SINGLE MODE LAMB WAVE INSPECTION OF COMPOSITE LAMINATES

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INTRODUCTION

Flaw detection in composite plates presents a very difficult problem. Conventional echoscopic techniques are not feasible because the back-scattered signal from a possible defect is usually overshadowed by much stronger reflections from the walls of the thin plate and by additional scattering from inherent inhomogeneities such as imbedded fibers and alternating plies. Single or double transmission attenuation measurements offer a convenient, but rather insensitive alternative. Fig. 1 shows the schematic diagrams of the conventional normal incidence and the oblique incidence so-called Lamb wave inspection techniques. At normal incidence, we can use a focused transducer of very good lateral resolution, but the sensitivity might be rather low when the defect exhibits a very small scattering cross-section from this particular direction of interrogation. This occurs, for instance, in the case of weak porosity when the defects tend to be concentrated in a thin layer parallel with the plies, or as is shown in Fig. 1, in the case of transverse cracks. In such cases, oblique incidence inspection can be expected to give better sensitivity since Lamb modes propagating parallel to the plate are more attenuated. At the same time, the lateral resolution will be inherently lower, therefore the ultrasonic contrast must be carefully optimized on a case-by-case basis.

Fig. 2 shows the schematic diagram of the Lamb wave inspection technique. A detailed description of this method can be found in Ref. 1. The transmitted signal is greatly amplified at certain frequencies where dispersive Lamb modes are phase-matched to the incident wave at that particular angle of incidence. We can obtain a Lamb wave C-scan of the composite plate by moving the transducer parallel to the reflector and using narrow-band, e.g. tone-burst, ultrasonic inspection tuned to the frequency of the most sensitive mode at that particular angle of incidence.

Selective use of certain Lamb modes has already been suggested in connection with characterization of adhesive joints [2,3]. The crucial problem is, naturally, finding the most sensitive mode. Selection must be done on a case-by-case basis depending on the physical nature,

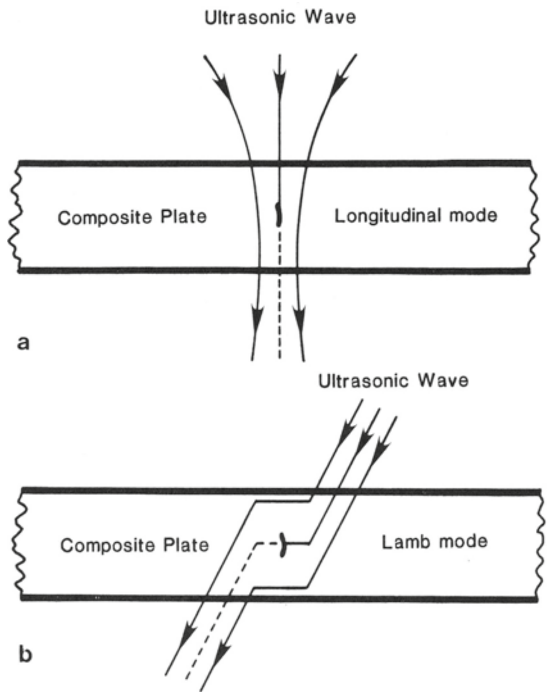

Fig. 1. Schematic diagrams of ultrasonic inspection at normal (a) and oblique (b) incidence.

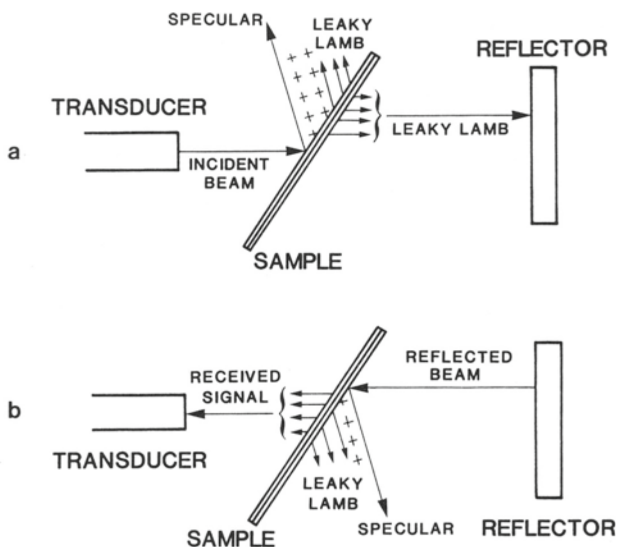

Fig. 2. Schematic diagram of the Lamb wave inspection technique.

orientation, location, and size of the expected defect. Besides the somewhat reduced lateral resolution, this complication is the price that must be paid for the increased sensitivity. This approach should involve some kind of learning mechanism as well to optimize the diagnostic capability of the ultrasonic inspection technique.

EXPERIMENTAL RESULTS

It is well known that gross porosity in the order of 0.5 - 5% can be readily detected by ultrasonic attenuation measurements. Within certain limits due to the uncertain nature of the aspect ratio of the usually elongated pores, quantitative assessment of the porosity volume fraction is feasible, too [4]. Detection problems start when the volume fraction drops to 0.1% or below and the resulting ultrasonic contrast of 1 - 2 dB cannot be distinguished anymore from the inherent background noise. Fig. 3 shows the ultrasonic attenuation spectrum in a composite plate including clusters of weak porosity in the order of 0.2% volume fraction (the inherent attenuation of the porosity free sample was accounted for in the measurement).

Fig. 4 demonstrates the substantial improvement offered by the Lamb wave inspection technique. At 22° angle of incidence corresponding to approximately 4000 m/s phase velocity, the strongest mode is generated at 6 MHz. This mode is attenuated by as much as 12 dB, i.e. roughly four times more than the normally incident longitudinal wave, by the same weak porosity. This enhancement can be taken advantage of in order to push the detection threshold well below 0.1%.

Another fairly common defect in composite plates which is difficult to detect at normal incidence is a transverse crack. Such cracks usually run parallel to the reinforcing fibers and they tend to grow in transverse directions through ply boundaries separating plies of the same fiber orientation, but they stop at boundaries between plies of different orientation. Consequently, the strongest cracks run in certain directions which have the most consecutive plies of the same fiber orientation. Such cracks can reach four or six plies, or approximately 0.5 - 0.8 mm, and they produce roughly 3 dB drop in the C-scan intensity. Unfortunately, smaller cracks of two ply height have been repeatedly missed by conventional normal incidence C-scan inspection. The detection threshold is

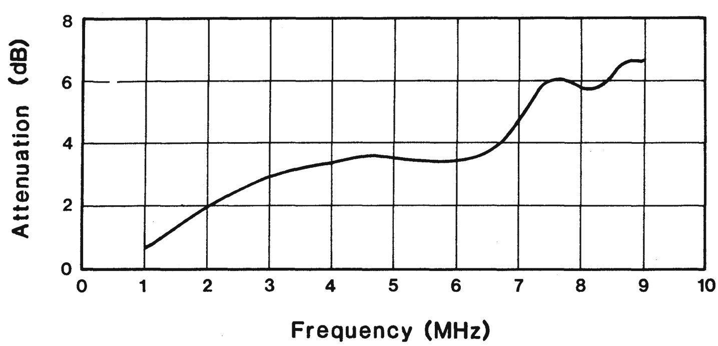

Fig. 3. Ultrasonic attenuation spectrum in a composite plate of approximately 0.2% porosity (sample #ACL 6804).

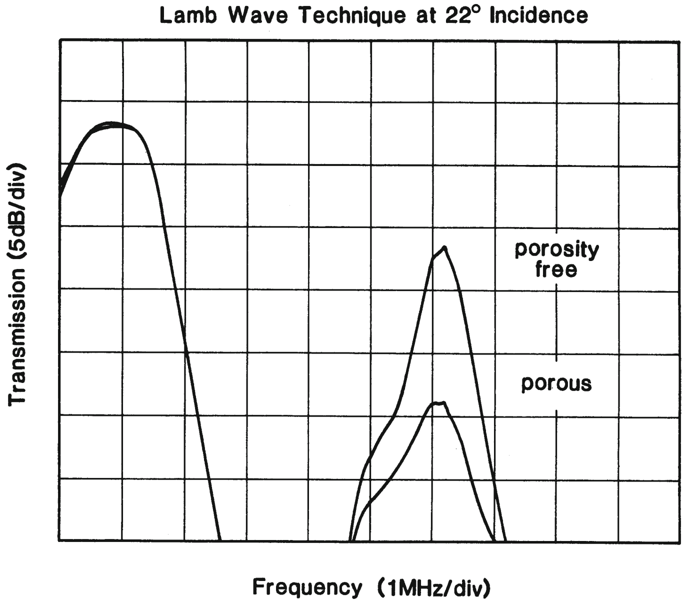

Fig. 4. Transmission spectra through porosity-free and porous parts of a composite plate (sample #ACL 6804).

mainly limited by the inherent inhomogeneity of the composite plate which causes about 1 dB uncertainty in the transmitted signal. As an example, Fig. 5 shows a cluster of one- and two-ply cracks in a fiber reinforced composite plate.

The ultrasonic contrast produced by such clusters of transverse cracks at normal incidence is in the order of 1 - 3 dB, i.e. barely detectable. Fig. 6 demonstrates this low detectability through examples of transmission spectra at defect-free and defective parts. The scatter of the defect-free spectra is approximately 3 dB at 5 MHz, while the average contrast produced by these multiple cracks is roughly 3 - 5 dB. Fig. 7 shows the ultrasonic transmission spectra of the same defect-free and defective parts at 20° angle of incidence. The principal Lamb mode of 4 MHz is attenuated by as much as 20 dB, approximately five times more than at normal incidence.

Fairly strong, five-ply single cracks give only about 3 dB contrast at normal incidence. Considerable improvement can be achieved by Lamb wave inspection. Fig. 8 shows the frequency spectra of the double transmitted signals through a composite plate at 20° angle of incidence at a defect-free part and over a single five-ply high transverse crack. All modes are more-or-less attenuated by the crack, but the one at 3 MHz seems to be affected much more than the others. Fig. 9(a) shows the normal incidence 5 MHz C-scan of a 2" by 2" area of the same sample. The only apparent long crack produces a meager 3 dB contrast on this conventional C-scan, but gives a strong 16 dB peak on the Lamb mode picture shown in Fig. 9(b). Naturally, the increased sensitivity reveals otherwise hidden inhomogeneities as well, i.e. the long crack of Fig. 9(b) is not

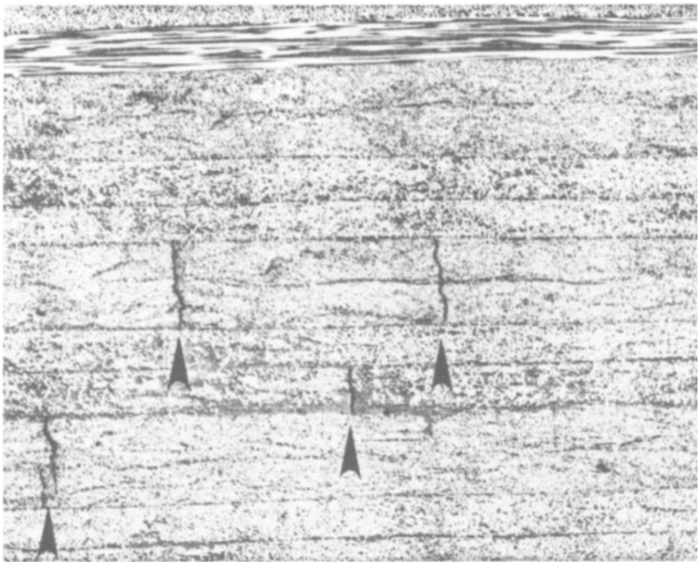

Fig. 5. One- and two-ply transverse cracks in a composite plate (sample #AMD 1530, x 50 magnification).

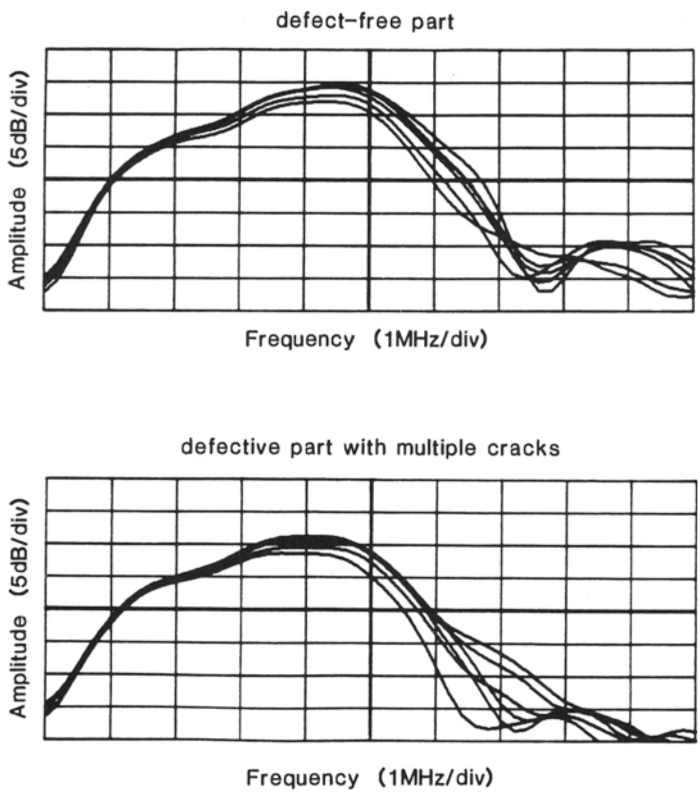

Fig. 6. Ultrasonic transmission spectra at normal incidence through defect-free and defective parts (sample #AMD 1642).

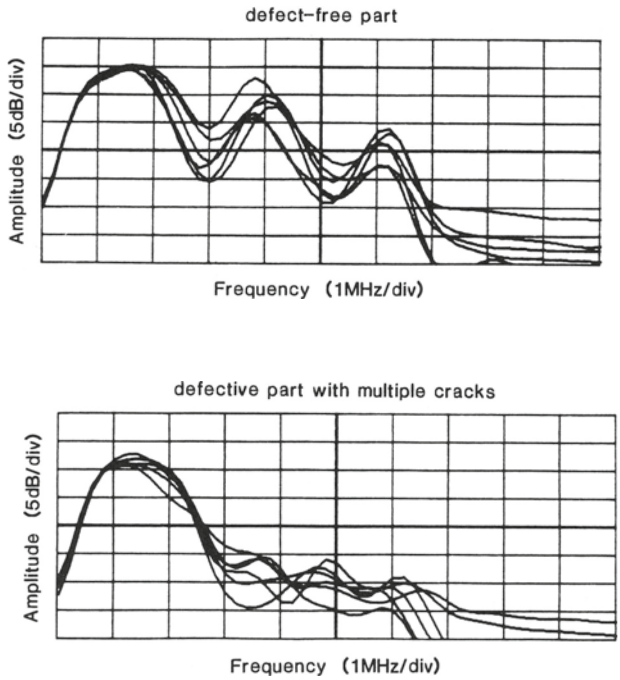

Fig. 7. Ultrasonic transmission spectra at 20° angle of incidence thru the same defect-free and defective parts as in Fig. 6.

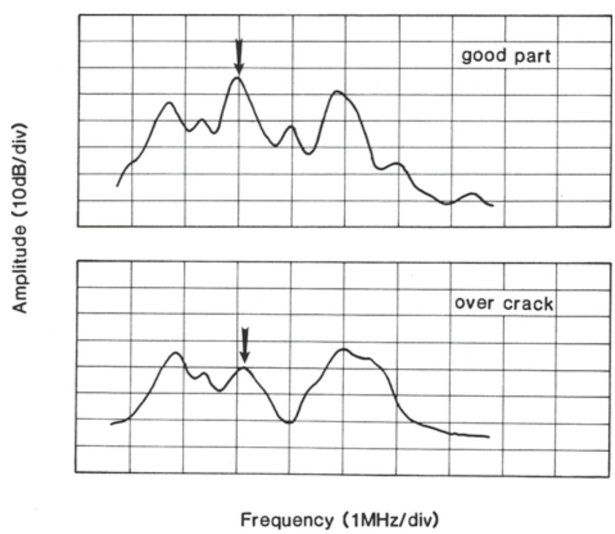

Fig. 8. Ultrasonic transmission spectra at 20° angle of incidence thru a composite plate with a single long crack (sample #AMD 1357).

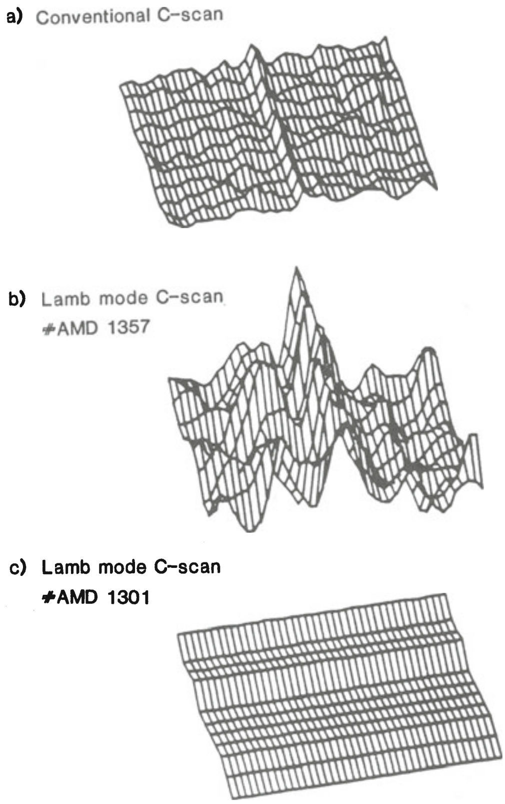

Fig. 9. Conventional and Lamb wave C-scans of composite plates with and without cracks.

necessarily better separated from smaller peaks of the surroundings than the much smaller peak on the normal incidence C-scan. If these additional peaks were caused by inherent inhomogeneities, e.g. by bunching of fibers, the increased sensitvity would not get us any further in our drive for better crack detection. On the other hand, if these peaks correspond to smaller, otherwise undetected cracks, we accomplished our primary goal.

In order to identify the source of the additional peaks in Fig. 9(b), we carried out the same experiment on a similar, but crack-free reference plate. As is shown in Fig. 9(c), the ripple of the background was roughly 1 - 2 dB, a fairly low value regarding the inevitable measuring uncertainties and sample inhomogeneities. According to these results, the additional peaks of Fig. 9(b) must have been caused by smaller cracks. The presence of these smaller cracks, which eluded detection on the normal incidence C-scan, was confirmed by subsequent destructive inspection. Because of the reduced lateral resolution, it is not always possible to correspond a certain peak to a single crack. Actually, many of these additional peaks represent a bunch of small cracks close to each other, as was shown in Fig. 5, too.

As a last example, Fig. 10 compares the conventional normal incidence and Lamb mode C-scans of a composite plate with many transverse cracks.

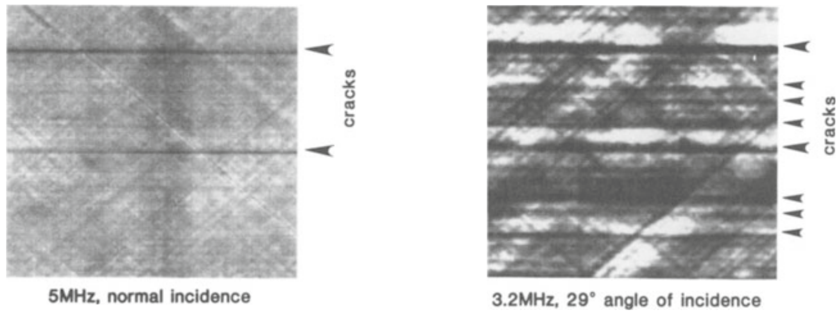

Fig. 10. Conventional and Lamb mode C-scans of a composite plate with transverse cracks (sample #AMD 1332).

The normal incidence C-scan was taken at 5 MHz and it features very good lateral resolution. There are two strong cracks of about 1.5 - 2 dB contrast running at horizontal direction and the background is fairly even. At first glance, the Lamb mode C-scan seems to be much worse, mainly because it has lower lateral resolution and its contrast is much higher. On the other hand, this C-scan reveals a number of additional cracks actually present in the plate, which is much more important than simply producing a nice picture.

CONCLUSIONS

Selective use of Lamb modes in composite plates can improve flaw detectability by a factor of three to five, but some of the lateral resolution must be sacrificed in the process. The ultrasonic interrogation technique should be optimized on a case-by-case basis to assure maximum flaw detectability.

REFERENCES

1. P.B. Nagy, W.R. Rose, and L. Adler, "A single transducer broadband technique for leaky Lamb wave detection" in Review of Progress in Quantitative NDE, edited by D.O. Thompson and D.E. Chimenti (Plenum Press, New York, 1987), Vol. 6A, pp. 483-490.
2. G.A. Alers and R.B. Thompson, "Application of trapped modes in layered media to the testing of adhesive bonds" 1976 Ultrasonics Symposium Proceedings, IEEE Cat. #76 CH1120-5SU, 138-142 (1976).
3. A. Pilarski, J.L. Rose, and K. Balasabramaniam, "On a plate/surface wave mode selection criteria for ultrasonic evaluation in layered structures" J. Acoust. Soc. Am. 82, S21 (1987).
4. D.K. Hsu and S.M. Nair, "Evaluation of porosity in graphite-epoxy composite by frequency dependence of ultrasonic attenuation" in Review of Progress in Quantitative NDE, edited by D.O. Thompson and D.E. Chimenti (Plenum Press, New York, 1987), Vol. 6B, pp. 1185-1193.