NONDESTRUCTIVE TESTING OF "THICK" AEROSPACE HONEYCOMB STRUCTURES USING THROUGH-TRANSMITTED ULTRASONIC GUIDED WAVES

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INTRODUCTION

The idea of using guided elastic waves for the purpose of assessing the fitness for service of aerospace composite structural materials is not new. "Pure" longitudinal or shear waves cannot exist in layers whose thickness dimension is of the order of an ultrasonic wavelength.

In the last decade, considerable attention has been focused on the more fundamental aspects of Lamb-wave propagation in fiber-reinforced composites such as those used as face sheets on Nomex and metal honeycomb cores. This work has led to an in-depth understanding of the underlying physical phenomena and their relationships to material parameters [1,2].

Concurrently with the development of theories of guided wave propagation in a variety of structural laminate materials, "improved" ultrasonic nondestructive testing (NDT) procedures and instrumentation have also been developed. Most of the advances appear to involve the use of ever more sophisticated data-acquisition schemes. However, new NDT procedures based on novel transduction techniques have also gained limited acceptance. The most notable developments in this area include improved air-coupling, electro-optical, acousto-optical, dry-coupling, and even electromagnetic-acoustic transduction (EMAT) schemes.

Very few of the so called "new" NDT schemes appear to be based on a genuinely recent idea. For example, nearly twenty years ago, in 1971, Luukkala et al. suggested that obliquely-incident, air-borne ultrasonic waves may be useful for generating guided (Lamb) ultrasonic waves in thin organic layers[3]. They also proposed using this technique to inspect paper, but warned of potential instrumentation difficulties. In recent years, considerable improvements in semiconductor and piezoelectric transducer material technologies have made it feasible to design and fabricate commercially-acceptable ultrasonic NDT instruments that utilize air as the coupling fluid[4,5]. However, because of the inherent inefficiency of the air-coupling mechanism, the use of such instruments has been restricted to the "thin" composite structures that do not utilize the honeycomb-core construction.

The steady pace of advances in aerospace technology has resulted in ever-increasing utilization of honeycomb-core structural materials that utilize fibrous-laminate face sheets and inorganic cores. Such structures often appear to be very difficult to inspect in the through-transmission mode, because the propagation of ultrasound is severely impeded by the geometrical complexity of the sandwich. Structures utilizing very thick (0.15-meter and thicker), multi-segmented cores are particularly difficult to inspect.

In many cases, components can only be adequately inspected by using the full spectrum of available technologies (system approach) including the latest advances in instrumentation and by taking advantage of the preferred ultrasonic modes. In addition, allowances must also be made for modifying the "conventional" NDT procedures. In this year, we provide two examples that illustrate the practical benefits of utilizing modified ultrasonic NDT procedures in conjunction with improved ultrasonic "front-end" instrumentation.

THE TECHNICAL APPROACH

Conventional inspection of honeycomb structures often use a "water-squirter", through-transmission technique, where by the ultrasonic transducers are aligned coaxially and normal to the face sheets. This method is fundamentally limited in terms of achieving the highest signal to noise performance.

The fluid-coupled transducers first excite ultrasonic shear and longitudinal waves in the top face sheet. The polar distributions of the transmission coefficients for the two types of waves are well understood in nominally-isotropic plates[6,7]. Very recently, significant progress has been made in the understanding of the roles of fiber-induced anisotropy[8,9]. The role of the fluid loading is also being studied[10].

The ultrasonic signals emergent from the walls of the honeycomb-core again generate shear and longitudinal waves in the bottom face sheet. In turn, these waves generate compressional waves in the surrounding coupling fluid, water or air. By symmetry, the signals generated in the coupling fluids, are obliquely inclined and, therefore, cannot be efficiently sensed by the normally-aimed receiver transducer. Consequently, a very significant loss of sensitivity to "non-bonds" is incurred.

Our technique is fundamentally different from the "conventional" techniques in that the ultrasonic beam axes of either one of both transducers are obliquely inclined with respect to the surface normal of the test panel. As a consequence of this arrangement, efficient coupling can be achieved to the shear waves propagating in the face sheet. However, as in the "conventional" set-ups, both ultrasonic beam axes are co-planar and parallel to the medium plane of the test panel. This configurational difference is clearly depicted in Fig. 1. Empirically, we have observed an approximately two-to-one improvement per interface in transmitted amplitude by coupling to the shear waves as opposed to coupling to the longitudinal waves in the face sheets. In terms of the overall system signal-to-noise performance, this is equivalent to 10-12dB gain.

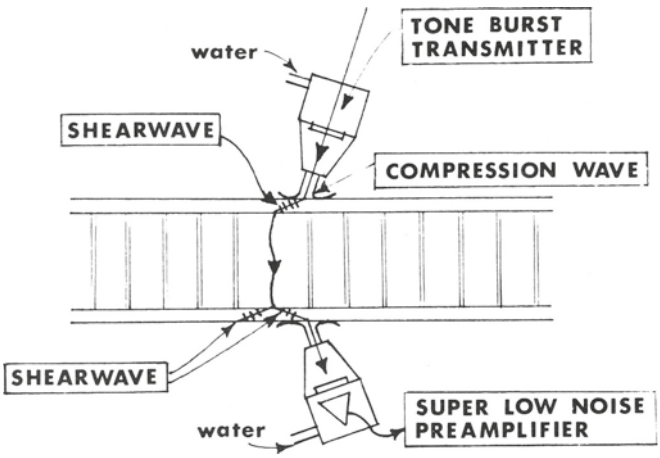

Fig. 1. Experimental configuration used for through-transmission ultrasonic inspection of very thick aerospace honeycomb structures.

Depending on the type of fluid couplant, i.e., water vs. air, and composition of the face sheets, the angle of incidence for maximum transmission varies from 8 to 15 degrees. Inspection frequencies range from 0.4 MHz to 2.25 MHz. To achieve an additional improvement in signal-to-noise performance, we operate in a "tone-burst" mode. We have found empirically that approximately 10 cycles of RF are required to maximize the transmitted signal amplitude. However, we expect that this number can be reduced by at least a factor of two in the future through better matching of the electrical characteristics of the "tone-burst" transmitter amplifiers to those of the ultrasonic transducers.

PRACTICAL THROUGH-TRANSMISSION INSPECTION TECHNIQUES

Although "water-squirt" techniques are preferred at the present time, we also would like to comment on the applicability of inspection configurations that utilize other procedures for introducing the sound waves into the honeycomb structure. In the future, as a result of further improvements in instrumentation, it may be possible to extend the range of applicability of such techniques to the thicker composites.

"WATER-SQUIRT" AND IMMERSION TECHNIQUES

Honeycomb structures, utilizing graphite-resin and/or Kevlar face sheets and having either metallic or organic cores with an overall thickness 1/2-inch, or greater, are generally inspected at the normal test frequency of 1 MHz, or lower. It is standard practice to employ "water-squirt" techniques with water-column diameters in the 1/8-1/4-inch range. Total immersion is less preferable, because the use of low-frequency collimating devices results in the loss of desired ultrasonic beam characteristics and generation of undesirable artifacts in the C-scan images.

Immersion testing is preferred to "water-squirt" testing for pulse-echo work. In this case, the material is inspected in the reflection mode using a focused transducer.

All-metal honeycomb structures usually present no difficulties, because they exhibit relatively insignificant propagation loss. Consequently, such structures can generally be inspected using "conventional" inspection set-ups in which the ultrasonic beam axes are normally aligned with respect to the surface of the face sheets.

All-organic or organic/metal honeycomb sandwich structures tend to exhibit significantly higher propagation losses than all-metal structures. As a result, they present a much more challenging inspection problem, particularly when the section thickness exceeds 1 inch, or so. Structures employing a septum are particularly difficult to inspect. In such cases, the use of our techniques, based on the use of inclined ultrasonic beams and improved electronic "front-end", becomes very appropriate.

We have employed our technique to inspect all-organic honeycomb structures with overall thicknesses of 7 inches. However, we expect that even thicker structures will become inspectable using better instrumentation, which is currently under development. We also expect that the improved dynamic performance of our instrumentation will facilitate inspection of certain honeycomb structures that employ a septum.

Figure 2 depicts an experimental configuration used to inspect 7.5 inch thick inorganic honeycomb test panel. The corresponding 400 kHz gray-scale C-scan is shown in Fig. 3. The high definition is made evident by the presence of the distinct honeycomb pattern in the image. The larger features represent intentionally-introduced "non-bonds" between the face sheet and the honeycomb-core.

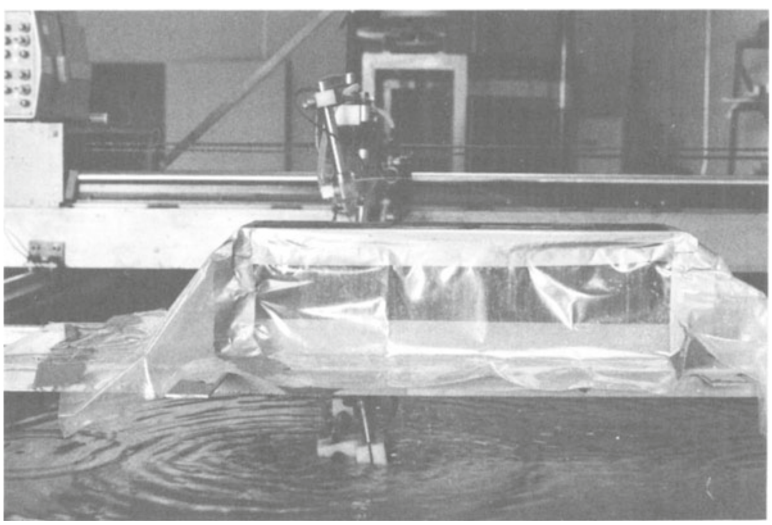

Fig. 2. Photo of experimental set-up used for inspection a 7-inch thick, honeycomb test panel. Note the angular alignment of the "water-squirt" transducers with respect to the face sheets.

Fig. 3. C-scan obtained using the experimental set-up of Fig. 2.

Figure 4 shows a different inspection configuration that was used to inspect a different honeycomb test specimen with a prominent taper. The corresponding 400 kHz gray-scale C-scan is shown in Fig. 5. It should be noted that most of the indications represent test tapes that were attached to the top of the panel. In this case, all of the intentionally-introduced "non-bonds" were also detected.

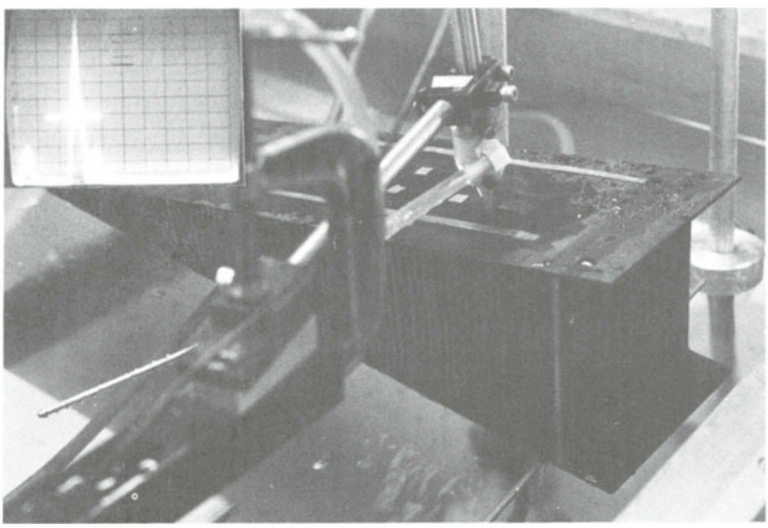

Fig. 4. Photo of experimental set-up used for through-transmission ultrasonic inspection of a very thick honeycomb test section. Note the CRT signal in the inset.

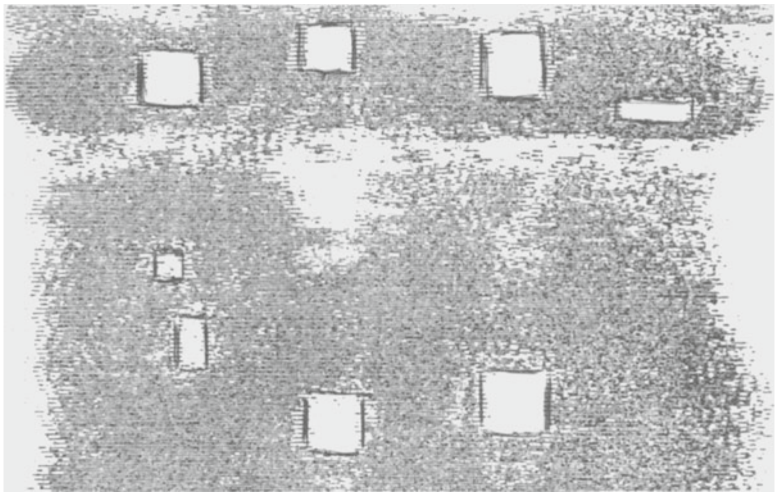

Fig. 5. C-scan obtained using the experimental set-up of Fig. 4.

DRY-COUPLED TECHNIQUES

Certain soft, pliable plastics can be used to "dry-couple" ultrasonic vibrations to metal and organic structures. Typically, such materials are employed in the construction of the so-called "soft-tip" and "roller" probes. Both types of probes are recommended mainly for manual inspection applications.

AIR-COUPLED TECHNIQUES

In many cases, it is desired to prevent wetting or contaminating materials, such as carbon-carbon composites, foams, porous structures, certain laminates, etc. The use of efficient unipolar and bipolar tone-burst generation combined with large signal-to-noise preamplification and tuning now makes it possible to conduct valid through-transmission tests on such materials. So far, ultrasonic air-coupled, focused transducers are used at test frequencies between 400 kHz and 1 MHz. It is expected that in the near future the better "air-matched" transducers[11]. The air-coupled technique also benefits from angulation of the incident sound beams.

ELECTRONIC INSTRUMENTATION CHALLENGES

In addition to propagation losses, the signal-to-noise performance of a through-transmission inspection system is markedly affected by the physical characteristics of components that constitute the "front end" of the system: transducers, transmitter circuit, receiver amplifier chain, and cabling. Very often, the electrical characteristics of such components are not judiciously balanced, resulting in decidedly sub-optimum system performances. Typically, a 30-dB signal-to-noise performance is required in order to produce a good-quality C-scan.

In principle, digital signal averaging techniques can be used to improve the signal-to-noise performance. However, the use of this technique results in a considerable slowing-down of the inspection process, very adversely affecting the economics of NDT. Therefore, we are not advocates of this approach.

Perhaps the greatest gain, in terms of significantly improved signal-to-noise performance, can be achieved by reducing the Noise Factor of the receiver amplifier chain. The "front ends" of commercial ultrasonic NDT instruments are equipped with very robust self-protection circuits. Also, front-end filtering is included to de-emphasize response below 1 MHz, or so. Unfortunately, such measures tend to result in extremely high Noise Factors. At this time, we believe that a typical commercial transducer/receiver amplifier chain exhibits a 30 dB Noise Factor and higher.

Certain manufacturers of ultrasonic instrumentation recommend that a pre-amplifier, mounted in very close proximity to the piezoelectric element, be used in through-transmission NDT applications. We have found that following this recommendation can be very helpful in terms of reducing the Noise Factor, but that further significant improvements are possible. To demonstrate this point, we employed a very low-noise pre-amplifier of our own design.

The relevant electrical characteristics of our pre-amplifier design are: approximately 0.6 nanovolt/root-Hz equivalent input noise, 50 dB voltage gain, and 100 kHz-10 MHz bandwidth. We found that the use of this design has resulted in a further 10-20 dB improvement in signal-to-noise in the 0.4-1.0 MHz frequency region, which is of particular interest in the NDT of "thick" composites.

To achieve an additional increase in system signal-to-noise we drive our transducers with a 450-volt, "tone-burst" pulser of our own design. By operating in this mode, we take advantage of low-loss transducer materials to "pump-up" the amplitude of the transmitted signal. Ultimately, the piezoelectric coupling constant of the transducer material and the dielectric breakdown characteristics (2 volts per micron for a typical PZT material) limits the maximum amplitude.

Piezoelectric transducers, particularly those used in generating and receiving waves in air, remain an area where further improvements appear to be possible[11]. We are continually investigating new techniques in this area. Of particular interest are improved materials for fabricating the acoustic impedance matching layers and different lens designs.

SUMMARY REMARKS

Judicious system integration approaches can result in ultrasonic through-transmission NDT systems with very significantly improved signal-to-noise performance. Such systems are required for determining the fitness for service of "thick" honeycomb structures that are used by the aerospace industry. Proper system design is also important in making air-coupled ultrasonic NDT systems practical. Such systems may eventually replace the more-conventional water-coupled systems in many applications.

In this paper, we have reported that significantly improved NDT system signal-to-noise performance can be achieved through a combination of incremental improvements in the electronic "front end" (30-40 dB) and selecting the most strongly coupled ultrasonic modes (10-12 dB). In particular, by inclining the ultrasonic beam axes with respect to the face sheets, we have shown how to take advantage of the stronger coupling to the shear waves, which, in turn, couple strongly to flexural waves in the thin honeycomb-cores.

By taking advantage of the improved signal-to-noise performance, we have been able to inspect 0.15m thick organic honeycomb structures using "water-squirt" techniques. By employing similar procedures, we have also been able to increase the range of applicability of air- and dry-coupled ultrasonic inspection systems.

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