Using a Single Transducer Ultrasonic Imaging Method to Eliminate the Effect of Thickness Variation in the Images of Ceramic and Composite Plates

Don J. Roth

Received September 3, 1996; Revised March 30, 1997

This article describes a single transducer ultrasonic imaging method based on ultrasonic velocity measurement that eliminates the effect of thickness variation in the images of ceramic and composite plate samples. The method is based on using a reflector located behind the sample and acquiring echoes off the sample and reflector surfaces in two scans. As a result of being thickness-independent, the method isolates ultrasonic variations due to material microstructure. Its use can result in significant cost savings because the ultrasonic image can be interpreted correctly without the need for precision thickness machining during nondestructive evaluation stages of material development. Velocity images obtained using the thickness-independent methodology are compared with apparent velocity maps and c-scan echo peak amplitude images for monolithic ceramic (silicon nitride), metal matrix composite and polymer matrix composite materials having thickness and microstructural variations. It was found that the thickness-independent ultrasonic images reveal and quantify correctly areas of global microstructural (pore and fiber volume fraction) variation due to the elimination of thickness effects. A major goal achieved in this study was to move the thickness-independent imaging technology out of the lab prototype environment and into the commercial arena so that it would be available to users worldwide.

KEY WORDS: Ultrasonic imaging; thickness independent; velocity images; microstructural characterization.

1. INTRODUCTION

Ultrasonic c-scan imaging is an effective nondestructive evaluation (NDE) technique used for materials analysis and quality control in the aerospace, electronics, and other industries (Ref. 1). C-scan imaging in its most conventional implementation is used to map variations in ultrasonic echo peak amplitude that occur when scanning across a material part (Ref. 1). In the pulse-echo c-scan configuration, echoes that are sometimes monitored or "gated" include those reflecting off the sample front and back surfaces (Ref. 1). For commercially available commercial scan systems, the amplitude variations are generally scaled to values between zero and 255 [8-bit dynamic range] and displayed on video in terms of gray or color scale. In this manner, gray scale variations in the image are associated with amplitude, or attenuation, variations. An additional implementation of c-scan imaging involves mapping variations in the time of occurrence of an ultrasonic echo peak with respect to a reference time. These "time-of-flight" variations are scaled and displayed in a similar fashion to echo peak amplitude. Both amplitude and time-of-flight variations of a back surface echo can many times be related to variations in a volumetric microstructural property such as density which can affect physical material properties such as stiffness and thermal conductivity. However, a weakness of conventional ultrasonic c-scan imaging regarding both peak amplitude and time-of-flight modes is that gray scale variations in images for back surface re-
reflections indicate part thickness variations as well as microstructural variations unless the part is uniformly thick.

2. BACKGROUND

By their very nature, both peak amplitude and time-of-flight measurements of back wall echoes are directly dependent on thickness. Back wall peak amplitude \( A \) is affected by thickness according to the expression for pulse-echo attenuation where (Ref. 1)

\[
A = A_0 \exp(-\alpha(2d)) \quad (1)
\]

where \( A_0 \) is an initial reference amplitude, \( \alpha \) is the material attenuation coefficient, and \( d \) is the thickness of the part. In practical application, the severity of the effect of thickness variation on peak amplitude depends on the frequency of ultrasound used because the ultrasonic attenuation coefficient normally increases with increasing frequency. Generally it is desirable to use the highest frequency of ultrasound possible to maximize resolution of nonuniformity. As an example of the effect of thickness variations on peak amplitude, Fig. 1 shows the effect of thickness on back wall ultrasonic signal amplitude obtained from PMR-15 polyimide samples for pulse-echo experiments conducted at NASA Lewis Research Center. Thickness of the samples ranged from approximately 2.3–5 mm. The experiments were conducted using both 5 and 20 MHz broadband transducers. Results are shown for both the time-domain broadband back wall pulse (Figs. 1a, c, e) and the frequency-domain power spectra of the pulse (Figs. 1b, d, and f). Figure 1 illustrates that the back wall echo amplitude increases with decreasing thickness at both frequencies, but much more significantly so at 20 MHz than at 5 MHz due to the considerably higher attenuation coefficient at 20 MHz for PMR-15 material \( \alpha_{\text{PMR-15}} \) at 20 MHz \( = 2.761 \pm 0.2 \) Neper/cm and \( \alpha_{\text{PMR-15}} \) at 5 MHz \( = 1.184 \pm 0.1 \) Neper/cm as obtained from experiments at Lewis). Thus, peak amplitude c-scan images, including the effect of thickness variations on them, will be highly frequency-dependent.

The situation is more straightforward for interpreting the effect of thickness variations on time-of-flight of ultrasonic pulses off the sample back wall. Back wall pulse-echo time-of-flight \( 2\tau \) is affected by thickness variation according to

\[
2\tau = \frac{(2d)}{V} \quad (2)
\]

where \( V \) is the velocity of ultrasound in the material. No frequency dependence exists as does for attenuation [disregarding dispersion effects of frequency on material velocity \( V \)]. Thickness effects on time-of-flight can also be interpreted by rearranging Eq. (2) to calculate velocity according to

\[
V = \frac{(2d)}{(2\tau)} \quad (3)
\]

such that velocity is inversely proportional to time-of-flight. For velocity mapping from scan results, only one thickness value can be used practically in the velocity map calculation (Eq. 3). This value is usually an average value obtained from several measurements at different sample locations. For scan locations where actual thickness is less than the value chosen for the calculation, time-of-flight will be less, and apparent velocity will be greater, than that if the scan location had the chosen value of thickness. The situation is opposite for scan locations where actual thickness is greater than the value chosen for the calculation. Hence, velocity and time-of-flight maps will be affected similarly by thickness variations, and velocity maps are used in this investigation to indicate time-of-flight variations.

Since the attenuation coefficient \( \alpha \) and velocity \( V \) in a material will not be constant if microstructural variations are present, Eqs. (1)–(3) indicate that maps of peak amplitude, time-of-flight, and velocity will show a combination of microstructural and thickness variations.

3. RELATED WORK

Several attempts to account for thickness variation effects in ultrasonic measurements were noted in the literature. Reference 2 used a two-transducer method whereby the transducers, located on opposite sides of the sample, were used in both pulse-echo and through-transmission mode to produce thickness-independent peak amplitude c-scans. Accurate thickness at each scan location was obtained via both transducers using the time-of-flights acquired from pulse-echo front surface reflections off both surfaces of the sample, and using the known constant velocity in water and the known distance between the two transducers. Peak amplitude information was obtained in through-transmission mode. A peak amplitude c-scan free of thickness effects was then computed using Eq. (1) where \( A, A_0, d, \) and \( \alpha \) were the thickness-corrected peak amplitude, measured peak amplitude, measured thickness, and assumed constant material attenuation coefficient, respectively, at each