ISSN 1392-2114 ULTRAGARSAS. 1996. Nr.1(26).

Ultrasonic phase imaging of multilayred structures

R.Kažys, L.Svilainis

Prof.K.Baršauskas Ultrasound Research Center
Department of Theoretical Radioengineering
Kaunas University of Technology

Introduction

For ultrasonic inspection of the intrinsic structure of thin laminates a phase information is not widely used due to the masking effect of a strong echo reflected from the front surface of a sample. The differential signal extraction (DSE) method allows to eliminate the masking effect of the frontal echo and, in addition to this, to extract the information about the internal structure of the object under investigation [1]. The signals obtained after the DSE were visualized directly and superior results have been obtained. It was also proposed to use the conventional spectral analysis for an investigation of the subtle structure of multilayred plates. This approach of also exposed good results.

This paper deals with a phase information exploration for imaging of subsurface defects in order to achieve a spatial resolution better than the wavelength of ultrasonic signals used for an investigation.

Multilayered composite plate

The main purpose of this investigation was to develop the NDT procedure suitable for detection of delaminations in multilayered composite laminates. The commonly met delamination configuration is presented in Figure 1. The protection layer is much thinner (6μm) than any layer of the laminate, but also must be taken on account since it is influencing the ultrasonic signal. Two aluminum sheets (each 0.25mm thick) are bonded together by a prepreg layer (0.125mm thick) reinforced by unidirectional glass fibres. Three zones with different features can be distinguished:

- zone I corresponds to a flawless composite. All layers are perfectly bonded together so the reflected signals contain reflections from all interfaces;
- zone II contains a delamination between the first aluminum sheet and prepreg, therefore, due to a shielding there are no reflections caused by the interfaces located deeper than the delamination;
- zone III also posseses a delamination located between the second aluminum sheet and prepreg, therefore some reflected signals are also missing.

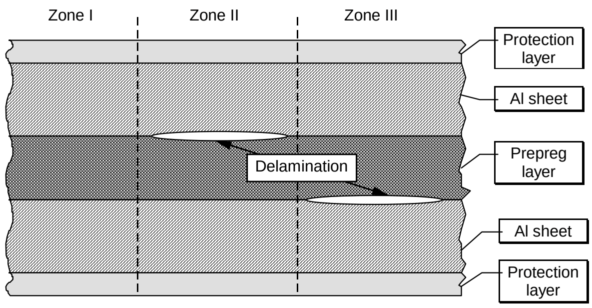


Fig.1. **Multilayered composite material with delaminations between different layers**

Differential signal extraction procedure

The DSE procedure is performed using the modified L1 norm iterative deconvolution algorithm. This algorithm is based on the assumption that each wavelet *s(t)* reflected by the object under a test can be expressed as a convolution of the pulse response of the object *p(t)* with the reference wavelet *w(t)*:

$$s(t) = \int_{-\infty}^{+\infty} p(t')w(t-t')dt' \ . \qquad (1)$$

Each position of the reference wavelet is analyzed as a candidate for a spike train member. The position Δt minimizing the L1 norm

$$I_1 = \left| \int s(t) - Kw(t+\Delta t) \right| ,(2)$$

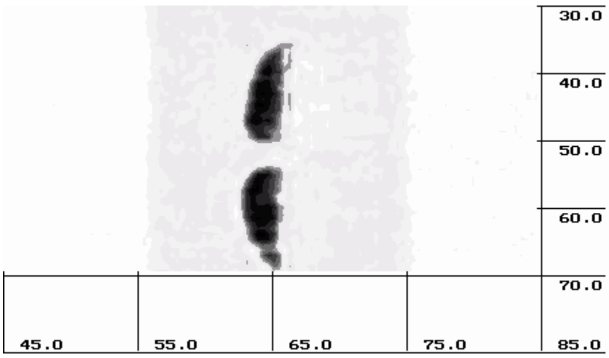
is the best candidate. Amplitude of the spike is adjusted according to the ratio *K* of the reference and wavelet envelope amplitudes. During each iteration of the deconvolution one spike is extracted. After the optimal position Δt and the amplitude ratio *K* of the current spike are found, they are subtracted from the initial wavelet:

$$s'(t) = s(t) - Kw(t+\Delta t) \ . \qquad (3)$$

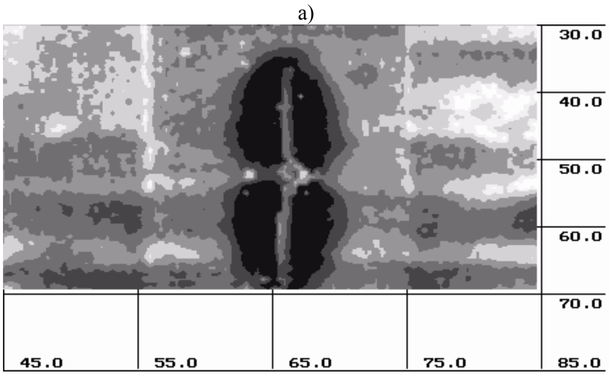
The new residual signal *s'(t)* is used as a raw data for the next iteration. Usually, as a reference wavelet the signal reflected from a single interface is used. We have proposed to exploit the signal reflected by a flawless area (zone I) as the reference wavelet [1]. Moreover, we suggest to stop the deconvolution after the first spike train extraction and to use the residual signal, which usually is thrown away, as the output data. In addition to this, the residual part of the signal is shifted according to the spike position in a train:

$$s''(t) = s'(t - \Delta t)\,. \tag{4}$$

The procedure described above we call the differential signal extraction, since the resulting signal contains the differences between signals reflected by flawless and defective regions. If the shift of the residual part given by Eq.4 is used, a geometry and roughness of the surface are eliminated and just intrinsic differences remain. Such a solution enables to obtain the image of the object just after the DSE procedure. However, in order to acquire the complete picture of the sample under an investigation, an inspection from both sides of the composite plate is necessary. This problem has been partially solved applying a spectral analysis of the signal after the DSE procedure [1]. Unfortunately, a spectral analysis does not extract the signal with a sufficient signal/noise ratio. The results of a spectral analysis of the reflected signals collected from one side of the plate at different frequencies are presented in Fig.2. For radiation and detection of ultrasonic signals the focused 5 MHz ultrasonic transducer was used. The delamination clearly seen on the left side of Fig.2 at the frequency *f*=5 MHz is resolvable, but the delamination on the right side can be detected only analyzing together the images at two different frequencies 5 MHz and 6.3 MHz .Note, that these delaminations are located at different interfaces. In other words, the simple spectral analysis does not enable to resolve the delaminations located at different depths what is a serious shortcoming of the conventional spectral approach.



a)



b)

Fig 2. **Spectral image of the signal after the DSE procedure: a- *f*=5 MHz ; b- *f*=6.3 MHz.**

Imaging of the phase spectrum

In order to extract integral parameters of a signal, we suggest as in the previous case to perform the Fourier transform of the DSE signal collected at each point *x,y*:

$$S''(\omega) = \mathcal{F}\left(s''(t)\right), \tag{5}$$

where $S''(\omega)$ is the complex spectrum of the residual part of the signal given by Eq.4.

Afterwards, the phase spectrum is calculated:

$$\varphi(\omega) = \arctan\left\{\frac{\mathrm{Im}\left[S''(\omega)\right]}{\mathrm{Re}\left[S''(\omega)\right]}\right\}. \tag{6}$$

Then, the phase unwrapping is performed. This procedure adds or subtracts multiples of the 2π phase angle if a phase jump in this range appears at the neighboring frequencies. Bearing in mind, that the reflected signal *s(t)* is acquisited at different points *x,y*, the phase at each is frequency is normalized in respect to its maximal value in the *x*0*y* plane:

$$\varphi(x, y, i) = \left.\frac{\varphi(x, y, \omega)}{\max\left[\varphi(x, y, \omega)\right]}\right|_{\omega = ki}. \tag{7}$$

The normalized phase at the selected frequency ω_s is displayed as a 2D image $\Phi_{\omega_s}(x_i, y_j)$.

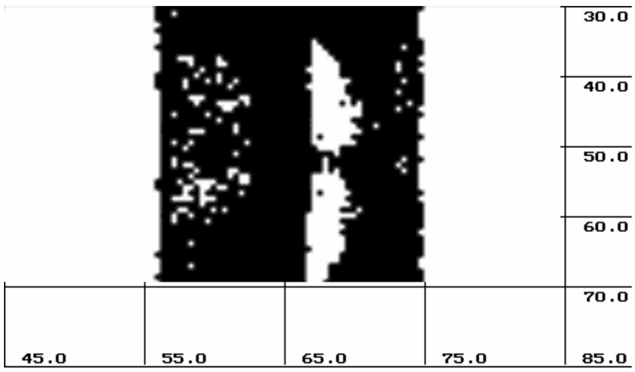


Fig.3**. Low frequency (0.8 MHz) slice of the phase spatial distribution.**

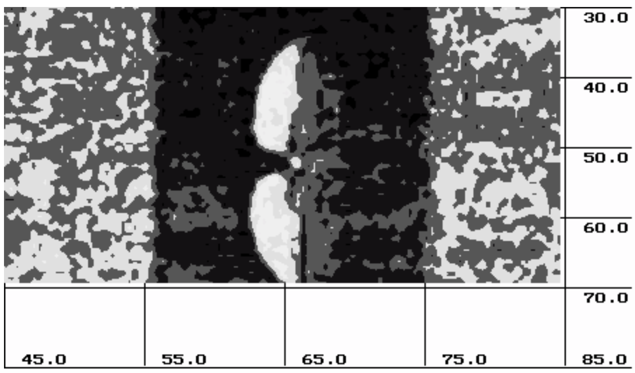


Fig.4. **High frequency (5.6 MHz) slice of the phase spatial distribution.**

After introduction of such a phase spectra, it becomes possible to resolve the delaminations at various depths, using an inspection from one side of the composite plate only Fig.3,4. Moreover, the extremely thin coating layer (thickness 5μm) is also detected with a resolution better than the wavelength used for the inspection (Fig.4).

Conclusions

The 2D phase spectrum of the DSE signal provides possibility to resolve delaminations at different depths of the multilayred object even when the layers are much thinner than the wavelength of the ultrasonic wave used for inspection and only one side access to the sample is feasible. Using this approach it is possible to expect to measure thickness of very thin coating layers also, but the measurement procedure must be improved and an absolute accuracy evaluated.

References

1. **R.Kažys, L.Svilainis**. Ultrasonic detection and characterization of delaminations in thin composite plates using signal processing techniques. Submitted to Ultrasonics, (1996)
2. **Barrodale, I., Zala, C.A., Chapman.** Comparison of the L1 and L2 norms applied to one-at-a-time spike extraction from seismic traces. Geophysics (1984) **49**, 2048-2052

R.Kažys, L.Svilainis

Ulragarsinė daugiasluoksnių struktūrų fazinė vizualizacija

Reziumė

Pasiūlytas ultragarsinis daugiasluoksnių kompozicinių struktūrų vizualizacijos metodas, leidžiantis surasti ir atskirti atplyšimus tarp sluoksnių, kai sluoksnių storiai yra mažesni už naudojamos bangos ilgį. Metodas paremtas diferencinio signalo, gauto po L1 normos iteracinės dekonvoliucijos, spektro vizualizacija tiriamo pavyzdžio plokštumoje.