Preprint of a paper to appear in February 1999 issue of jour. Aircraft Engg. Aero. Tech, MCB Press, UK.

PHENOMENAL ADVANCEMENTS IN NON-CONTACT ULTRASONIC ANALYSIS

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Keywords: Ultrasound, Non-contact, NDE, Characterization, Composites, Ceramics

ABSTRACT

This paper provides an introduction to the much-desired non-contact mode of ultrasonic materials analysis. It is based upon the synthesis of phenomenally high transduction piezoelectric transducers (patent pending and in process) and the equally unconventional mechanism of transducer excitation and signal processing. The power of this development is realized by the fact that, not only can we propagate MHz frequencies into low acoustic impedance (Z) media such as polymers, composites, and consolidated materials, but we can also accomplish this in extremely high Z metals, ceramics, and multi-layered materials. Furthermore, the results obtained by our Non-Contact Ultrasound (NCU) are virtually comparable to the traditional ultrasonic contact method. We show specific observations to demonstrate this.

INTRODUCTION

Non-contact ultrasound for non-destructive evaluation of materials has been the dream of those who are involved with materials, whether advanced or not. To accomplish this, we must first overcome the Z mismatch of several orders of magnitude between the air/gas coupling and the test media. To do that we need transducers which are intrinsically characterized by extremely high electro-mechanical coupling plus a mechanism for equally high transduction in the gaseous coupling medium. With such transducers, we need a suitable mechanism of excitation and analysis of signals as a function of the test material characteristics. Finally, the combination of the two must provide easy-to-interpret information about the test material. This is the subject of our paper.

After creating the bread-board science and technology for Non-Contact Transducers (NCT) and the Non-Contact Analyzer--the NCA-1000--we anticipated the need for exhibiting their extraordinary characteristics and applications-oriented observations to the experts in this field. This is necessary not only because NCU represents a dramatic departure from traditional contact ultrasound, but also we must disqualify our own prior art relative to this subject. For more that 15 years we have been making air-coupling transducers (our catalogued air/gas propagation transducers) used for simple air-coupling and sensing applications. They have also been utilized for complex composites evaluation, when excited with extremely high energies.

We are also cognizant of other air-coupling transducers based upon piezoelectric and capacitance phenomena. We do not think it is prudent for us to compare our NCT with these transducers, or the NCA-1000 with commercial air-scan systems. However, in this paper we compare NCT with our old air/gas propagation transducers, which are believed to be as sensitive as others like them today. In this exercise our NCT are also compared with traditional contact immersion transducers. We also provide a one-to-one performance comparison of the NCA-1000 with a high energy ultrasonic system in non-contact mode. A brief description of NCT and NCA-1000 is given below. Note that the term "air-coupling transducers" denotes older piezoelectric transducers featuring polymer impedance matching layers; while the term "non-contact transducers" denotes the current piezoelectric transducers based upon 100% transmission into air/gas through a proprietary impedance matching system.

NON-CONTACT TRANSDUCERS

These are piezoelectric transducers characterized by extraordinarily high transduction in air and other gases. Depending upon the frequency, typically the NCT sensitivities range from <–30dB to >-60dB, Signal to Noise Ratio (SNR) >30dB, and bandwidths from 30 to >100% of the center frequencies. Transducers based upon this technology have been successfully produced and tested from 100kHz to 5MHz. Trials up to 10MHz and higher have also been successful, however, no specific applications for such high frequencies have so far been developed. Non-contact transducers are rugged in construction and capable of withstanding both laboratory and factory environments for indefinite operation. It may be useful to note that for over a year now these transducers in conjunction with the NCA-1000 have been successfully undergoing a field trial in the factory of a major materials manufacturer.

NON-CONTACT ANALYZER

The Non-Contact Analyzer--the NCA-1000 system--is based upon the synthesis of a computer-generated chirp with the best attributes of broadband NCT. Its dynamic range is >140dB and accuracy of time of flight (tof) measurement better than +/-1ns in closed conditions and +/- 20ns under ambient air environment. In transmission mode the distance between transmitting and receiving transducers can be varied from <5 wavelengths to >50 wavelengths in air. For example, by manipulating the chirp duration, 1MHz transducers can be operated from <1.7mm to >200mm distance in air. In order to minimize the effects of air turbulence while operating under ambient conditions, it is beneficial to keep the transducer-to-test-material-surface-distance as small as possible, i.e., between 5 to 10 wavelengths in air. When accuracy of measurements is not a main consideration, these distances can be as large as 20 to 50 wavelengths in air.

A typical setup of the NCA-1000 and transducers in transmission mode is shown in Fig. 1. It is important to note that no further controls are necessary after the NCA-1000 has been set for specific transducers separated by a defined distance in air. One simply needs to insert the test material between the transmitting and receiving transducers, and the system calculates and displays all the necessary information on the monitor screen. This data pertains to test material thickness, time-of-flight, velocity, frequency- and phase-dependent characteristics. The system also provides relationship of this information directly to the characteristics/properties of the test medium. In this sense, the NCA-1000 is truly an analyzer, not merely a flaw detector.

TRANSDUCER COMPARISON

We selected and evaluated by the transmission technique 1MHz-broadband, 19mm active area diameter transducers belonging to three categories—water immersion, conventional air-coupling, and current non-contact. In all cases the transmitting transducers were excited by a 16V single sine wave pulse and the output from the receiving transducers was directly fed into the oscilloscope input. For the immersion mode transducers, the transmitter and receiver were separated by 10mm water; for the air-coupling and non-contact mode transducers, they were separated by 10mm ambient air.

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TABLE-I shows time and frequency domain, sensitivity, and Signal to Noise Ratio (SNR) data for the three sets of transducers.

CONTACT IMMERSION AND NON-CONTACT MODES COMPARISON

Here we selected and tested in the transmission mode 2MHz-broadband, 12.7mm active area diameter transducers belonging to two categories—water immersion and current non-contact. A commercial short pulse –ve 100V spike pulser with a broadband receiver was used for water the immersion transducers, while the NCA 1000 was utilized for the non-contact mode transducers. Figures 2 and 3 show transmitted signals through a 4.7mm multi-layer graphite fiber plastic composite, respectively, for water immersion and non-contact modes of testing. From this comparison it is obvious that the sensitivity and resolution by non-contact ultrasound is virtually equivalent to the traditional immersion contact mode.

AIR-COUPLING AND NON-CONTACT MODES COMPARISON

For this purpose we selected 1MHz and 19mm active area diameter transducers belonging to two categories: old air-coupling and the current non-contact. The former transducers were used with a high power ultrasonic pulser-receiver that provides 400V +ve square wave into 4Ω output, 3 pulses per burst and all the available 64dB gain of the receiver. The non-contact transducers were connected to the NCA-1000, Fig. 1.

In order to make a performance comparison of the two systems, we purposely selected "very-difficult-to-examine" materials, and at "high NCU frequencies." These are: 25mm composite-laminated kevlar honey-comb @ 1MHz, figures 4 and 5; and rocket motor insulation on steel, also @ 1MHz, figures 6 and 7. These observations were generated by keeping the distance of the transducers to test materials surfaces at approximately 15mm from each side. The presentation of these observations is in a familiar time domain A-scan format.

From these observations it is obvious that the old style air-coupling transducers when used with high energy ultrasonic system, cannot produce discernible ultrasound signals corresponding to the materials examined. On the other hand, when we performed a similar experiment, but with a 9mm sheet of plastic, the older technology presented no problem of ultrasound propagation through it.

MATERIALS ANALYSIS WITH THE NCA-1000

Applications--such as defect detection, bond/disbond conditions, overt impact damage in composites and other materials--are relatively trivial issues to resolve with the NCA-1000 and non-contact transducers. It is extremely significant that with the new approach it is also possible to characterize fine inhomogeneities in materials, whether they are formed during material processing or during its service. Such conditions may pertain to subtle microstructural, compositional, or other like variations in test materials. Their analysis by our non-contact ultrasound is illustrated through the examination of varying density green powder compact cylinders (12.8mm diameter and 19mm long) produced from fine grain Al_2O_3. Figure 8 shows the relationship between density and non-contact ultrasonic velocity, and Fig. 9 shows relative attenuation of the same samples as a function of density. From this analysis it is obvious that two independent measurements of ultrasonic

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parameters (velocity and attenuation) exhibit the same trend of scatter in the data, confirming the authenticity of non-contact ultrasound.

A key question in this investigation is the significance of scatter, since the relationship between velocity and attenuation--Fig. 10--also exhibits the same phenomenon. Meanwhile, it is also important to note that upon examination of thinner disks of a large number of specimens produced from the same Al_2O_3 powder we did not observe such a scatter of data as seen with the samples reported here.

Upon close inspection we discovered that several specimens had developed internal micro-cracks and fine delaminations, thus off-setting the relationships between velocity, density, and attenuation. In green powder compacts--particularly those that are joined together without binders (such as in the present case)--it is not unusual to find micro-cracking or delaminations once the pressure is released. From the standpoint of the significance of the characterized data, it is important that such conditions (depending upon the severity of damage) may not necessarily alter the velocity/density significantly, but they are certainly more sensitive to transmissivity or attenuation of ultrasound through the material.

CONCLUSIONS AND FUTURE WORK

The significance of non-contact ultrasound is obvious. In this paper we also demonstrate its reality; it is no longer a dream for quality and process control personnel and materials scientists and engineers. We have provided several comparative and analytical observations for turn-key applications of this new advancement. However, it needs to be further developed for nondestructive characterization of materials. These endeavors, including synthetic aperture based reflection and transmission imaging, will continue in our laboratory.

RELATED REFERENCES OF OUR WORK

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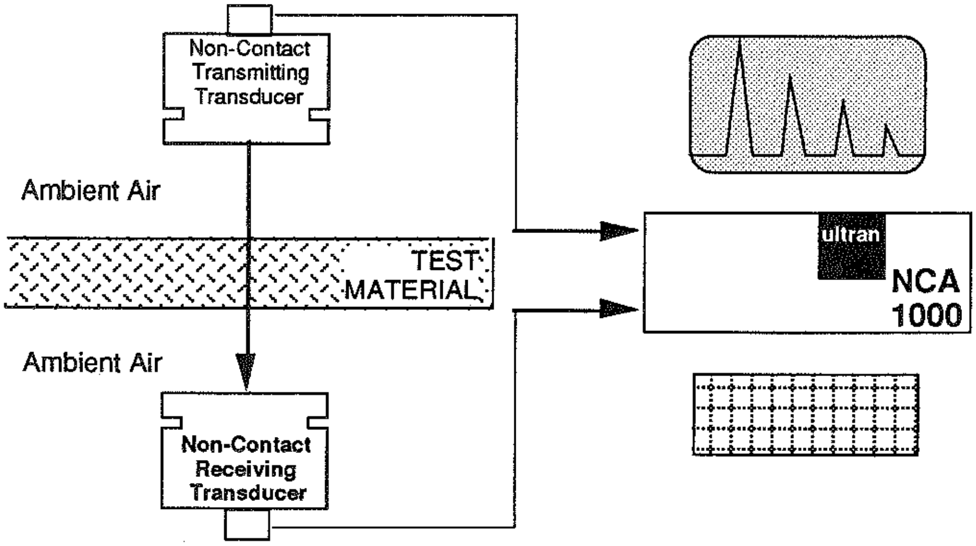

Fig. 1. A typical setup of NCA-1000 in non-contact transmission mode.

TABLE-I. Salient characteristics of 1MHz, 19mm active area diameter water immersion, air-coupling, and non-contact transducers.

TRANSDUCER TYPE	PEAK FREQUENCY (MHz)	BANDWIDTH (MHz), %	SNR (dB)	SENSITIVITY (dB)	SENSITIVITY Rel. Water (dB)
Water Immersion	0.89	0.6, 65%	40	-32	---
Conventional Air-scan	0.93	0.3, 32%	<20	-67	Below 35dB
Current Non-Contact	**0.89**	**0.6, 65%**	**36**	**-50**	**Below 18dB**

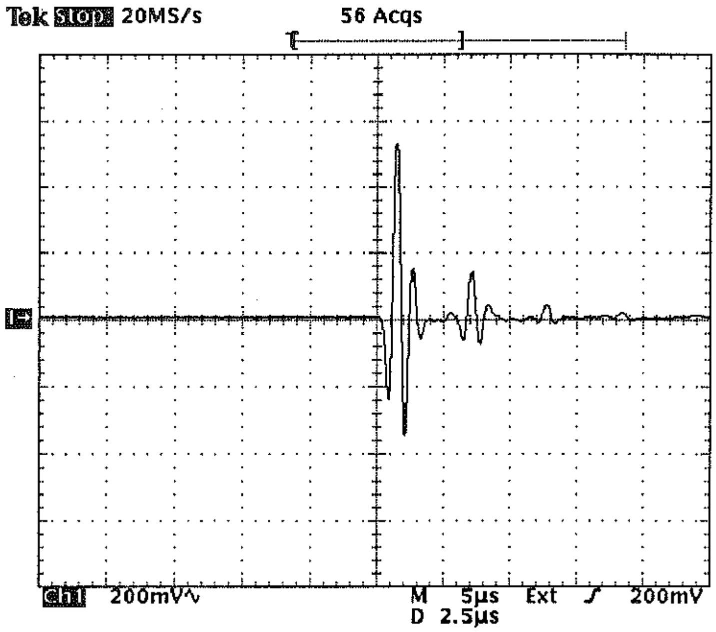

Fig. 2. Transmitted signal through 4.7mm thick multi-layer graphite fiber re-inforced plastic composite generated by water immersion technique @ 2MHz with a commercial short pulse ultrasonic pulser-receiver. First peak is directly transmitted through the material, while the rest smaller peaks correspond to reflections from the material thickness. Compare with Fig. 3.

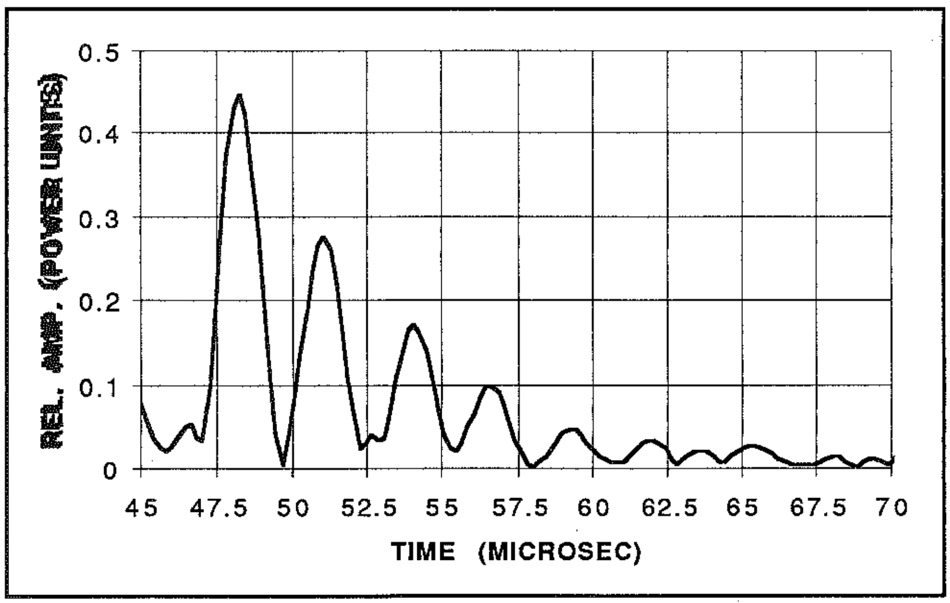

Fig. 3. Same as Fig. 2, except with non-contact technique in ambient air @ 2MHz and NCA-1000. Compare with Fig. 2.

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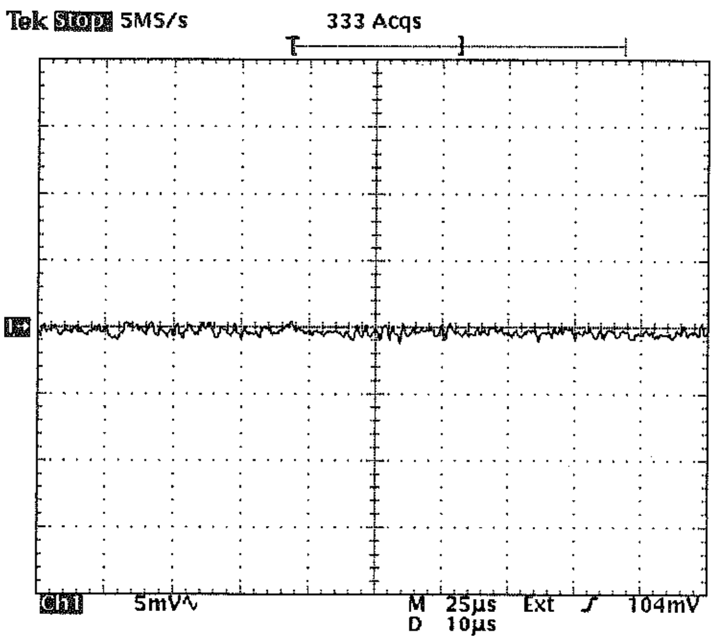

Fig. 4. Transmission signal through 25mm composite-laminated kevlar honeycomb generated by a high power pulser-receiver with air-coupling 1MHz transducers. Compare with Fig. 5.

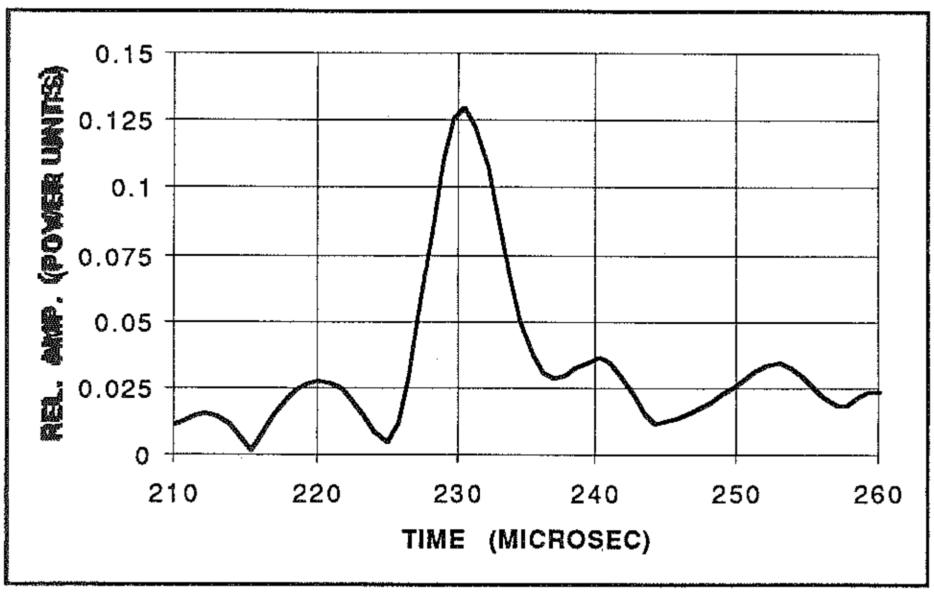

Fig. 5. Same as Fig. 4, except data obtained by NCA-1000 and 1MHz non-contact transducers.

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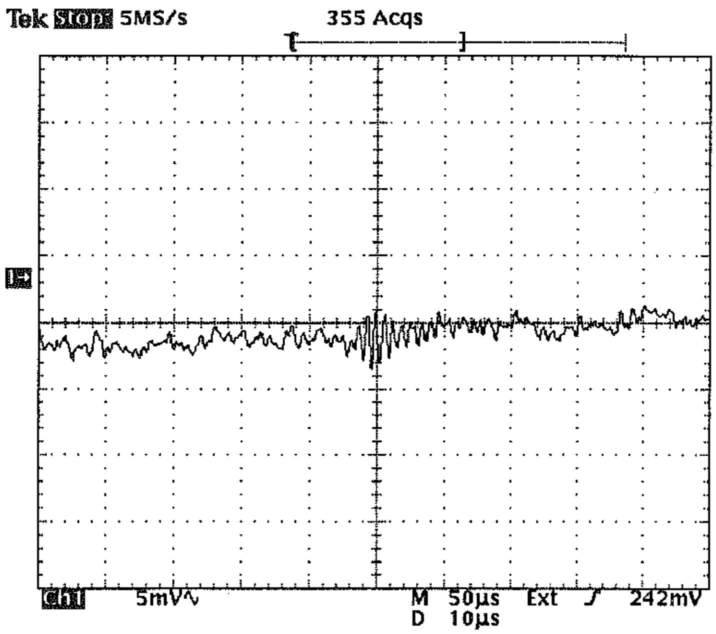

Fig. 6. Transmission signal through 3mm rocket motor insulation bonded to 12mm steel generated by a high power pulser-receiver with air-coupling 1MHz transducers. Compare with Fig. 7.

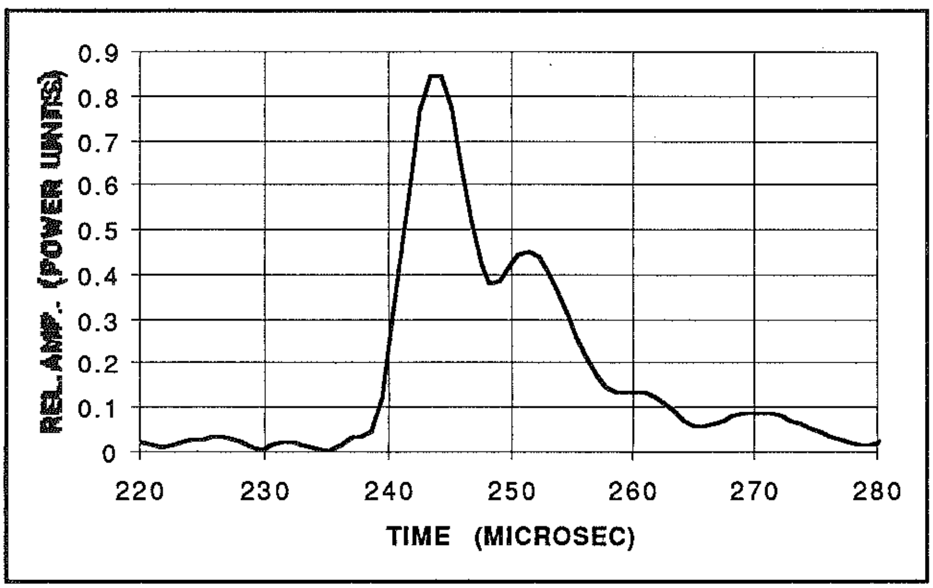

Fig. 7. Same as Fig. 6, except data produced by NCA-1000 and 1MHz non-contact transducers.

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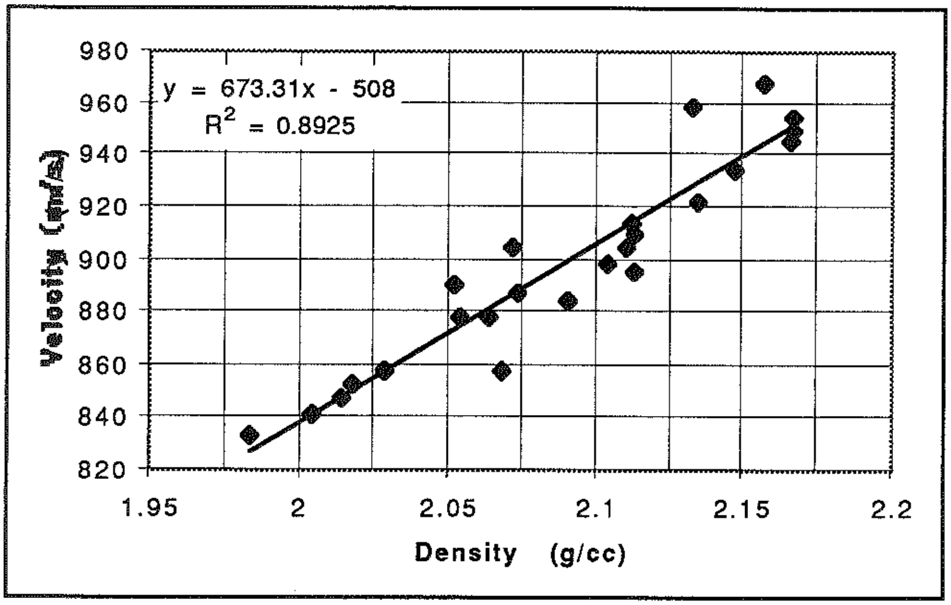

Fig. 8. Velocity-density relationship for green Al_2O_3 cylinders. Compare with Fig. 9.

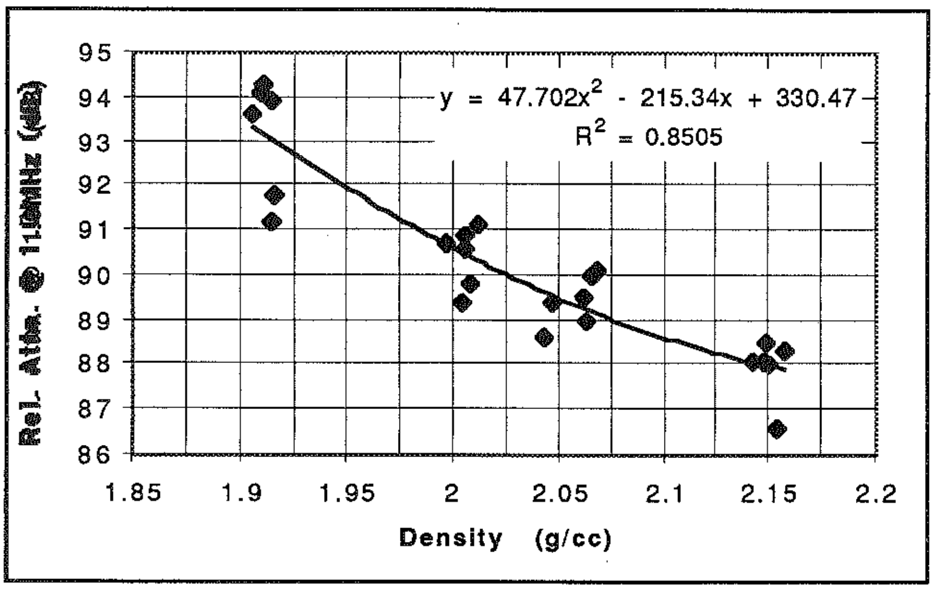

Fig. 9. Density-attenuation relationship for green Al_2O_3 cylinders. Compare with Fig. 8.

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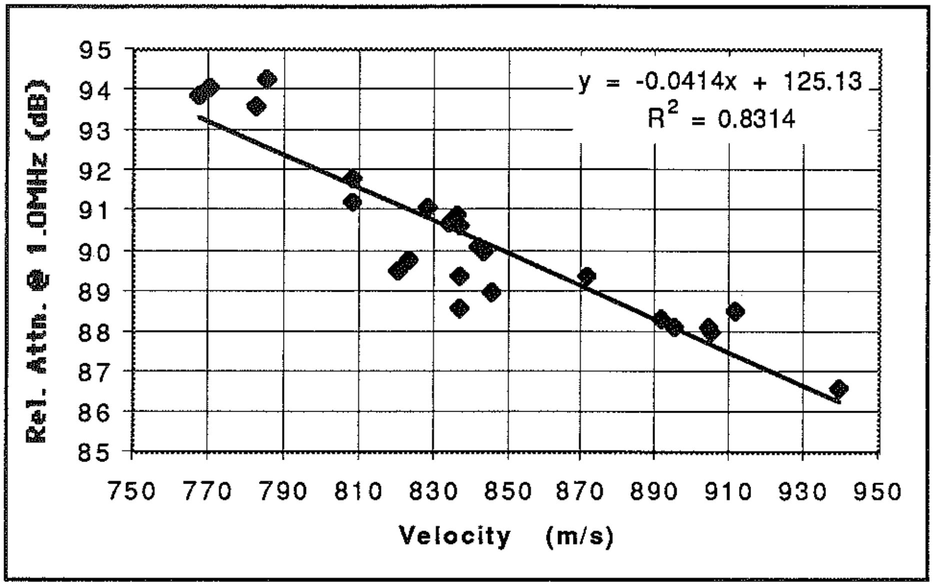

Fig. 10. Relationship between ultrasonic velocity and attenuation for green Al_2O_3 cylinders.

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