Application of Multifrequency Spectral Method of Lamb Waves for Structural Health Monitoring of Composite Laminates

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ABSTRACT

In this article, a novel Multifrequency Spectral Method of Lamb waves was introduced. This article is devoted to a new approach of the implementation of the method of Lamb waves applied for SHM (Structural Health Monitoring). The new approach borrows the pulse synthesis method from the techniques of microwave frequency. The approach consists of the application of multi-frequency band measurements and the integral spectral transformations to interpret the results. The method is focused on the application for the reinforced composite materials to solve the SHM problems. The nonlocal frequency method and a local method of Lamb waves can be implemented within the framework of this approach and measuring equipment. The article describes the method and the experimental results that demonstrate the possibilities of the method.

KEYWORDS : *Lamb waves, composite materials, multi frequency measurement, FFT, AFC transducer*

INTRODUCTION

The method of Lamb waves is one of the main of the SHM methods. SHM technology can be represented as a union of NDT methods and the use of the embedded sensors. SHM technology development is on the way of the development of typical ultrasonic methods for NDT.
At the same time there are the differences from the typical tasks.
The first difference
The main difference between the Lamb waves and traditional longitudinal and transverse waves is the dependence of the velocity of the wave propagation on the frequency and the plate thickness. This is a geometric dispersion. In this regard, it is impossible to use the short probe pulses. It is impossible to obtain a good resolution in the time domain while using the conventional approaches.
The second difference
A system of fixed sensors allows getting the best results for the repeatability of the measurements, especially in terms of measuring the signal amplitudes. In addition, it is possible to use longer measurement procedures that is not possible with traditional probe pulses.

Inverse filtering is suggested to be used to improve the temporal and spatial resolution techniques [1].
It is possible to use the method of pulse synthesis based on multi-frequency measurements on a fixed frequency bandwidth. This approach is borrowed from the microwave frequency technique [2].
The conceptual approach distinguishes the domain of measurements and the domain of results interpretation.

Measurements of amplitude variations and phase shifts in monochrome Lamb wave propagation are performed at equidistant frequency values in a fixed frequency band.

The measurement results are subjected to the spectral integral transformation. The interpretation of the tests results is carried out in the domain of integral transformation.
In the field of SHM, there are some examples of the measurements in the frequency domain [3], and examples of the Fourier transformation applying for the transition from the measurements field to the interpretation field [4]. Multifrequency measurements are also associated with a nonlocal frequency response methods of the SHM [5]

Monochrome long signal measurements have the following advantages compared with the probe pulses:

- To minimize the waveform distortion during propagation in the test object, that is caused by the influence of the dispersion of the wave velocity.
- To use an optimal filtration (synchronous detection) of the measured signal. It allows getting the best signal / noise ratio at the receiver output [6] and provides the best accuracy of the signal parameters.
- To improve the energy of the probing signal with a minimum oscillation's amplitude by increasing the duration of the signal

Transition from measurements' domain to the interpretation's domain is carried out by spectral transformation of the measurements' results in the frequency domain. For example, the applying the Fourier spectral transformation, allows obtaining the smallest error recovery of the waveform in the time domain of the interpretation. [7]

Oscillations in the Lamb waves are complex. The fluctuations' distribution in the plate thickness depends on the frequency. The structural reinforced composite materials have a layered structure with different predominant direction of fibers for each layer. Multifrequency measurements in a wide frequency band can be more informative compared with pulse measurements on the same frequency, especially for structural reinforced composite materials.
Currently, the piezoceramic plate transducers are used as transducers of the Lamb waves in the SHM systems [8]. These transducers generate and receive vibrations perpendicular to the surface of the object of control. These transducers can be excited by long or short electrical pulses.
An important aspect of multi-frequency spectral method is the use of transducer based on long fibers piezoactive materials for the radiation and reception of Lamb waves [9]. These transducers generate and receive the tangential oscillations on the surface of the object of control. Unlike flat transducers with normal vibrations, the used transducers can be excited mainly by the long pulsesIndeed the used transducers can be excited by long pulses, unlike common transducersThe use of transducers based on long fibers piezoactive material has the following advantages:

- The elastic parameters of the transducer, as a solid, are close to those of the majority of structural composite materials. This makes the transducers "friendly" to the object of control and provides long-term strength of the assembly: controlled object and transducers, and it minimizes the impact of the glued transducers on the mechanical properties of the object of control.
- These transducers have a primary direction of the oscillations' generating and registering. This direction coincides with the direction of the fibers in piezoactive transducer. This allows making a selection of the received oscillations depending on the polarization. This may increase the informative aspect of the Lamb waves method to solve the tasks of material performances' evaluation, especially applying to the composite materials which are reinforced with long fibers.

The article deals with the multi-frequency spectral method of Lamb waves for the SHM of the composite materials. This article demonstrates the feasibility of applying of the concept of pulse synthesis in the framework of Lamb waves. Nonlocal frequency response method of free oscillations is considered as a special case of multi-frequency spectral method. This case demonstrates the information and technical capabilities of multifrequency measurements for solving SHM tasks for the structures made of reinforced plastics.

1 METHOD DESCRIPTION

The structural scheme of the measurements in the framework of the Lamb waves is presented in the figure1.

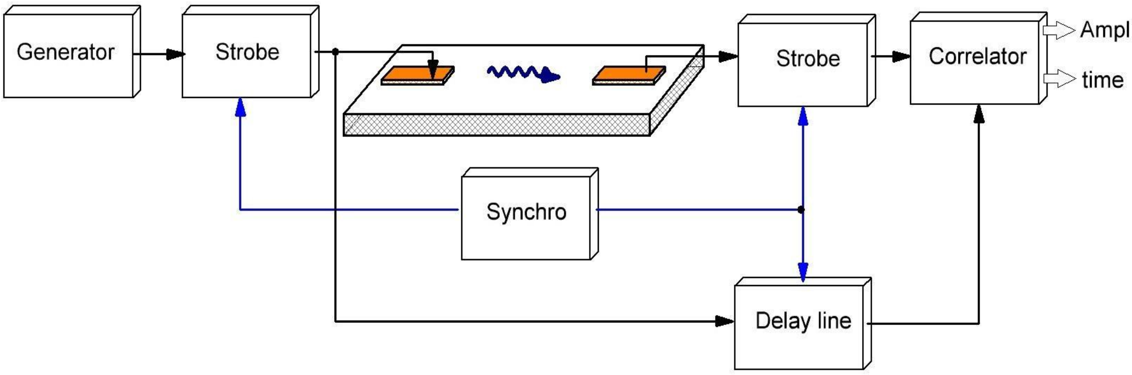

Figure.1 Structural scheme of the measurement system

The measuring system comprises three units: a waveform generator, a receiver and a synchronization unit. The generator must ensure signal stability in frequency and amplitude.. The generator produces sinusoidal signals with frequencies f_n

$$f_n = f_{\min} + ndf \tag{1}$$

$$n = 0..N \; ; \; N = \frac{f_{\max} - f_{\min}}{df}$$

where $f_{\max}$, $f_{\min}$ - initial and final frequency of measurement band;
df - step of frequency changes.

The receiver is implemented under the scheme of the received signal and the correlation of the emitted signal. The samples frequency dependence are formed at the receiver output $R(f)$

$$R(f_n) = A_n \exp(i2\pi f_n \tau_n) \tag{2}$$

where A_n, τ_n - amplitude and wave propagation time for f_n

The synchronization unit consists of a generator of time delay strobe devices. On the output, the strobe device provides the formation of an electrical generator of the probe pulse which must consist of several full periods of the sinusoidal signal. The strobe device at the receiver provides a selection of vibrations that correspond to the wave S0 and A0.
The fFlat piezo-transducers are used for generating and receiving vibrations. The piezo-transducers are glued to the surface of the object of control. The ceramic plates can be used as piezo-transducers, to generate and register the vibrations with respect to the surface normal polarity of the controlled object or AFC(Active Fiber Composite), which detect the vibrations with tangential polarization.

Given that the measurement system operates in the low frequency range, the technical implementation of the measurement's algorithms is possible in the digital domain.
Depending on the choice of the parameters of the strobe device, it is possible to implement the local method of Lamb waves or the nonlocal method of free oscillations. The local method of Lamb waves is used, if the spatial length of the emitted pulse is not greater than the distance between the transducers. The non-local method of free oscillations is applied, if the spatial length of the emitted pulse is much greater than the distance between the transducers and these geometrical dimensions is comparable to the controlled structure.
When implementing the non-local method of free oscillations, the informational value for the control is the frequency dependence of the amplitude of the transmitted waves on the frequency of the emitted wave. This dependence has a singular point, the so-called natural frequencies, which are determined by the geometrical dimensions of the object of control, speed of wave propagation and attenuation of wave energy in the material. The amplitude value of the dependence on the natural frequencies is informative sign for the control.
For the nonlocal frequency response method the information characteristics is the dependence $A(f)$ of the transmitted waves amplitude of the wave frequency. This dependence has a singular point as eigenfrequencies $\{f_0\}$. Values of the eigenfrequencies are determined by the geometrical dimensions of the object of control and by the speed of wave propagation and by the attenuation of wave energy in the material. The amplitude value $A(f_0)$ of the eigenfrequencies is informative sign for inspection.
Pseudo-infinite sinusoidal signals are used in nonlocal frequency response method. Here, measurements are performed in conditions of the steady-state oscillation, without the influence of random transients. This provides high-precision measurements in the frequency domain measurements.
The nonlocal frequency response method can detect non-local changes in material design. For example, for a fiber reinforced composite material the accumulation of microcracks, disbonding between fibers and binders can be detected. Degradation of the material must be sufficiently large and comparable to the size of the control object.

The function of the amplitude of a wave propagating in the material between the emitting and receiving transducer is measured, when implementing a local method of Lamb waves. In most cases, selective reception of S0 and A0 waves type is possible.
Wave attenuation and propagation time carries information about the state of the material of construction in the area, what is located between the emitting and receiving transducers. It is possible to detect local defects, such as a crack or a local bundle of material, as well as small areas with accumulation of microcracks or other local material degradation.
For monitoring of the reinforced composite materials, the main informational value is the measurement of the amplitude of the wave. The dispersion curve of the wave velocity depends on the geometry of the object and depends on the elastic coefficients of the material. For many constructional materials, which are similar CRFP, elastic coefficients are determined mainly by the elastic coefficients of the reinforcing material. Here, the degradation of material does not change the elastic parameters of the reinforcing material or does not change of the structure geometry. Therefore, control of material degradation based on measurements of the velocity of wave propagation is not efficient.

The local spectral method, unlike the nonlocal spectral method, utilizes short pulses.
In order to increase the signal to noise ratio at reception, the integral transformation of the amplitude signal is performed. It enables to improve measurement accuracy.
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The integral transformation of the frequency-dependent amplitude is applied for minimize the effects of random noise and improve measurement accuracy.

$$r(t) = FFT\ \{A(f)\exp(i0)\} \tag{3}$$

The mean square error of amplitude-time-dependent measurements is minimized by applying the Fourier transformation of the frequency-dependent amplitude. [7]
This transformation process can be interpreted as a synthesis of the pulse $r(t)$ in the time domain based on the results of multi-frequency measurements.
The concept of the multi-frequency spectral Lamb wave based method is specific, especially in the separation of the measurement and interpretation domains.
The integral transform of frequency-dependent amplitude in the measurement domain is converted to a short pulse in the time domain interpretation. Synthesized pulse duration τ_{imp} is determined by the bandwidth of multi-frequency measurements.

$$\tau_{imp} \approx \frac{1}{f_{\max} - f_{\min}} \tag{4}$$

Synthesized short pulse, unlike the traditional multiperiodic momentum impulse control, better localizes informative parameter. This enhances the accuracy and sensitivity of control.

2 EXPERIMENTAL RESULTS

2.1 The equipment

The experimental equipment is realized using devices Oscilloscope DSO -2090 and waveform generator HANTEK DDS -3x25. The signal receiver is implemented in the form of a numerical algorithm. Software is realized on the basis of LabVIEW. Graphic User Interface GUI is shown in Fig.2

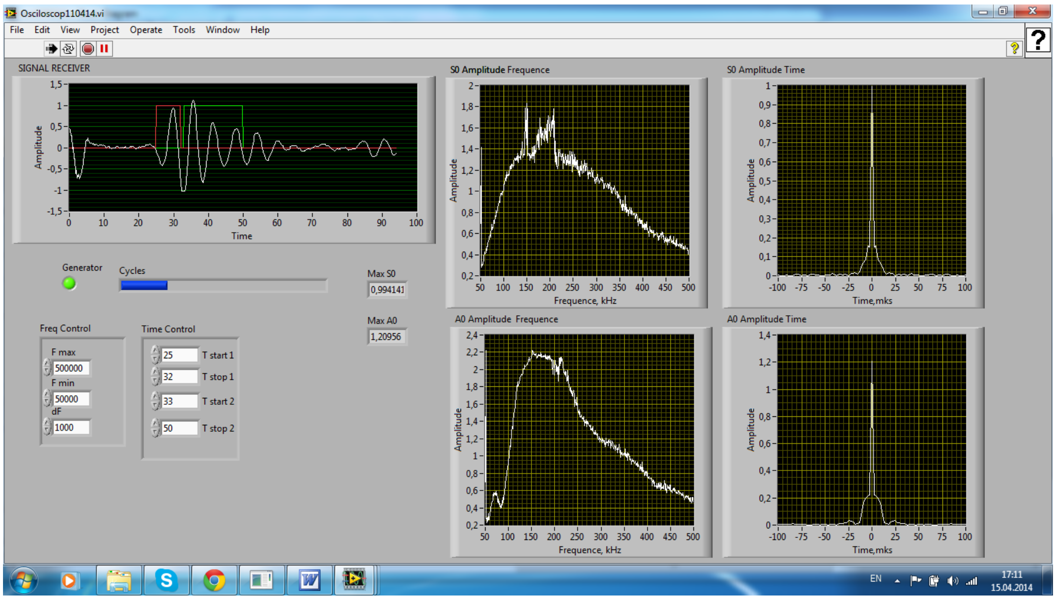

Figure 2. GUI of the experimental equipment

The control panel «Freq Control» is designed for controls of the Multifrequency measurement parameters : initial f_{min} and final f_{max} frequency measurement bandwidth and df step of frequency change. The amplitude of the sinusoidal signal generator output is 3 V. Duration of the probing signal is equal to two periods of oscillation.

There is display signal at the receiver input «SIGNAL RECEIVER» in the GUI.

The control panel «Time Control» is design for selection the time windows «Tstart1» , «Tstop1» «Tstart2», «Tstop2» for the selective measurement of the amplitude of the S0 and A0 wave type. Time windows are displayed on the graph of the signal at the receiver input.

The multifrequency measurement results for S0 and A0 type of the Lamb waves are displayed on graphics «S0 Amplitude Frequency» and «A0 Amplitude Frequency». Amplitudes are normalized to a stable value of the amplitude of the emitted signal. The synthesized pulse $r(t)$ for S0 and A0 wave type is displayed on graphics «S0 Amplitude Time» and «A0 Amplitude Time».

Amplitude value of the $r(t)$ is displayed on indicators «Max S0» and «Max A0».Additional indicators provide information on generator state and progress.

2.2 Exemple of experimental investigations performed with the nonlocal multi-frequency spectral method.

This experiment demonstrates the sensitivity of the multifrequency method for detection of degradaations inreinforced plastics.

The samples considered in this experiment have a carbon content above 60% and an I-beam geometry. The wall or plate thickness is 4 mm.

Sample is I-beam. The I-beam wall thickness is 4 mm. Sample materials is CRFP with carbon content more than 60%.

Material degradation was simulated by mechanical loading. Four point bending tests have been performed (see fig. 3 and fig.4).

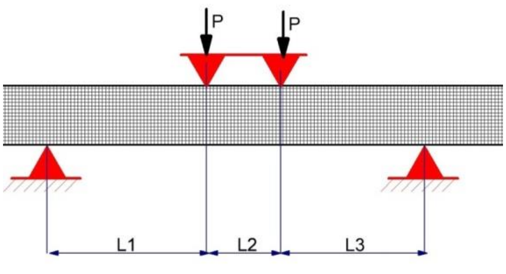

Figure 3. Four-point bending beam

Figure 4. Four point bending experimental system

Emitting and receiving transducers are glued to the upper part of the I-beam (fig.5)

Figure 5. Transducer on the sample.

Several loads were applied to the sample beam: 3 kN, 5 kN, 7 kN, 9 kN. Measurements were carried out.
The measurements were carried in the frequency band from 50 kHz to 145 kHz with 100 Hz steps.
The frequency-dependent amplitude $A(f)$ for each load are shown in the Fig.6

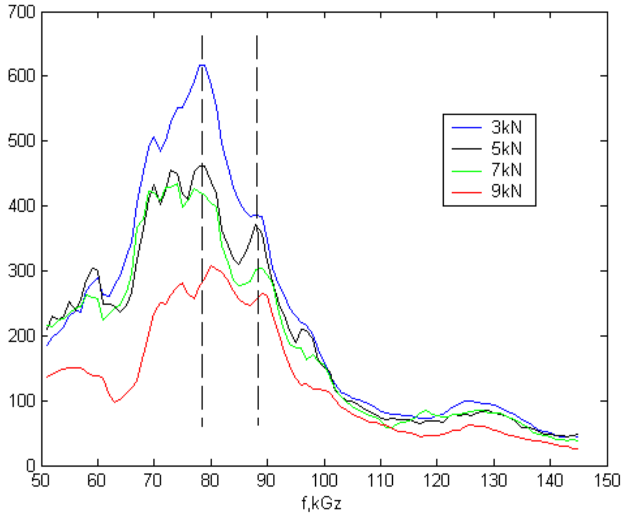

Figure 6. Results of $A(f)$ measurement.

There are two igenfrequecies values at 79 kHz and 89 kHz.
The amplitudes $A(79\,kHz)$ and $A(89\,kHz)$ exhibit dependence on the load applied to the sample.
Repeatability of $A(f)$ measurements for eigenfrequencies is ± 0,1 dB.
Note that the light loads applied are in the range of elastic loading and do not cause permanent deformations. Multifrequency method has a sensitivity that can detect "footprints" of the loading in materials such as CFRP.

2.3 Exemple of experimental investigations performed with the local multi-frequency spectral method

The samples considered in this experiment are CFRP plates. The plate thickness is 4 mm.
Transducers are glued at the ends of the plate, as shown in Fig. 7

Figure 7. Composite plate with surface-mounted transducers.

Multi-frequency measurements were performed in the frequency range from 50 kHz to 500 kHz, with 1 kHz steps. Measurements results are shown in Fig. 2.
As seen in the results of the initial measurement of the amplitude-frequency dependence, baseline measurements have a large variation in amplitude.
Repeatability of measurements research was conducted in multiple measurements. The total number of measurements is greater than 100 measurements.
The range of variability of the results of measuring the amplitude of the synthesized pulse does not exceed ± 0,15%.
These results demonstrate the possibility of the method for detection of degradation of the material in the initial stage on based the evaluation of the synthesized pulse amplitude variations.

CONCLUSION

The article describes the implementation of a multi-frequency spectral method.
of Lamb waves. The method is focused on the application to problems SHM structural reinforced plastic laminates. Shown to demonstrate the possibilities of this method, in terms of implementation of the nonlocal frequency response method and the local method of Lamb waves.
The method provides high accuracy and stability of the measurement of the amplitude of waves, that propagate in the test object. This allows you to use the method for monitoring the state of the construction material and can detect degradation of the material in the initial stage.

The direction of the future research is applicability of the method for the characterization of material degradation problems and solving problems detecting macroscopic defects on large objects of control.

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