Using Hilbert Transform for Signal Processing in Mechanical Impedance Analysis

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Abstract. These papers describe using of Hilbert transform in processing signal received from standard mechanical impedance sensor. It's shown that Hilbert transform allows extract additional information from the signal and increase reliability of non-destructive testing. Presented mathematical model of typical signals received form mechanical impedance sensor and described ways to extraction and using in non-destructive testing process wide known characteristic of the signal like instantaneous phase and instantaneous frequency. Also described another parameters based on mentioned characteristics which are more stable in diagnostic decision-making compare to another widely used in contemporary flow detectors. Shown experimental results obtained from scanning samples of composite materials used in development of light-weight aircrafts.

Introduction

Contemporary aerospace industry is hard to imagine without using composite materials (CM). They can be used for development of the interior panels inside the cabin and also in some aircraft, as parts of the most important bearing elements. The process of developing composite elements of an aircraft is complicated and can be exposed to various errors which lead to the appearance of flaws in a complete product. A significant part of manufacturing defects changes mechanical characteristics of a structural element below the nominal levels. Also during the time of an operation, constructional elements of an aircraft are exposed to the different environmental factors and unpredictable mechanical stresses leading to changing the internal structure of composites. There aren't general requirements for allowed parameters of defects, but typically for commercially used aircraft it is not more than 12.5 mm [1].

There are different methods used in the aerospace industry for testing CM. Each of them has its own sphere of application and limitation caused by the type of material and geometrical characteristics of tested element. On is most popular and easy to use is method based on mechanical impedance analysis or MIA. This method is widely used in Post-Soviet countries and Western Europe for testing flaws in honeycomb sandwich panels, multilayer panels made by polymer composites, and their combinations [2]. MIA is included to the nondestructive testing manuals of different aircraft for detecting delaminating between honeycomb structure and outer coverage. This method is recommended by state civil aviation administrations for testing composite construction in passenger and transport aircraft like IL-76, IL-86, IL-96-300, Tu-204, Tu-214, Yak-42 and

AN-124 "Ruslan" [3]. In Airbus aircraft MIA based testing used as addition method for testing honeycomb sandwich structures [4].

One of the main objectives in developing methods and systems for NDT is discovering informative parameters of signals obtained from sensors that carry out information about the mechanical condition of an object under testing. Also different parameters of the signal have different sensitivity to various types of defects. So the task of increasing the number of informative parameters with high sensitivity to possible defects is urgent. The purpose of this article is present the way of increasing amount of information parameters for pulse type of MIA method.

Problem solving

1.1 Mechanical impedance analysis

Mechanical impedance (MI) is a complex ratio of the force acting on the surface (or point) of the mechanical system to medium oscillation velocity on the surface (or point) in the direction of force actions:

$$\dot{Z} = \frac{\dot{F}}{\dot{v}}.$$

In general, it’s a complex quantity described as:

$$Z = R + jX = |Z|e^{j\phi},$$

Where R is an active part and X reactive; $|Z| = \sqrt{R^2 + X^2}$ - called module, $\phi = arctg(X/R)$. The value of R depends on dissipations while X connected to elastic properties of an object state.

Piezoelectric transducers with dry dotted contact typically used to evaluate mechanical impedance on tested object. Changing values of impedances in different zones is because in defect-free zone value of $|Z|$ is maximized and determined by all layers of tested objects joint in a single mechanical system. In case of flaw which leads to damage of joints between layers hardness in the area is less in defect-free area and value of $|Z|$ determined just by surface layers. Generally, in zone with flaw takes place changing of ratio between active and reactive parts and sometimes a sign of the reactive part is changing too [2, 5].

Approximate model of the information signal received from sensor can be represented as the sum of two exponentially decaying sinusoidal functions:

$$v(t) = A_1 \sin(2\pi f_1 t + \varphi_1) \cdot e^{-\delta_1 P(t)} + A_2 \sin(2\pi f_2 t + \varphi_2) \cdot e^{-\delta_2 P(t)}$$

where δ_1, δ_2 - attenuation constants; f_1, f_2, - main frequencies A_1, A_2 - amplitudes; $P(t) = 2 \cdot \left(\frac{t}{a} - \left\lfloor \frac{1}{2} + \frac{t}{a} \right\rfloor \right)$- model of the sawtooth signal where a - the duration, $\lfloor \ \rfloor$ - the operator of rounding to the nearest integer.

In MIA method mechanical impedance of tested area influents on amplitude [2], phase of signal [5] and frequency spectrum [6]. In most cases, flow detected after current value of just one parameter cross the threshold. In case of spectrum analysis alarm activates when level of energy in the frequency range most sensitive to the selected type of defects cross the critical level. However, these parameters - amplitude, phase and frequency can be sensitive to different noises which can increase rate of false alarms and decrease quality of testing. Therefore, it is necessary to extent the list of information parameters that are more sensitive for defects and more resistant for noises.

In contemporary flaw detectors based on MIA method, frequency measuring of implemented only for the devices that operate in continuous excitation mode, but they spread much less than the device with pulse excitation, because of relatively high power consumption, which complicates the development of mobile flaw detectors. Thus, for today, the most popular are devices with pulsed excitation. However, because of pulse nature of received signal, it is impossible to provide direct measuring if its frequency. So in this research proposed to use Hilbert transform to obtain phase characteristics of the signal received from MIA sensor. Firstly, it allows to measure mentioned parameter, and secondly give a chance to obtain additional parameters that allow getting more information about the mechanic characteristic of the tested object.

1.2 Hilbert transform

The result of applying Hilbert transform to the input signal $x(t)$ is the Hilbert's image $\tilde{x}(t)$ defined in the time domain [7]. The sum of input signal and obtained image $z(t) = x(t) + j\,\tilde{x}(t)$ called "analytical" signal $z(t)$. Using these results it's possible to calculate pulse envelope $A(t)$ and instantaneous phase $\theta(t)$ as functions of time. Envelope can be obtained like:

$$A(t) = \left[x^2(t) + \tilde{x}^2(t)\right]^{\frac{1}{2}}$$

and phase calculated through:

$$\theta(t) = arctg\left[\frac{\tilde{x}(t)}{x(t)}\right]. \tag{1}$$

The instantaneous frequency f_0 can be obtained with the help of phase:

$$f_0 = \left(\frac{1}{2\pi}\right)\cdot\frac{d\theta(t)}{dt} \tag{2}$$

Instantaneous phase in expression (1) defined on the interval $\left[-\pi/2 \ldots \pi/2\right]$, so calculate the phase characteristics of the interval $\left[0 \ldots 2\pi n\right]$ it should be transformed to the form:

$$Q(t) = arctg\left[\frac{\tilde{X}(t)}{X(t)}\right] + \frac{\pi}{2}\left[2 - sign\tilde{X}(t)(1 + signX(t)\right]$$

and with the special algorithm converted to the unwrapped phase characteristic:

$$\Phi(t) = arctg\left[\frac{\tilde{X}(t)}{X(t)}\right] + \frac{\pi}{2}\left[2 - sign\tilde{X}(t)(1 + signX(t)\right] + 2\pi L\left[X(t), \tilde{X}(t)\right]$$

Algorithm of phase unwrapping, i.e. the transformation sequence outside $\left[-\pi/2 \ldots + \pi/2\right]$ borders based on eliminating jumps at the points where the phase is set to more or less over $\pm\pi/2$. If the difference between two adjacent values in the array more then π phase is calculated as:

$$\Phi[i]=\begin{cases} Q[i]-\left\lfloor \dfrac{Q[i]-Q[i-1]}{2\pi}+0.5 \right\rfloor \cdot 2\pi, & i=1,....,N-1 \\ Q[i], & i=0 \end{cases},$$

Where $Q[i]$ - an array of samples of instantaneous phase - $\Phi[i]$ phase characteristics - N array size and $\lfloor\ \rfloor$ - the operation of rounding to the nearest integer.

Therefore, the instantaneous frequency can be transformed to the next form

$$f_0=\frac{\Phi(t)}{2\pi T},$$

where $T=t_2-t_1$ - interval of the time determined on the phase characteristic $\Phi(t)$.

Fig. 1 shows signals received from MIA sensor and charts of instantaneous phases of flawless and defective areas of the test sample.

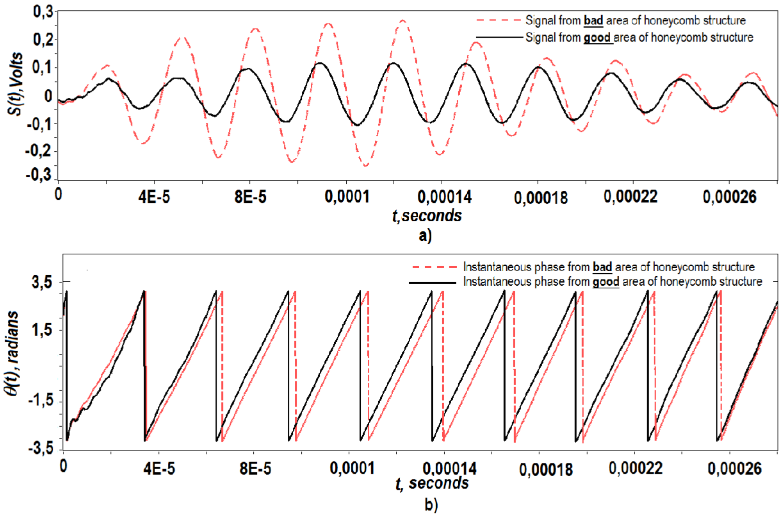


Fig.1. Signals received from MIA sensor in good and damaged areas (a). Instantaneous phase obtained from received signals (b).

As seen from the fig.1, a, reducing the carrier frequency of the received signal changes the phase characteristics. Direct using of instantaneous frequency as a parameter that depicts this fact, connected with some difficulties in choosing of the time interval for the calculation. The changing of phase characteristics of the signal is not linear, because of a deviation of the carrier frequency of the analyzed signal. As shown in Fig. 2.6, b, the maximum difference between the observed realizations for appeared in the interval of time [0..00022] seconds and then gradually decreases. The maximum sensitivity of instantaneous frequency will be provided only if phase characteristics obtained from defective and defect-free areas have the greatest difference between them on the time interval chosen for calculations. This may complicate the choice of the time interval during conducting of the testing.

For a more qualitative evaluation of the flow impact on the characteristic of the received signal it's possible to perform integration of instantaneous phase and use the resulting value of *Fa* as informative parameter:

$$Fa=\int_{t_1}^{t_2}\Phi(t)dt$$

Using this parameter simplifying the choice of the time interval for calculation. Time mark t_1 can be equal to the first point of phase characteristics while t_2 may be chosen experimentally maximizing the sensitivity and decreasing the level of random noise. Also, t_1 and t_2 may be chosen to obtain the maximum differences between phase characteristics received from defective and good areas of tested sample. Besides extent of the difference between the realizations of information signals received from various area of tested sample, may be determined based on the research of phase characteristics throughout the full lifetime of the signal.

It is possible to offer the following algorithm of research. The first step is obtaining signals and calculating phase characteristic $\Phi_1(t)$ from the flawless area of tested sample and save it as the reference. Then scan the sample and calculate phase characteristic $\Phi_2(t)$ for every received current signal. Then get absolute value of the difference between $\Phi_1(t)$ and $\Phi_2(t)$. It will be the greater, the more different mechanical characteristics of the controlled area is. Fig. 2 shows the difference for phase characteristic obtained if flawless and defective areas.

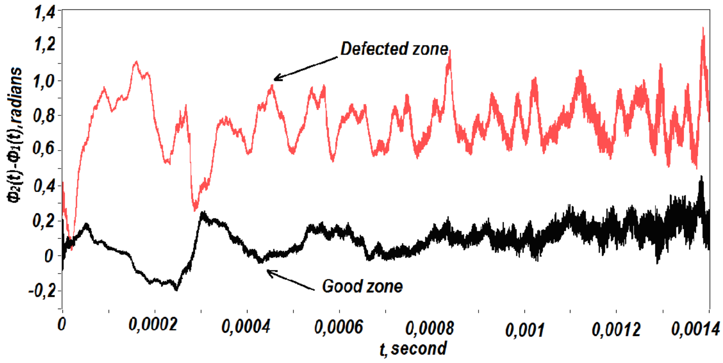


Fig.2. The differences between the phase characteristics obtained from defective and flawless zones of tested sample

As seen from the figure, the population mean of the difference for the characteristics obtained from the defect area is much larger than the one received from the flawless zone. I as informative parameter characterizing the degree of, it is proposed to use the Fb value, which is calculated as the integral of the difference:

$$Fb = \int_{t_1}^{t_2} [\Phi_2(t) - \Phi_1(t)]dt \, .$$

The principle of t_1 and t_2 marks choosing is similar to Fa criteria. The reference phase characteristic is calculated based on the average signal received from different parts of the flawless region of the sample.

1.2 Experimental testing

There was an experimental research for reliability comparison between flaw detection process based on tradition characteristics of the information signal and the introduced ones. For the testing, we chose the sample (see Fig.2) of honeycomb composite panel thickness of 20 mm consisted of honeycomb filler named PDP 1-2.5, casing made with carbon fiber ELUR® P-0.1 and glue VK-41. The damaged zone was modeled as a break of connection between the casing and honeycomb. From the side of scanning, the outer layer of the sample has no visual trace of the flaw, opposite one was restored by gluing carbon fiber fragment of a similar type.

The experimental research consisted of two parts. The first one included obtaining dependency between the geometrical position of the mechanical sensor above the defect and the value of calculated characteristic of obtained signal. The second one relates to calculating the reliability of informative characteristics introduced in the first part of this article. All scanning of the samples surface was performed from the side opposite to the reduction zone.

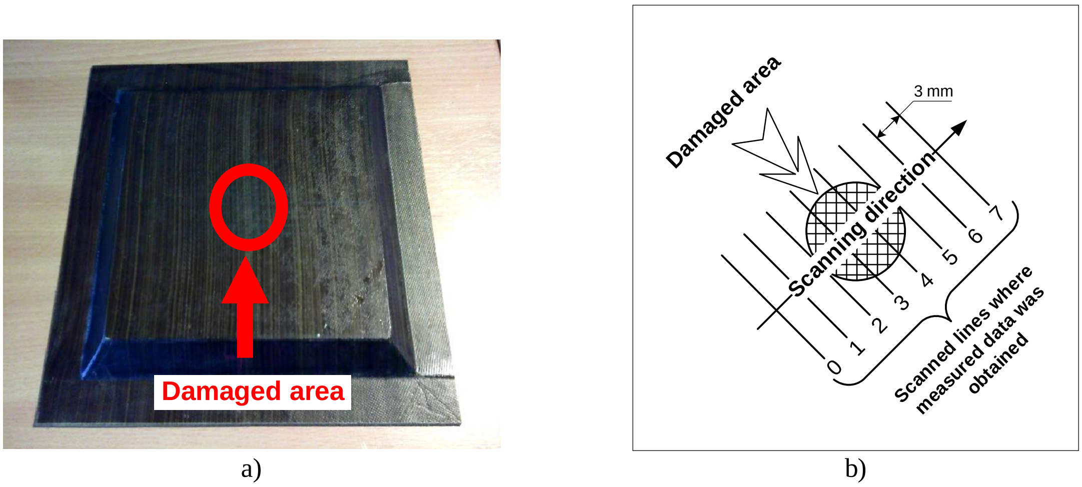


Fig. 3. Experimental sample

All scanning of the surface was performed from the side opposite to the reduction zone. For the first part experiment was conducted in a next way. Mechanical sensor for 30 times was put on the surface on a randomly selected point within the scan line (Fig. 3b) and five realizations of information signals were obtained for every point. Further, for every realization, the next characteristics were calculated: peak-to-peak amplitude of the signal U_0, instantaneous frequency f_0, integral of unwrapped phase Fa, and integral of the difference of unwrapped phases Fb. On the last step medium values was calculated from arrays of values for each characteristic. Obtained results shown on the figure 4.

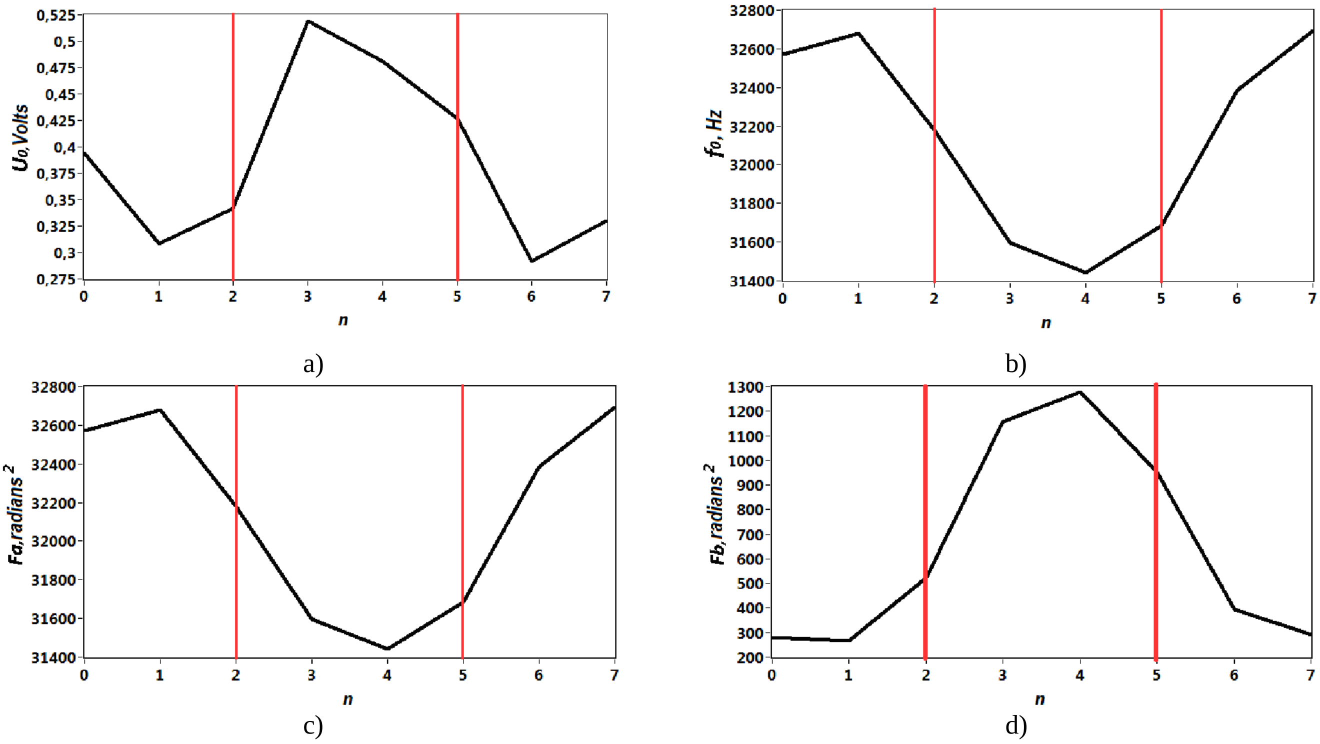


Fig. 4. Relationship between measured parameter and sensor position above the defect a) Peak-to-peak amplitude, b) insnteneous frequency, c)integral of phase characterisics, d) integral of the diffrence between phase characteristcs

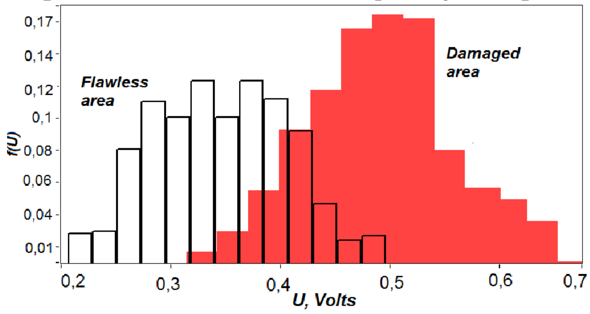
It’s possible to make some conclusions from the fig. 4 presented above:

1) all introduced parameters depend on the state of the controlled area, indicating the possibility of their use for making diagnostic decision;

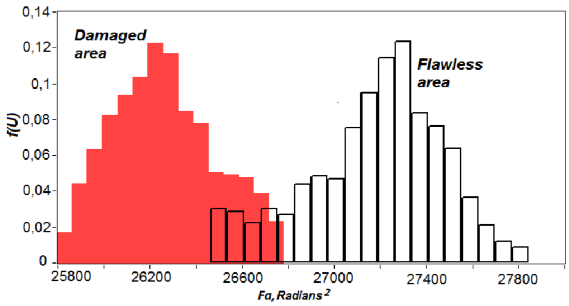
2) on the moving to the center of defect instantaneous frequency is a gradual decrease and achieves the minimum value in the middle of a damaged area that corresponds to the theoretical assumption;

3) approaching the center of the defect increases the degree of difference between the phase characteristics resulting in the increase of the absolute value of the Fb parameter.

To compare the quality of defect detection based on selected informative parameters the evaluation of the reliability of the control was performed. For each flawless and damaged region received 1,000 implementations informative signals, and described informative parameters were calculated. Fig. 5 shows the empirical distribution of amplitude, instantaneous frequency and phase integral characteristics.



a)



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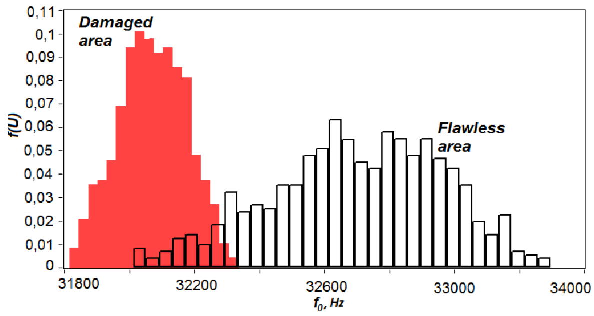

c)

Fig. 5. The empirical laws of distribution of informative parameters: a) Peak-to-peak amplitude, b) insnteneous frequency, c)integral of phase characterisics

This study evaluated the reliability of control with the help experimental research. The threshold was calculated with the help of Neyman–Pearson method. Initial data was collected from the damaged and flawless areas of the tested object and approximated by the Normal distribution. Then the threshold was calculated and true reliability was rated. The values of reliability are presented in Table 1.

Table 1. Comparison of estimates of reliability for different informative parameters

	Typycal	Introduced		
The name of informative parameter	U	f_0	Fa	Fb
Reliability of control, %	73	91	93	96

According to the data given in the Table. 1, parameter U (peak-to-peak amplitude), has the lowest reliability when it is used for making diagnostic decisions. The highest reliability obtained for *Fb*, or integral of differences of phases characteristics between the reference and current signals.

Conclusions

Theoretical and experimental research displayed the possibility of using frequency characteristic of the signal received from MIA sensor as informative parameters. Experimentally demonstrated that introduced parameters are sensible to mechanical characteristics of tested samples. Also, shown that suggested parameters are provided better reliability than traditionally used in mechanical impedance analysis.

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