Quantitative Non-Contact Ultrasound Testing and Analysis of Materials for Process and Quality Control

Ronnie Y. VUN, Thomas EISCHEID, Mahesh C. BHARDWAJ
The Ultran Group, State College, PA, USA

Abstract. Ultrasound materials testing modality has advanced dramatically with the development of extremely high air/gas transduction transducers. The advantage of not needing physical contact of the transducer to the test media has opened numerous non-destructive testing (NDT) possibilities that are not feasible by conventional ultrasound testing techniques. Such possibilities are inspection of materials in the early stages of their formation, or materials that are porous, or are texturally and compositionally complex. The importance of NDT has shifted into non-destructive characterization (NDC) of materials, which is necessary towards quantifying the service performance and durability of the products or structure. This study showcases the Non-Contact Ultrasound (NCU) analytical capabilities for composites varying in porosity and differing in number of plies, by using 0.5 MHz and 1.0 MHz NCU transducers. The results show that the ultrasound transmittance increases linearly with increasing porosity, whereas, the velocity decreases. The percent porosity derived from the NCU method matches that determined by conventional methods, thereby indicating excellent feasibility of the quantitative NCU analysis of materials. Limitations and phenomenon of signal propagation in the materials are discussed and further calibration studies are recommended.

1.0 Introduction

Ultrasound has come a long way since the discovery of piezoelectricity by Pierre and Jacques Curie in 1876 [1] and its application by Richardson in 1913 for sonar [2]. Today, ultrasound is widely used in health care for non-invasive diagnostics and in industry for non-destructive testing (NDT). Its testing based on wave-material interactions that produced responses identifiable to the unique material characteristics. As compared to other wave-based methods, ultrasound testing does not require sample preparation, is non-hazardous, and its time, attenuation, frequency and image domains encompassed a wide and potential applications. See details in Table 1 of [3]. With the advent of electronics and digital signal processing, the importance of NDT has shifted into a detailed domain of non-destructive characterization (NDC) of materials. Today customers have desires for more structural, physical, and composition information of their products, not limiting to overt flaws detection.

Efficiency of the conventional ultrasound relied on physical contact of the transducer on the test materials, due to the enormous high attenuation of ultrasound in air. Since 1980, the development of transducers has superseded our expectation by our high transduction power of gas matrix piezoelectric-based transducers in air [4]. This achievement to circumvent the exorbitant mismatch of air has defied the reality [5], but has indeed opened up an unlimited spectrum of applications. Many in-process products could be inspected at its natural state without contamination of the coupling medium, such as consolidated particles, green ceramics and powder metals; plastics, prepreg; materials in formation; porous, liquid-, or touch-sensitive materials in food, pharmaceutical, and bio-medical products. Achieving non-contact ultrasound (NCU) is analogous to "throwing a rubber balloon and seeing it spearing through a stainless steel wall." Numerous investigations have been done feasible in many in-process materials such as plastics, rubber and foam [6]; wood and lumber [7]; concrete, highway, bridges and air strips [8]; and, ceramic, refractories, and filters [9,10]. Recently, we have successfully demonstrated quantitative NCU analysis of green ceramics, road asphalt, and wood composites [11,12,13,14,15,16,17,18]. Also, calibration models for process quality control were developed [19,20].

This paper showcased the advantages of Ultran's non-contact ultrasound (NCU) transducers and technology, not needing physical contact for inspection, widening up a new breath of industrial applications for quantitative and analysis of material processing and quality control domains. The fundamental inspection techniques [10] are briefly illustrated. An in-depth analysis of composites material [21] is discussed in through the thickness transmission. Specifically, the objectives of the present investigation are (1) to find the effects of frequency on the different CFRP sample thickness, porosity, and number of plies; (2) to determine the intensity and distribution of the transmitted ultrasonic parameters as a function of frequency.

2.0 Non-Contact Ultrasound Techniques

The technique used in non-destructive inspection depends on the investigation objectives, medium compatibility in application, and the nature of the material acoustic properties. There are three basic techniques used in non-contact ultrasound; (1) direct transmission, (2) same-side pitch-catch of transmitter to receiver, and (3) pulse-echo of a single transducer.

The direct transmission technique in **Fig. 1** is useful for detection of defect, crack, debonding, delamination, etc. using transmittance and time-of-flight parameters. Other derived parameters such as velocity, thickness, and frequency can also produce a remarkable mapping of the material characterization. Creative transmission in oblique incidence and understanding refraction is opening up a wider variant of ultrasound applications and researches in material science. This technique is also not limiting to the use of shear wave as in the investigation of anisotropy properties and imaging of the material. The understanding of the signal signature and anatomy is essential to the interpretation of the data in the effort of calibration and correlation to the material structure, composition, and defects.

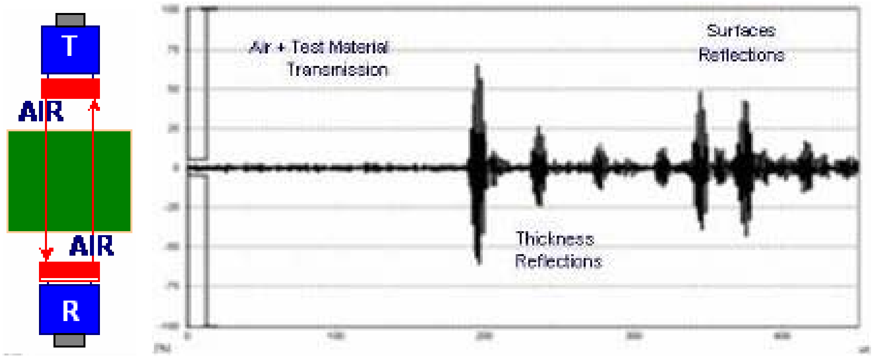

Fig. 1 Direct transmission schematic diagram and the typical A-scan showing various signals as a function of air and test material. Sample is 50 mm thick polystyrene.

When only one side is available for testing, two options of approaches are preferable; the pitch-catch (PC) as shown in **Fig. 2** and the pulse-echo (PE) in **Fig. 3**. The PC technique can easily detect the location of discontinuities, delamination, corrosion, and overt crack. PE at this time is useful in surface imaging, surface roughness profiling, surface acoustic analysis, reflectance,, object identification, etc.

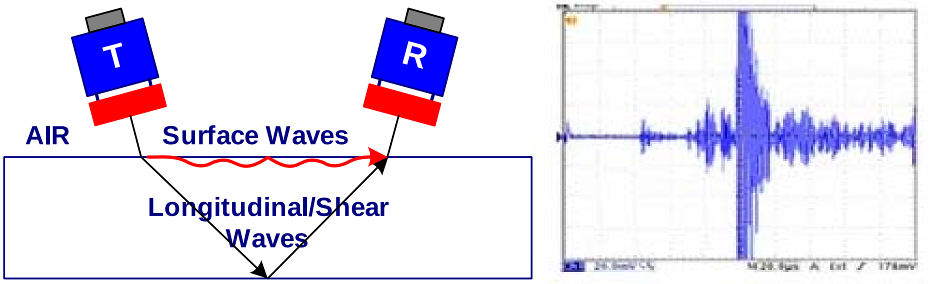

Fig. 2 Pitch-catch schematic diagram and typical A-scan showing the appearance of surface and bulk waves in a 50 mm thick section of polystyrene.

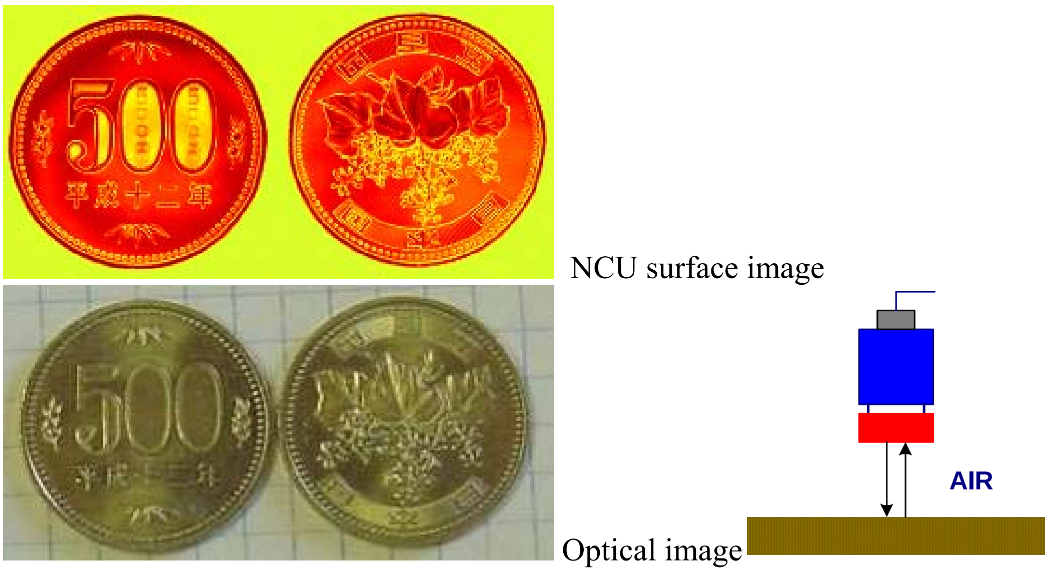

Fig. 3 Pulse-echo schematic diagram and surface images of a Japanese 500 Yen coin characterized by very fine features. Compare the NCU and optical images

To reap the full potentials of the high transduction and sensitivity of the transducers for these applications, this study utilized the Ultran's commercial iPass (**Fig. 4**) system. This system is capable of continuously rolling single or multi-channel, array linear scans, custom-designed with high speed online motion computer-controlled frameworks, or stationary benches. The digital data and C-scans obtained are post-processed for further correlations and analyses.

Fig. 4 The iPass^{TM} Non-Contact ultrasonic systems with a variety of single and multi-channel/array transducers for laboratory and online applications.

3.0 Material and Methodology

Samples of Carbon Fiber Re-enforced Plastic (CFRP) composites varying in porosity were obtained from the Boeing Company Phantom Works see **Table 1**) for non-contact ultrasound investigation. The samples were cured at 180 °C at variable pressure to create the estimated levels of porosity. The test was setup in through thickness transmission and conducted at ambient conditions using the Ultran iPass system (**Fig. 4**). The high transduction air-coupled transducers used were planar, nominal 500 kHz, and 12.5 mm active diameter. The transmitter was excited at 400 volts with a square wave pulse, and set at a gain of 70.2 dB. The transducers were spaced at about 65 mm air column. In addition, the 8-plies samples were also investigated using planar, nominal 1 MHz, 12.5 mm active diameter transducers, which were spaced at about 40 mm in air. The C-scanning of the samples of 70x70-mm area was done at ambient conditions. The NCU relative transmittance (mv) and the material velocity (m/s) values were digitally stored for post-processing, and images were obtained.

Table 1 CFRP samples for NCU analyses.

Number of plies	Porosity levels	Average thickness (mm)
8	0, 0.8, 2.3, 5.6%	1.86
16	0, 0.9, 2.6, 3.2%	3.64
24	0, 1.0, 2.1, 3.3%	5.47
32	0, 0.9, 1.7, 4.2%	7.39

4.0 Results and Discussions

4.1 Signal Response to Frequency

The tests were conducted for the two frequencies (0.5 MHz and 1.0 MHz) under the same active diameter and gain setting. The typical signals captured in the 8-plies samples of 0.0% are compared in **Fig. 5**. From the morphology of the transmitted signal, the frequency of 0.5 MHz produced a completely separated from any potential effects of thickness reverberation. For the 1.0 MHz, the thickness reflection was also quite separated that would result in a better resolution than using 0.5 MHz. For example, for at 1.0 MHz, the velocity of 2,414 m/s is measured as compared to 2,360 m/s at 0.5 MHz, with an insignificant 2.2% coefficient of variations (CV). Correspondingly at the same gain, the power of the transmitted signal in 1.0 MHz (285 mv) is lesser than in 0.5 MHz (819 mv), a significant difference of 5.5 dB. Understanding this phenomenon is crucial in determining the limits and appropriate measurements and hence, the calibration of the ultrasonic parameters to the material properties and structure.

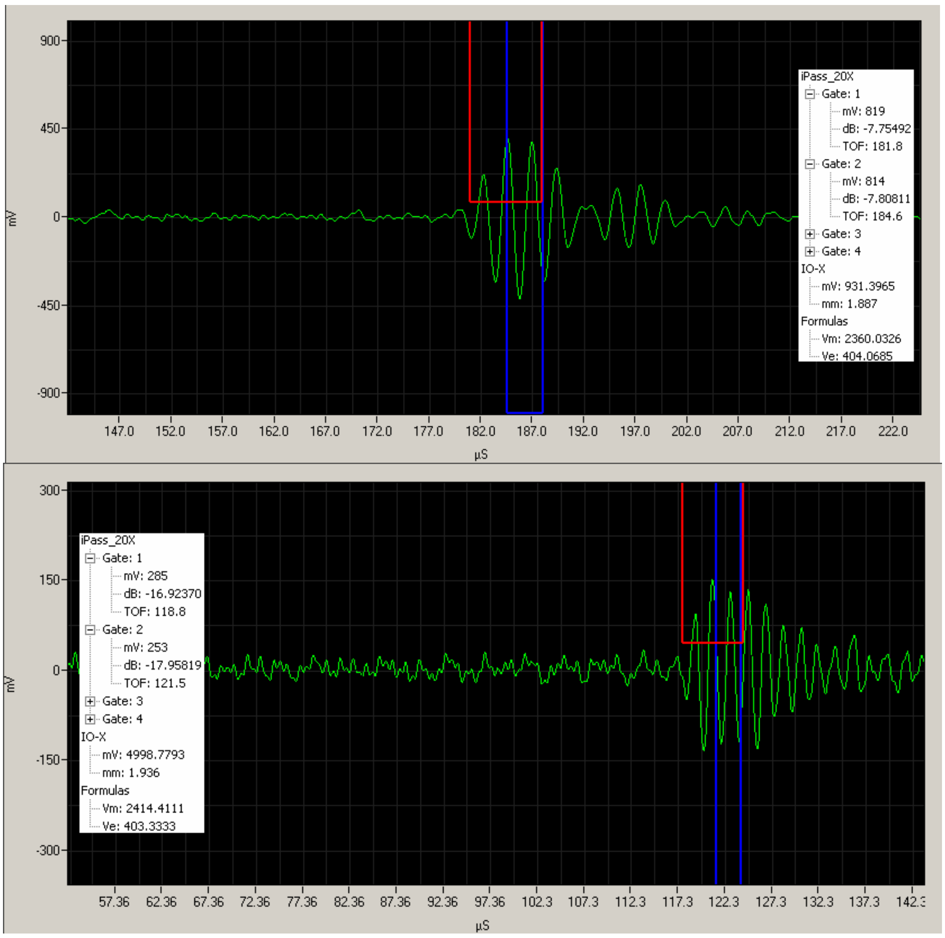

Fig. 5 Typical signal through the 8-plies 0% porosity CFRP sample: 0.5 MHz (top) and 1.0 MHz (bottom).

4.2 *Effect of Frequency to Porosity*

The data distribution for each of the relative transmittance and velocity measurements was collected in the central 70x70-mm area for the 8 plies 0.0% and 5.6% porosities samples. The respective relative transmittance images generated by 0.5 MHz are shown in **Fig. 6** and the respective velocity images in **Fig. 7**. For the 1.0 MHz, the respective relative transmittance images are shown in **Fig. 8** and the respective velocity images in **Fig. 9**. In general, both frequencies show a more consistency in the NCU parameters for the 0.0% porosity sample than the 5.6% porosity sample. When comparing the frequency responses, it is apparent that the image resolution improves with higher frequency. On this note, both of the features displayed by the transmittance and velocity are unique and complementary to the characteristic of the materials.

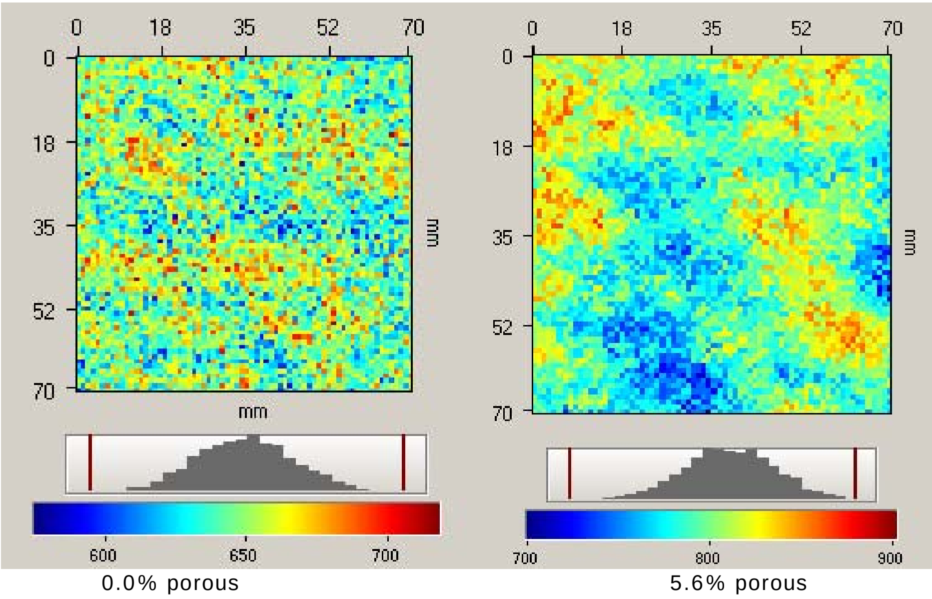

Fig. 6 Data 70x70-mm distribution of the 0.5 MHz NCU relative transmittance (mv) versus 0.0% (left) and 5.6% (right) porosities for the 8-plies CFRP sample.

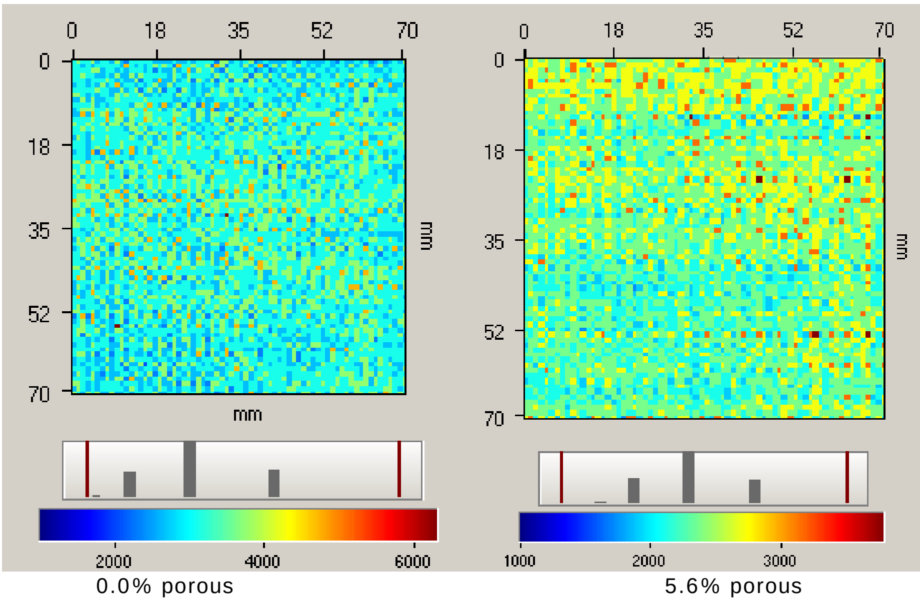

Fig. 7 Data 70x70-mm distribution of the 0.5 MHz NCU velocity (m/s) versus 0.0% (left) and 5.6% (right) porosities for the 8-plies CFRP sample.

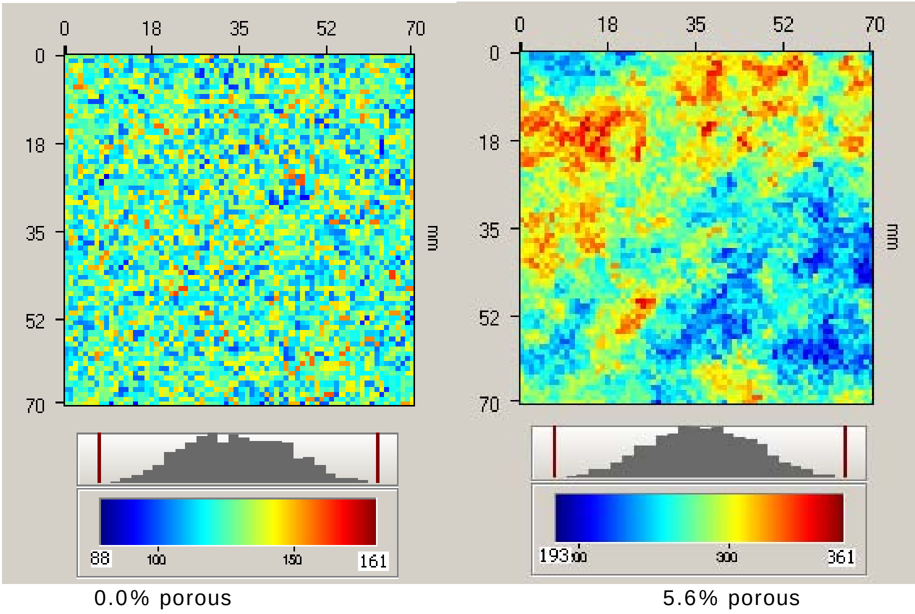

Fig. 8 Data 70x70-mm distribution of the 1.0 MHz NCU relative transmittance (mv) versus 0.0% (left) and 5.6% (right) porosities for the 8-plies CFRP sample.

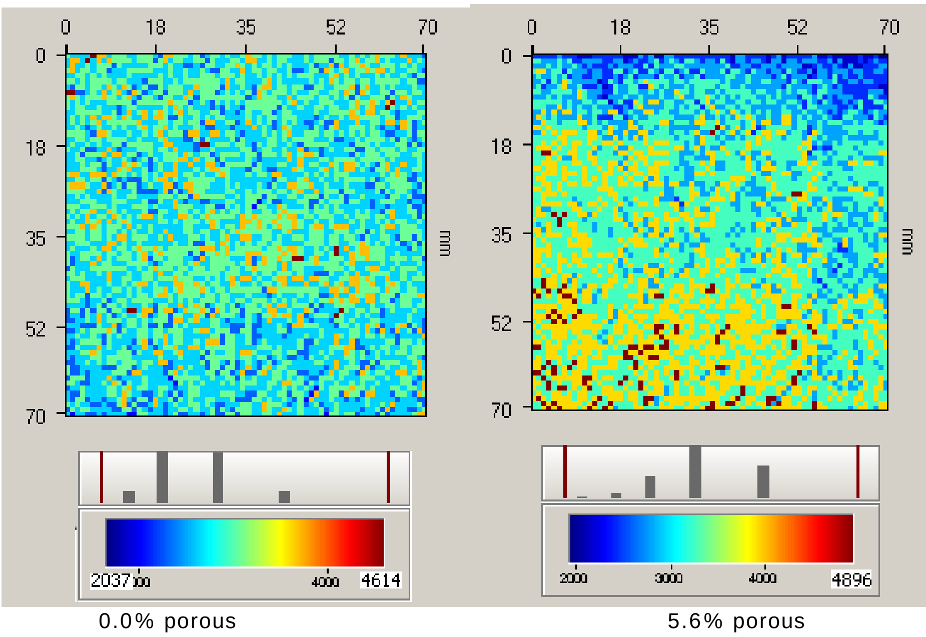

Fig. 9 Data 70x70-mm distribution of the 1.0 MHz NCU velocity (m/s) versus 0.0% (left) and 5.6% (right) porosities for the 8-plies CFRP sample.

Further analysis across the four levels of porosities was done and the relationship of the transmittance and velocity for the two frequencies are shown in **Fig. 10**. At the same gain setting, the transmittance and velocity parameters between the 0.5 MHz and 1.0 MHz are significantly different for all the four porosities. Particularly, the transmittance increases linearly with increasing porosity, whereas, the velocity decreases exponentially with the porosity levels. For both parameters, the standard deviation of the transmittance is increasing with porosity. For all porosity levels, the coefficient of variation for the transmittance is lower for 0.5 MHz (3.9%) than for 1.0 MHz (10.2%), whereas, the velocity is similar for 0.5 MHz (10.4%) and 1.0 MHz (12.0%). Within each frequency tested, the intensity of the transmittance and velocity correlates well to the nature of pore in the sample, indicating the test's feasibility is excellent.

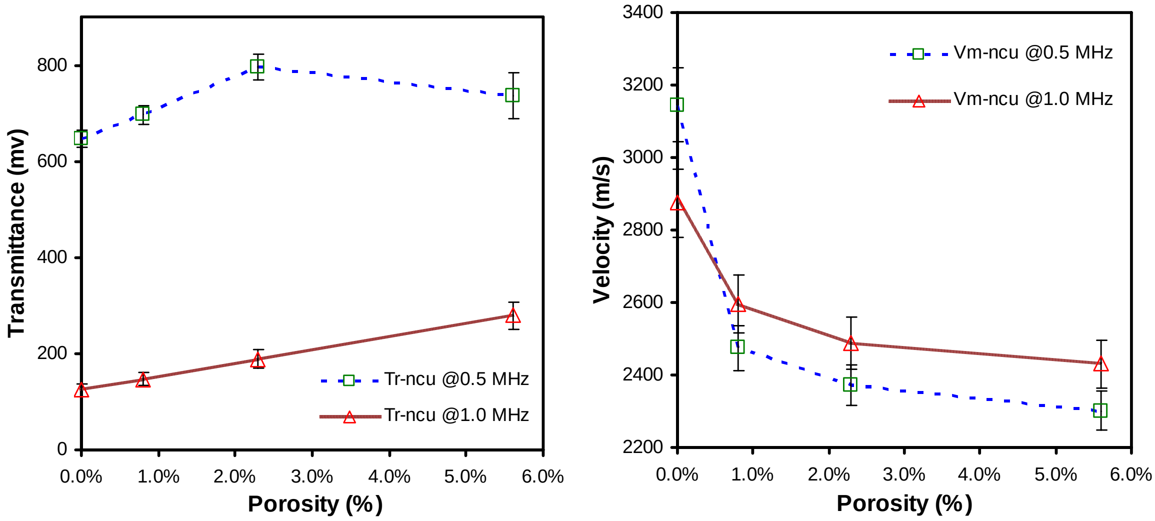

Fig. 10 Typical relationship of the NCU relative transmittance (left) and velocity (right) versus porosity for 0.50 MHz and 1.0 MHz nominal frequencies in the 1.9 mm 8-plies of CFRP samples.

4.3 Spatial Location of Pore

Spatial location of the pores can also be evaluated and located *in-situ* of the sample (corresponding to the image in **Fig. 11**). This feature obtained can be post-processed and/or be incorporated into the online quality control system. From the analysis of the Gaussian distribution of the transmittance values of the 5.6% porous, 8-plies sample, the average porosity for the 70x70-mm area is 5.8% ($p \leq 0.10$). The area indicated in blue includes transmittance values of less than 193 mv and greater than 230 mv.

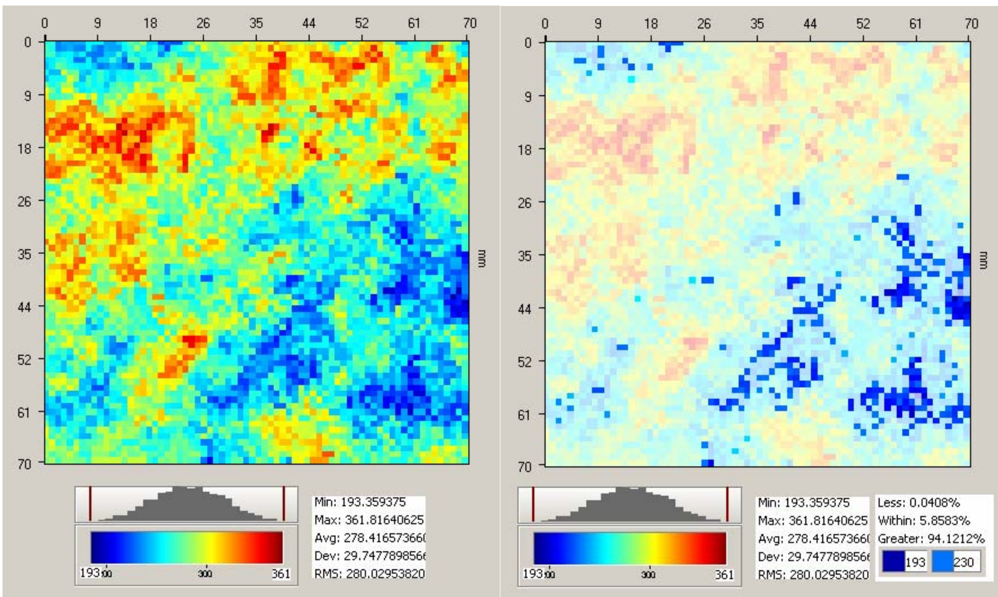

Fig. 11 Spatial distribution of the porous regions in blue (right) for the 5.6% porosity, 8-plies CFRP sample obtained by analysis of the Gaussian distribution of transmittance values, evaluated at 1.0 MHz. Using $p \leq 0.10$, the derived average porosity is 5.8% which includes the transmittance values of less than 193 mv and greater than 230 mv.

4.4 Correlation of Ultrasound to Number of Plies

The correlation analysis of the ultrasound parameters to the number of plies is based on the average of all four porosity levels at 0.5 MHz level. **Fig. 12** shows the distribution of the transmittance and velocity parameters across the number of plies in the samples. Both parameters increase with increasing number of plies. Also, both parameters correlate very well to the number of plies ($R^2 \geq 0.76$). The variability of velocity was found to be decreasing with the number of plies; from 10% CV at 8 plies dropped to 3.0% CV. However, the variability for the transmittance at 8 plies (6.3%) dropped and levelled off to about 3.8% for greater than 16 plies. The complimentary nature of these parameters is, therefore, important in calibration of a characteristic model.

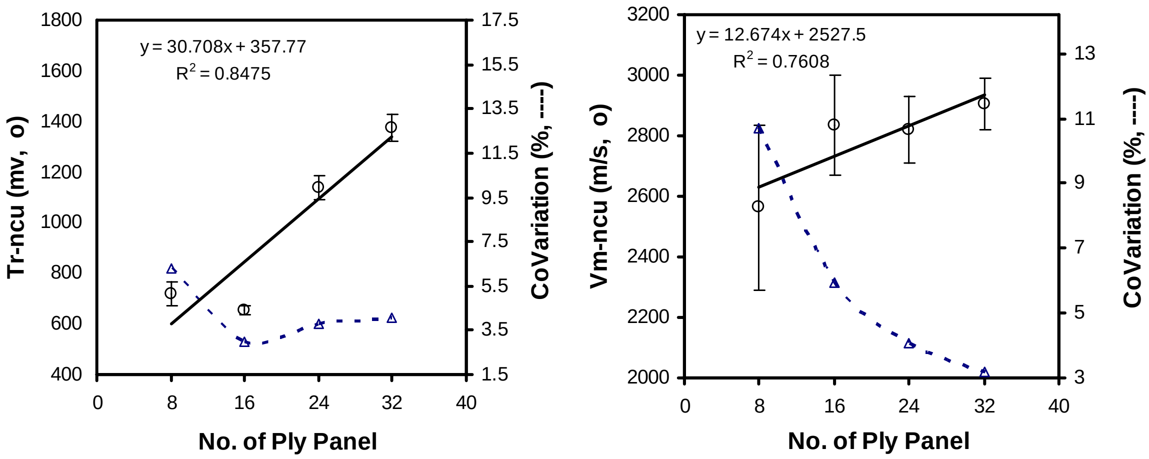

Fig. 12 Relationship of the transmittance and velocity versus number of plies samples.

5. Conclusion and Recommendations

The adverse effect of signal reverberation on the measurements has been identified and ruled out in this study. Both of the 0.5 MHz and 1.0 MHz cases had minimal or no reverberation due to thickness, in which case, the higher frequency gives higher resolution of measurements, but of weaker signal strength. Spatial distribution of the relative transmittance and velocity reflects more consistency in the 0% porosity sample as compared to that of the higher 5.6% porosity sample. The consistency trend is applicable to both frequencies. Particularly, the transmittance increases linearly with increasing porosity, whereas, the velocity decreases exponentially with the porosity levels. For each frequency, the intensity and the spatial location of the transmittance and velocity in the sample correlate well to the nature and locality of pore in the sample. The percent porosity derived from the NCU method matched to the determined porosity of the sample. This fact indicates that the study's feasibility is excellent to the porosity level and pore location as well.

Moreover, the ultrasonic parameters responses to the porosity levels are unique and positive correlation, and therefore, are complementary and a good fit to the characteristic of the materials in a calibration model. Further study is recommended (1) to ascertain acoustic attenuation in a controlled specimen with different level of thickness as a function of frequency; (2) to analyse the effect of stand-off distance and beam size on the results.

Acknowledgement

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