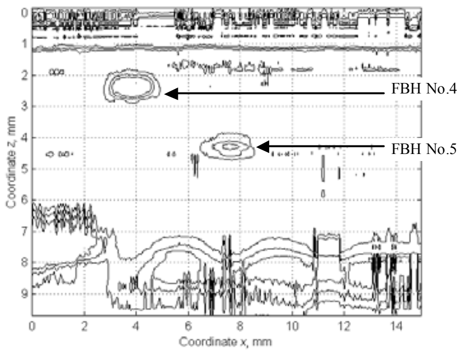
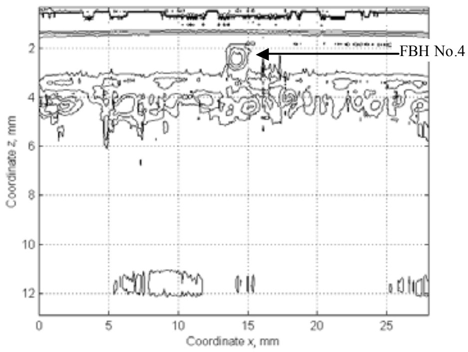



c




d

Fig.6. **The Hilbert spectrum of the first IMF of the ultrasonic signals of the one (a) and three (b) layers pipe samples with artificial defects along the coordinates *x*. The contour plots represent the amplitude of the Hilbert spectrum of the one (c) and three (d) layers pipe samples.**

In Fig.6 c and d we display the contour plot of the amplitude of the Hilbert spectrum. We can see that the upper and bottom surfaces and the artificial FBH defects No.4 and No.5 in the one layer pipe and No.4 in the three layer pipe samples are clearly displayed. However, the defects FBH No.6 in the one layer and SDH No.2 in the three layer samples are not reliably detected. To solve this problem we use a new presentation of the Hilbert spectrum. We compute the product of the instantaneous frequency $f_j$ and the amplitude $a_j$ and then display this product in a three-dimensional plot (Fig.7). The best result of this presentation is detection of the defect FBH No.6 in the one layer sample (Fig.7, a, c). However, the detection of the SDH No.2 defect in the three-layer sample is still complicated.

To determine the defect SDH No.2 in the second inhomogeneous layer of the three-layer sample we introduce the improved algorithm eliminating the signals reflected by regular discontinuities like interfaces. For that we use the new signal $s'(t)$ for calculation of the Hilbert spectrum. This signal we obtain by subtraction of the signal $s(t)|_{x=\text{const}}$ at the fixed point *x* without artificial defect from the original signals $s(t)$:

$$s'_{xi}(t) = s_{xi}(t) - s(t)\big|_{x=const.} \,. \tag{13}$$

The new signal $s'(t)$ we decompose in four intrinsic modes and then compute the Hilbert spectrum for each IMF. The best results to determining of artificial defect in the second layer we have with the second intrinsic modes $C_2$ of the investigated signals. The four-dimensional plot of the Hilbert spectrum of the second IMF modes along the coordinate *x* is presented in Fig.8, a. The contour plot of the amplitude of Hilbert spectrum is displayed in Fig.8, b.

From the results presented follows that the second mode gives information about the location of the defect SDH No.2 in the second inhomogeneous layer.

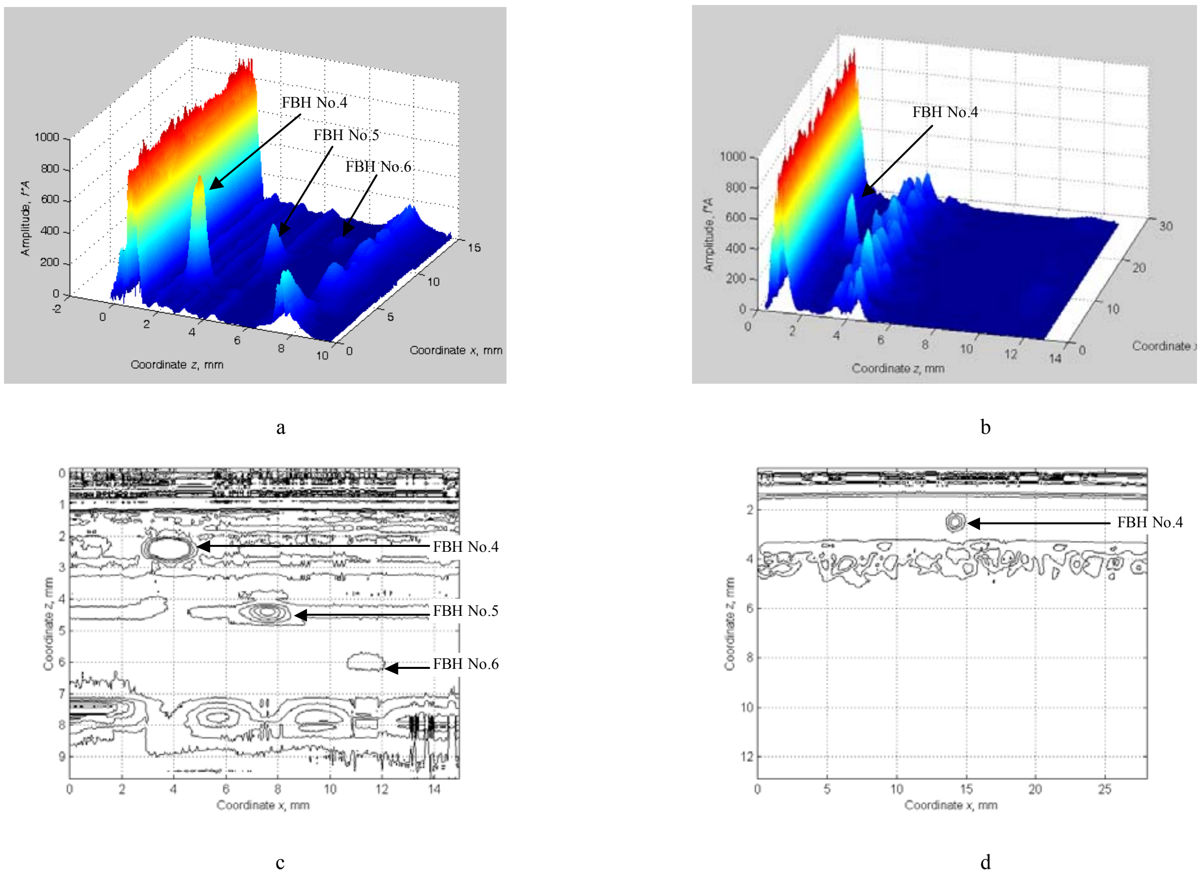



Fig.7. **The Hilbert spectrum of the first IMF of the ultrasonic signals of the one (a) and three (b) layers pipe samples with artificial defects along the coordinates *x*. The contour plots of the amplitude of the Hilbert spectrum of the one (c) and three (d) layers pipe samples**

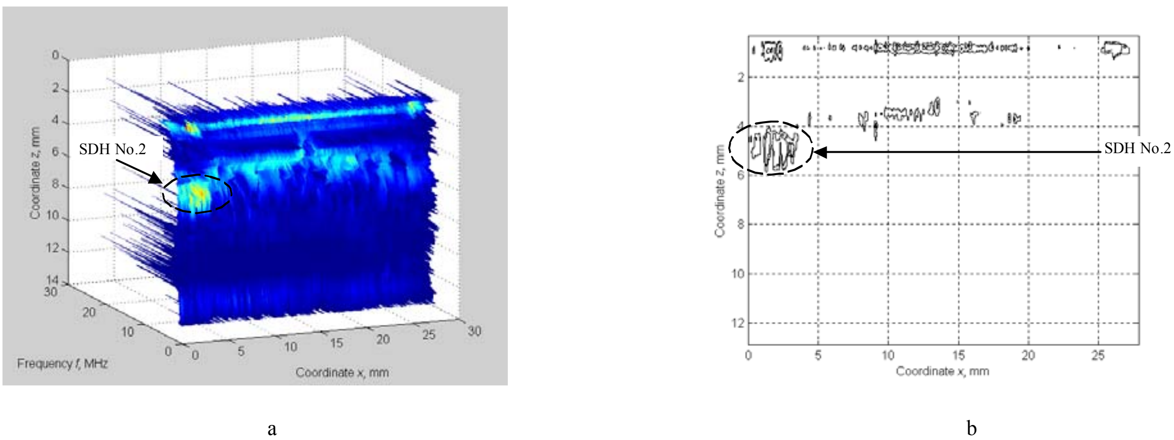



Fig.8. **The Hilbert spectrum (a) and contour plot of its amplitude (b) of the second IMF after subtracting signals of the three layers pipe samples with artificial SDH No.2 defect.**

## Conclusions

In this paper we present the application of a new time-frequency signal processing method called the “Hilbert-Huang method”. We adopted this method to detection of the defects in the composite plastic pipe samples. The experimental investigations of these samples have showed that the detection of artificial holes in a porous layer and under this layer is complicated. Therefore the aim of this study was to detect the artificial defects in a layer with glass fibers by the Hilbert-Huang signal processing.

For decomposition of the original signal we used data sifting to generate the intrinsic modes and applied the Hilbert transform to this modes. The decomposition results have shown that in a homogeneous one layer plastic pipe sample the information about defects represents the first mode or the combination of the first and second modes. In the inhomogeneous three-layers pipe sample detection of the defects is not simple. To determine the artificial defect in the second layer we used subtraction from the original signals the signal at the fixed point without artificial defect. This method gives a chance to determine the location of defects, but measurement of the coordinates of the defect with necessary accuracy is still a problem.

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**Hilberto ir Huango signalų apdorojimo metodo taikymas kompozitų ultragarsiniams neardomiesiems tyrimams**

Reziumė

Specifinės daugiasluoksnių polimerinių medžiagų mechaninės savybės skatina naujų ultragarsinių neardomųjų tyrimo metodų paiešką. Straipsnyje pristatytas naujas Hilberto ir Huango signalų apdorojimo metodas, pateiktas trumpas šio metodo signalų apdorojimo algoritmas, išnagrinėtos metodo taikymo tiriant vienasluoksnes homogenines ir daugiasluoksnes nehomogenines polimerines medžiagas, galimybės. Nustatyta, kad vienasluoksnių bandinių ultragarsiniams defektų tyrimams informatyviausios yra būdingosios funkcijos pirmoji moda bei pirmosios ir antrosios modų suma, tuo tarpu trijų sluoksnių, kai tarpinis sluoksnis nehomogeninis, tarpinio sluoksnio defektų tyrimams naudotina būdingosios funkcijos antroji moda.

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