CHARACTERIZATION OF FIBER-WAVINESS IN COMPOSITE SPECIMENS USING DEEP LINE-FOCUS ACOUSTIC MICROSCOPY

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INTRODUCTION

A line-focus transducer used as the transduction element in an acoustic microscope forms the basis of a powerful materials characterization tool. When such a transducer is excited with rf-burst signals the transducer output voltage V exhibits strong amplitude variations which are related to the transducer's defocus distance z, that is, the distance between the transducer's focal point and the sample surface. These amplitude variations result from the interference between the leaky surface wave and the direct-reflected wave from the surface of the specimen. Analysis of such $V(z)$ curves permits determination of the wavespeed and attenuation of the surface wave which is the basis of the materials surface characterization measurement. Developed by Chubachi and Kushibiki [1] the line-focus beam has been used by a number of investigators to detect and characterize material anisotropy and stresses. Using a small aperture and high f-number lens as well as high-frequency excitations, the system is capable of high spatial resolution on a specimen. It forms the basis of an *acoustic microprobe* for determining near-surface material properties. Scanning the transducer permits the mapping of material properties over a region of the specimen, c. f. [2]–[6].

A large aperture, lensless, line-focus transducer was recently developed by the Ultrasonics Group at NIST.[7]–[9] Possessing a focal length of 25.4 mm and an aperture of 28.2 mm this transducer has a low f-number of 0.9. It is fabricated using a polyvinylidene fluoride (PVDF) piezoelectric film which is backed by a tungsten powder-loaded epoxy. The transducer is capable of broadband, short-pulse operation and has a center frequency of approximately 10 MHz. These characteristics make the transducer ideal for time-resolved, polarization-sensitive ultrasonic measurements on materials.

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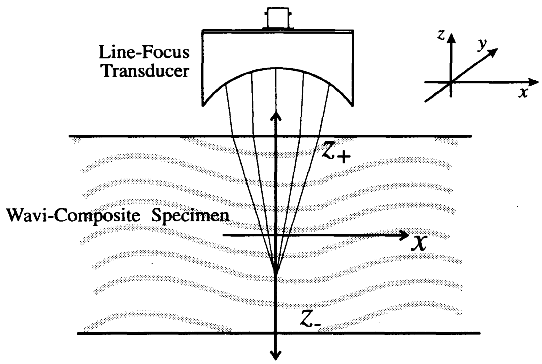

Figure 1: Schematic drawing of a wavi-composite and the ultrasonic testing configuration (deep focus configuration).

Operation of such a transducer has been demonstrated by measuring the wave arrivals and their amplitudes as a function of defocus distance in isotropic as well as anisotropic materials.[9] This data permits determination of a material's near-surface sound velocity and attenuation. Other applications have included the characterization of rough and porous ceramic coatings from measurement of the leaky surface wave velocity.[10]

In this paper we describe the use of such a system to detect and to characterize a composite material possessing waviness. We present results which are obtained when the focus of the transducer is near the front surface of the specimen. But further, we shall determine the sound field obtained when the transducer is focused on a region deep in the interior of a specimen.

SPECIMEN AND TEST PROCEDURE

A specimen possessing strong waviness was fabricated using graphite-fiber prepregs which were laid up unidirectionally, ten plies at a time, in an aluminum mold. The two-piece mold possessed mating sinusoidal surfaces with a spatial period of 40 mm and an amplitude of 2 mm. The completed layup, consisting of approximately 180 plies, was placed in a vacuum bag and then into an oven for curing. The density of the section of the cured composite specimen was 1524 kg/m^3 . The two opposite sides of the wavi-composite slab were machined flat and parallel. The specimen was subsequently polished to give a plate 15.93 mm thick.

We denote the direction along the thickness dimension as the z-axis and the x-axis is aligned with the average fiber direction. The specimen and its testing configuration are shown schematically in Fig. 1. Scans of the transducer were carried out along both the $x-$ as well as the $z-$directions as ultrasonic waveform data was acquired. A two-axis scanning system, operating under control of the waveform acquisition program running on a PC, was used for data acquisition.

The transducer was connected to a broadband ultrasonic system in which a short-duration pulse is used as excitation signal. Two commercially available systems were

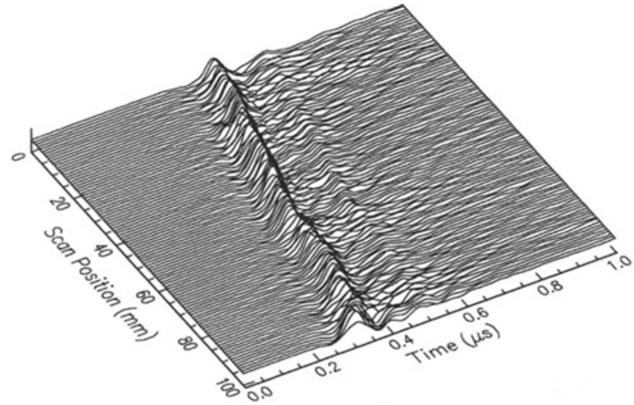

Figure 2: Scan image $v(x,t)$ at $z = z_+$ of sub-front-surface signals of a wavi-composite specimen.

used. One was a conventional 0.1 to 25 MHz bandwidth system and the other was a system whose bandwidth extended from .001 to 200 MHz. The signals were captured at up to a 450 MHz sampling rate, using an 8-bit digitizing oscilloscope which had capability for waveform processing and specifically, signal averaging to achieve a higher effective bit rate. Typically 1000 signals were averaged before the transducer was moved to the next position in a scan. A so-called *scan-image* is obtained by stacking the detected time-domain waveforms together. The axes of such an image are the transducer scan position, time and signal amplitude, in volts. In contrast to conventional $V(z)$ data we denote the measured ultrasonic time-domain waveform data by lower case v.

MEASUREMENTS AND MEASUREMENT RESULTS

Front Surface Scans, $v(x,t)$ at $z = z_+$

It is not surprising that when the transducer was focused on the front surface of the composite specimen, the largest signal was detected. Scans were then carried out as in a conventional line-focus acoustic microscope in which the transducer was slightly defocused below the front surface. We denote the near front surface defocus distance by z_+. The scans were along the x–direction and extended a distance of 90 mm to include more than two cycles of specimen waviness. A typical scan image of the near front surface signals is shown in Fig. 2. The variations in in first signal arrival-time and amplitude appear to be a function of surface roughness and apparently to a lesser extent, the local fiber orientation to the surface. The small amplitude signal following the first-arrival is probably the leaky wave but the variations in these small-amplitude signals do not appear to be sensitive to the sub-surface material waviness. It is clear that images obtained with the transducer slightly defocused below the front surface of the specimen will not readily provide information about microstructural features in the interior of a thick specimen.

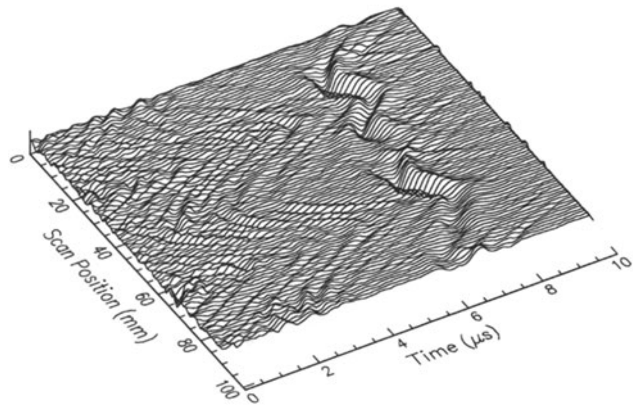

Figure 3: Scan image $v(x,t)$ at $z = z_-$ of *deep-focus* signals of a wavi-composite specimen.

Deep-focus Scans, $v(x,t)$ at $z = z_-$

By focusing the transducer deep in the interior of the specimen, at z_-, about 1–2 mm from the rear surface, we obtain the so-called *deep focus* configuration of the system. When the transducer has its line of focus oriented perpendicular to the fiber direction (aligned along the y–direction) and it is scanned in this configuration in the x–direction, the scan image shown in Fig. 3 is obtained.

It is seen that the rear-surface echo extends over a longer time period, and is correspondingly comprised of lower frequencies than are in the front surface specular reflection signal shown in Fig. 2. The surface roughness of the specimen does not seem to significantly influence the arrival-time and amplitude of the deep-focus signal. Further, the alignment of the specimen relative to the scanning transducer is not as critical as in conventional acoustic microscopy measurements.

It is immediately obvious that the deep-focus signal clearly reflects the variations of microstructure of a wavi-composite specimen. That is, the signal amplitude and arrival-times exhibit the periodicity of the waviness. In regions where the fiber waviness is closest to the transducer or farthest from the rear surface, the signal amplitude is reduced. The signal appears to become *de-focused*. In contrast, in regions where the fiber waviness is farthest from the transducer or nearest to the rear surface, the signal amplitude is largest and it arrives at long arrival times. The signal appears to become *focused*. Further, in regions of the scan image which arrive prior to the arrival of the deep-focus signal, there is also a structure reflecting the characteristics of the waviness, albeit more weakly than the deep-focus signal.

Measurements were also made in which the line of focus of the transducer was oriented parallel to the fiber direction (along the x–direction) and the transducer was set at deep-focus. In that case, the periodic structure visible in Fig. 3 is not visible. It becomes increasingly apparent in the scan images as the transducer is oriented to bring its line of focus to right angle to the fiber direction.

$v(z,t)$ Scans

In order to permit quantitative investigation of signal arrivals in a wavi-composite it is essential that the sequence of wave arrivals from the specimen be clearly identified. The time-resolution of signals which this film transducer possesses can be used to advantage if the transducer is scanned in the z–direction (direction normal to the specimen surface) at a particular location on the specimen from the maximum defocus distance to a point at which the focal spot is exterior to the specimen. Fig. 4 is one example scan. It is seen that the evolution of signal arrivals with z–scan position provides a powerful means for identifying many of the arrivals in the detected signals.

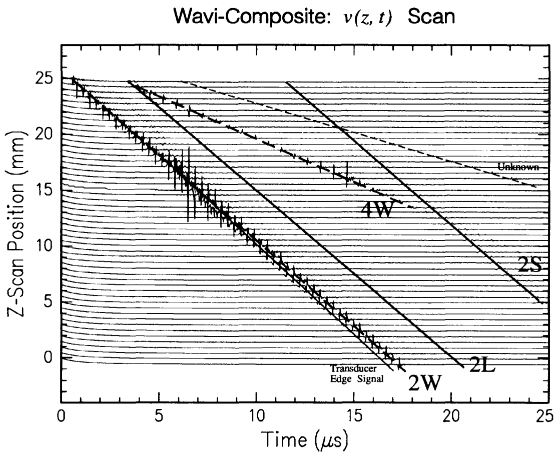

Figure 4: Signals detected as a function of z–focus distance.

The most obvious and clearly identified signals have been labelled in Fig. 4. There are the '2W' and '4W' signals which refer to signals corresponding to the waves which are specularly reflected once or twice, respectively, from the specimen surface directly under the line-focus transducer. Also clearly identified are the '2L' signal arrivals. These are the bulk longitudinal waves propagating at approximately 4.5 mm/μs down and back through the composite plate. Similarly, the signals arriving at the line labelled '2S' correspond to the bulk shear wave signals propagating at approximately 1.5 mm/μs one round-trip through the composite plate.

Visible also are some surprises and unknowns. Clearly identifiable are signals which emanate from the edges of the line-focus transducer. When the focus line is exterior to the specimen, these small signals arrive prior to the specularly reflected signal in a predictable way. The trace of the signal arrivals labelled 'Unknown' may be the result of the wave being propagated back and forth in the water between the transducer and specimen, corresponding to the '6W' signal. But this requires further investigation. The small signal amplitudes following immediately after the arrival of the '2W' signal when the transducer is positioned closer to the specimen than its focal length include the leaky wave signal.

The $v(z,t)$ scans clearly provide a powerful means for identifying many of the signals present in a transducer waveform. Further, by analyzing these images it is possible to clearly determine the wavespeed and attenuation of particular wave modes propagating in the specimen and surrounding fluid and from such data, the moduli and density of the composite specimen.[6]

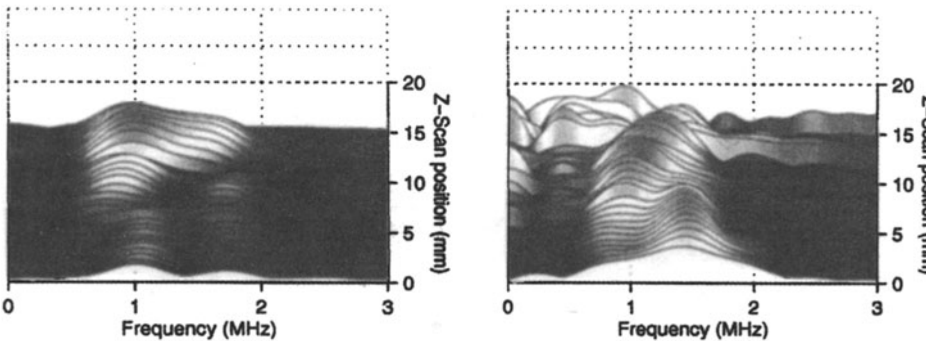

Figure 5: Fourier spectra of the deep-echo signals as a function of z in a wavi-composite. (a) At scan position 3 mm, (b) At 35 mm.

$v(z,x,t)$ Scans

An investigation of the heterogenous microstructure of a material such as a wavi-composite requires, in principle, that the wavespeeds and density of the material is determined for all points in the interior of a specimen. In some cases, it may be assumed that the material heterogeneity is only a function of x and y and it is constant in the thickness dimension. In that case, $v(z,t)$ scans collected at various x,y coordinates of the specimen are needed, i. e. $v(z,x,y,t)$ scans. In this paper we show the simpler case of $v(z,t)$ data collected along a second scan made along just one direction of the specimen, say the x–direction, that is, $v(z,x,t)$ scans.

It is a bit problematical on how to best present such data. What is required is a 4-dimensional representation of the values of x,z,t and v. The data shown in Figs. 2 and 3 are simply slices of such 4-dimensional data sets. An even more restricted view is obtained when one attempts to use conventional ultrasonic A- or B-scans or the $V(z)$ data of conventional acoustic microscopy measurements to characterize material heterogeneities. For some materials characterization applications it is unnecessary to collect a full 4-dimensional data set – or the 5-dimensional data set if the scans also include motions along the y–direction.

If data collection time is not an issue, it is possible to collect all the data and to extract from it specific features. For the case of the wavi-composite, we show in Fig. 5 the result that is obtained when one Fourier-transforms the windowed '2L' waveform as a function of defocus distance z, for two different x positions along a scan. While we draw no conclusions from the details of these spectra, we simply show that with today's powerful and fast signal processing software it is possible to rapidly extract slices of time-, frequency- or position-information from multi-dimensional ultrasonic data arrays.

CONCLUSIONS

We have described in this paper the application of the broadband ultrasonic, lensless, line-focus transducer with large aperture and low *f*-number as a critical element in an ultrasonic microscope which can be used to detect and characterize fiber waviness in a thick composite plate. We have shown that the waveforms obtained when the focus of the transducer is near the front surface of the specimen are insensitive to the waviness. But when the transducer is focused on a region deep inside a specimen, the waviness of a composite specimen is detected and can be clearly imaged provided that the line of focus of the transducer is co-linear with the waviness of the specimen. We show that the collection of $v(z,t)$ data aids in an unambiguous identification of wave arrivals. Waveform acquisition with the line-focus transducer scanned along two simultaneous scan directions has also been shown. The resultant multi-dimensional ultrasonic data arrays can be processed to extract slices of ultrasonic waveform information as a function of time (or frequency) and position.

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