Detection of Inner Defects [Delaminating] in Composite Structures using Ultrasonic Method [UT]

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Abstract. For inquiry of application of ultrasonic method [UT] possibilities at composite materials inspection specimens based on the carbon fibres that correspond to structure aircraft elements were designed and made. Applied specimens were made of different composite materials with various numbers of layers and various thicknesses. For simulation of delaminating in different layers of tested structure holes with flat bottom [disk-reflector] were drilled. The Masterscan 340 [SONATEST] device with straight probes was used in inspection of composite materials by ultrasonic method [UT] with different frequency array and crystal sizes.

Based on these tests the possibilities of ultrasonic method for NDT inspections of thick composite aircraft structure elements were proved.

Introduction

At present time composite materials are wide increasingly used in aeronautical structures. During the fatigue test execution it is necessary to detect the failure and crack inception caused by fatigue of material, their development and propagation by NDT methods. Most widespread kind if hidden failures (inner) rising in elements of composite structures during fatigue experiments is composite delaminating originating in various layers of material structure [1].

One of non-destructive testing method of material, which could be used for these purposes, is ultrasonic method.

Specimens design

For survey of application possibility of ultrasonic techniques (UT) for composite material non-destructive testing carbon fibre test specimens that correspond to elementary aircraft structure parts were designed and manufactured. These specimens were manufactured of various carbon fibres composite materials with various numbers of fibre layers (12, 28, 88 and 95) and the specimen thickness was also different (4mm, 10 mm, 14 mm and 40 mm). See Fig.1

Paradigmatic discontinuities and delaminating in different layers of aircraft structures in samples were simulated by drilled holes with flat bottom of 4 mm and 8 mm diameters (disc reflectors). The example of specimen and the direction of ultrasonic testing you can see in the Fig.2.

Fig. 1

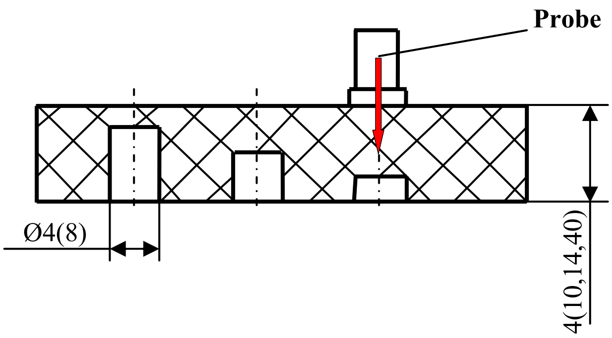

Fig. 2

Instrumentation

The Masterscan 340 (Sonatest) was used for ultrasonic technique inspection (UT) in composite materials in combination with direct type probes [2]:

- PRDT 2550 (frequency 5MHz ±10%,
  crystal size 0,25 in (6 mm)).
- SLM2-10 (frequency 2, 25 MHz ±10%
  crystal size 10 mm).

Fig. 3

UT application

When using ultrasonic technique the scan attenuation of ultrasonic propagation and the distance of near field are crucial factors for reliable inner discontinuity (delaminating) detection in composite materials.
The scan attenuation is caused by the loss of energy of the ultrasonic beam through absorption and dispersion. The absorption is dominant factor in ultrasonic testing of composite materials and it is transformation of acoustic energy into thermal one due to internal friction in tested material structure. The intensity of acoustic field will weaken without arising of an interference noise. The decreasing of echo by absorption can be compensated by increasing of energy output or gain. Since the total attenuation loss increases exponentially according to probe's frequency, the operator can achieve the decreasing of attenuation by proper wave type and its frequency selection only. Therefore to their decreasing it is necessary select the lower frequency prob. The decreasing of frequency leads on one hand to increasing of penetrating depth, o other hand to deterioration of resolution (sensitivity) of discontinuity detection. The transducer/probe comprises a piezoelectric ceramic material that generates short bursts of mechanical vibration or sound waves when it is excited by a short electric pulse from the Masterscan 340 UT device. The frequency of the generated sound waves is far beyond the range of human hearing and can be in the range of 0.1-20 MHz. Sound energy at these high frequencies does not pass well through air. For this reason, a coupling which in most cases is liquid has to be used between the transducer/probe and the test piece.

Higher frequency transducer/probes are more sensitive to small discontinuities due to their shorter wavelength. The wavelength is a function of the frequency and the sound velocity in the tested material according to the following equation:

$$\lambda = c/f$$

where:
- **λ** wavelength (mm)
- **c** velocity of sound in the material (km/s)
- **f** frequency of the transducer/probe (MHz)

In addition, higher frequency transducer/probes tend to have better resolution due to shorter energy bursts and the shorter wavelength. Resolution is the ability of a transducer/probe and instrument combination to give distinct and separate indications from discontinuities lying close to one another both laterally and axially. On the other hand, higher frequency sound energy attenuates more and tends to scatter in large grain material, causing a loss of sensitivity in thicker sections of material. Proper ultrasonic testing requires careful selection of the frequency to obtain a desired balance between sensitivity and penetration.
The sound field of a transducer/probe is characterized by a near field and a far field. The near field is the area directly in front of the transducer/probe where the sound energy goes through a series of maxim and minim both axially and radial. Responses from small discontinuities in the near field can be irregular. The far field of the transducer/probe is a region of more regular sound energy variations beginning with the highest maximum and gradually declining to zero. The highest maximum point is known as the near field distance and is represented by length N. This is also the natural focus point of the transducer/probe. The near field distance is a function of the transducer/probe frequency, diameter and the sound velocity in the test material according to following equation:

$$N = D^2.f/4.c$$

where:
- **N** the near field distance (mm)
- **D** diameter of the transducer/probe element (mm)
- **f** frequency of the transducer/probe (MHz)
- **c** velocity of sound in the material (km/s)

Transducer/probes also exhibit a characteristic called beam spread. Beam spread is an important consideration when inspecting discontinuities that may be close to geometric features of the test piece such as corners and fillets. Such geometric features can cause erroneous indications at distances where the beam spread is a factor. For flat or non-focused transducer/probes, beam spread is defined as the angle of the -6dB pulse-echo energy response according to the following equation:

$$\text{Sin } (\alpha/2) = 0{,}514.c/f.D$$

where:
- **α** angle of beam spread at -6dB (º)
- **c** velocity of sound in the material (km/s)
- **f** frequency of the transducer/probe (MHz)
- **D** diameter of the transducer/probe element (mm)

It can be seen from this relationship that beam spread can be controlled by selecting a transducer/probe with a combination of higher frequency or larger element diameter.
Straight beam testing is the introduction of the sound energy normal to the test piece surface utilizing longitudinal or compression waves. A longitudinal wave is one in which the particle motion is in the same direction as the propagation of the wave. Straight beam testing is used for most flaw detection.

Results

With respect to above mentioned specific features of composite materials and to possibilities of Masterscan 340 ultrasonic device, the probe PRDT 2550 (5MHz, crystal size 0,25 in) was used for composite material samples thickness of 4 mm, 10 mm and 14 mm. The velocity of propagation of longitudinal waves of ultrasonic beam in tested samples was 2880-2950 m/sec. The distance of near field N=16, 8 mm. Wave length λ = 0,6 mm. Under these circumstances the reliable disk reflectors indications were recorded in different depths of tested samples.
In Fig.4 the indication of disk reflector of 4 mm diameter in 2, 32 mm of depth in sample of 4 mm thickness by 38 dB of gain is displayed.
In Fig.5 you can see the indication of disk reflector of 4 mm diameter in 12 mm of depth in sample of 14 mm thickness by 54 dB of gain.

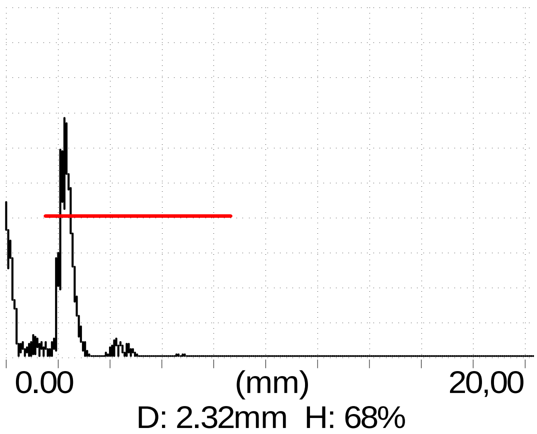

Fig. 4

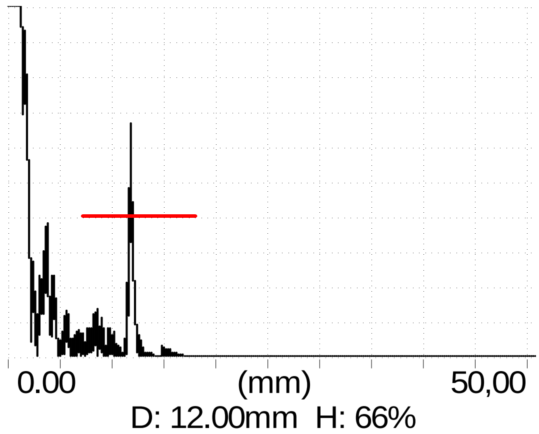

Fig. 5

The probe SLM2-10 (2,25MHz, crystal size 10 mm) was used for testing of composite material samples thickness of 10 mm, 14 mm and 40mm. The distance of near field N=18,8 mm. Wave length λ = 1,3 mm.
In Fig.6 the indication of disk reflector of 4 mm diameter in 12 mm of depth in sample of 14 mm thickness by 40 dB of gain is displayed.
In Fig.7 you can see the indication of disk reflector of 4 mm diameter in 32,4 mm of depth in sample of 40 mm thickness by 64 dB of gain.

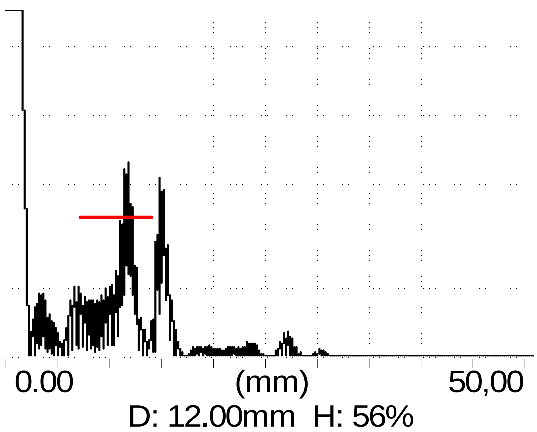

Fig. 6

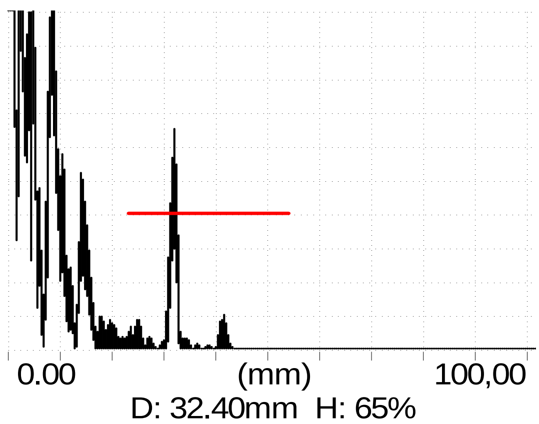

Fig. 7

Conclusion

During ultrasonic inspection of samples made of composite materials, in spite of high attenuation of ultrasonic wave propagation in composite materials and testing in near field of ultrasonic beam the application possibility of ultrasonic technique of NDT testing during composite sample inspection was proved like the non-destructive aircraft structures element method testing during fatigue tests [3].

For smaller discontinuities detection in composite structure and for thin structures testing (in our case in range 4 to 14 mm), it is necessary to use the probe with higher frequency (5 MHz). These probes have higher sensitivity (resolution ability) and shorter ultrasonic beam penetration. For inspection of structure of more thickness (14 to 40 mm) it is necessary to use the probe with lower frequency (2, 25 MHz).

On the contrary for reliable delaminating indication lesser then 2 mm^2 in composite materials (structures) thinner than 2 mm it is necessary to use probes with higher frequency for example 10MHz.

For reliable delaminating indication in composite materials based on glass fibres, where significant attenuation is present, it necessary to use probes with lower frequency then 2 MHz. However it is necessary to recon with loss of sensitivity.

Generally it is possible to say, that utilisation of standard ultrasonic techniques for NDT in composite materials has significant limitations for high attenuation of such and similar materials. It is possible to over cross them by probes and instrument tuning in some specific cases only. Always it is paid by loss of sensitivity and resolution.

For achievement of better results in branch of material with high attenuation NDT it is necessary develop and certify new techniques using non-linear methods.

Acknowledgements

This research was supported by grant MSM0001066903 of the Czech Ministry of Education, Youth and Sports.

References

[1] Bares Richard: Composite materials; SNTL Prague 1988

[2] Operator’s manual, Masterscan 340; Issue 3, SONATEST

[3] Forsyth D.S., Fahr A.: An evaluation of probability of detection statistics. Conference proceedings: Airframe Inspection Reliability under Field/Depot Conditions, RTO-MP-10, AC/323 [AVT] TP/2, Bruxelles, 1998