EXPERIMENTAL VERIFICATION OF ELASTIC WAVE GENERATION BY TIME-GATED MICROWAVES

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INTRODUCTION

The non-destructive evaluation and testing (NDE and NDT) of materials commonly involve the use of ultrasonic waves.[1] The standard techniques utilize an immersion medium (usually water) or a coupling agent between the material and the piezoelectric transducer.

For over two decades, techniques that do not need any contact or coupling medium have been developed. The non-contact techniques to generate ultrasound are based on the electromagnetic acoustic transducer (EMAT), air-coupled transducers or laser impact. [1]

Microwaves are frequently used in the non-destructive investigation of materials, like X-rays, to produce images of the transmitted intensity. [1] Although the production of ultrasound from laser impact was intensely studied experimentally and theoretically, the microwave impact was not well mentioned in the NDE community. Although R.M.White [2] presented the theoretical background in 1963, the production of elastic waves from modulated microwave energy was essentially noticed for their physiologist effects. Human subjects hear a "click" when the head is irradiated with high-energy microwave pulse. These effects were investigated by the microwave community. [3-4]

In 1984 R.L.Nasoni et al.[5] presented some preliminary results on the generation of ultrasound from electromagnetic waves through immersed interfaces. To the authors' knowledge, there have been no other attempts to use microwaves as a tool to generate ultrasound without contact. The purpose of this paper is to show the conditions for which microwaves can produce ultrasound at air-liquid, air-solid, solid-air interfaces, and to describe initial experimental investigations that will help to build the theoretical model of microwave-elastic wave interaction.

GENERATION AT AIR/WATER INTERFACE

The electromagnetic wave is produced by a magnetron in the frequency range of 5.4-5.9 GHz (C Band) with a peak power of 1 MW. A pulse of 0.56 μs is applied to the cathode of the magnetron. The bandwidth upper limit of this pulse is limited to around 1 MHz. The repetition rate, 585 Hz, is fast enough to permit fast averaging if necessary. The wave is delivered by a standard wave guide R48 (of cross-section = 22,15 x 47,55 mm) that imposes the propagation mode (TE10) [Figure 1]. At these frequencies, the microwave wavelength is around 52 mm in vacuum and 62 mm in the wave-guide. In order to use the lowest power as possible and to prove that compact sources could be designed in the future, a coupler was used to divide the power by ten. The amplitude of the pulse sent to the magnetron was adjusted to furnish a power at the end of the wave-guide varying from 0 to 100 kW. Another coupler diverted a small part of this energy to a milliwattmeter (HP 436A) in order to measure the microwave power delivered at the end of the wave-guide.

Figure 1 presents the apparatus used to observe the generation of ultrasonic waves in water. An immersion transducer at a central frequency of 1 MHz (PANAMETRICS V302) receives ultrasonic waves. The distance between the end of the microwave guide and the water surface is d2 (20 mm). The distance d1 (33-mm) is easily determined using the ultrasonic transducer in pulse-echo mode and measuring the times-of-flight between echoes reflected by the water surface. The time-of-flight between the two first echoes is 44.35 μs (velocity in water 1.49 mm/μs @ 22°C).

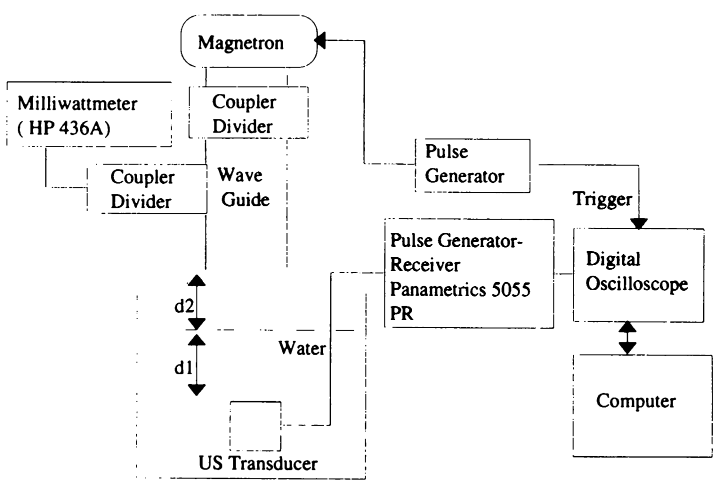

Figure 1. Experimental arrangement to generate ultrasonic wave in water.

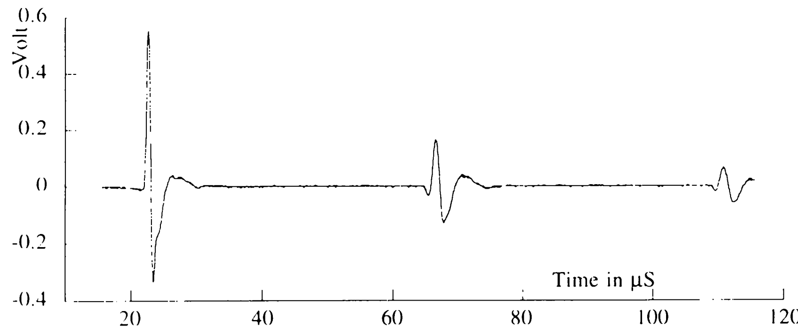

Figure 2. Ultrasonic waves generated by microwave at the air/water interface.

Figure 2 presents the time history of the ultrasonic wave generated by the microwave at the interface air/water. The first transmission through the water layer is shown with two successive echoes. The time-of-flight is 44.19 µs and 44.22 µs respectively between the first two echoes and the two subsequent ones. The time is measured with the cross-correlation function between echoes. The difference between the time measurement gives the order of the experimental errors that are mainly due to the slight shape difference of the echoes (Fig. 2). This observation proves that there is a transfer of energy between the time-gated microwave and ultrasonic waves near the air-liquid interface.

It is noticeable to consider time-of-flight as a function of source power. This time should be around 22.1 µs according to the previous measurement. This can not be known absolutely because there is an uncertainty between the trigger position and the beginning of the magnetron oscillation. However, the waveforms at various amounts of power can be compared. As shown in Figure 3, the times-of-flight decrease as the power increases. If a source region between microwave and elastic wave is considered near the surface, one can assume that the source region depth is increasing with power and the propagation distance of the ultrasonic wave is decreased. This depth can be estimated to around 370 µm (0.25 µs in water) for 50 kW and is about 100 times smaller than the electromagnetic wavelength.

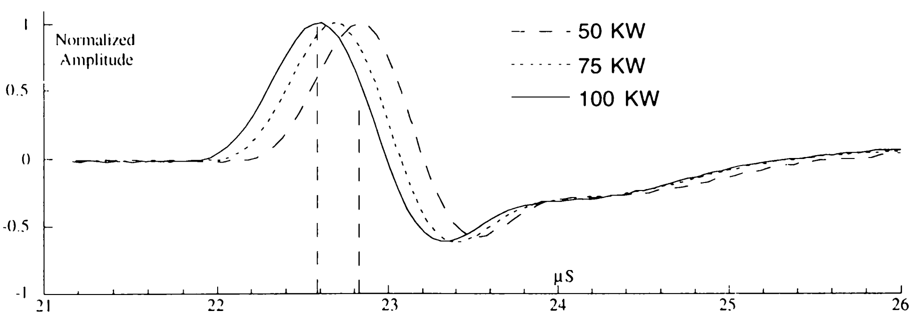

Figure 3. First echoes generated by the electromagnetic wave for various values of the electromagnetic power.

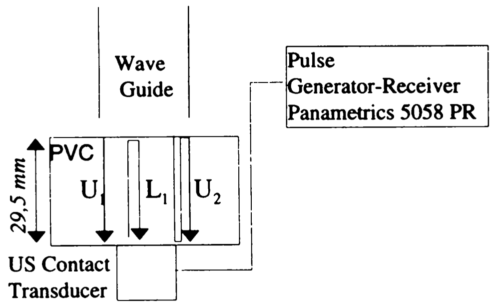

Figure 4 Experimental set-up to generate and receive ultrasonic wave in solid.

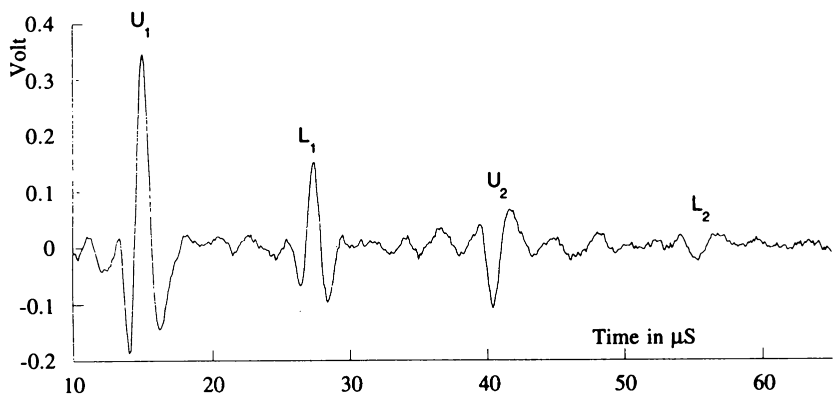

Figure 5 Ultrasonic waves generated by microwave source at air/solid and solid/air interfaces. (Electromagnetic power 100 kW)

GENERATION AT INTERFACES AIR-SOLID AND SOLID-AIR.

Weakly Absorbing Materials.

The experimental set-up [Figure 1] is slightly modified to investigate ultrasonic wave generation in a solid. A contact transducer (Panametrics 101; Central frequency 0.5 MHz) is connected to the solid through a coupling medium [Figure 4]. The receiver is replaced by a more powerful amplifier (Panametrics 5058 PR; Gain: 60 dB), since the ultrasonic wave amplitudes in the solid were much smaller than in water.

Using the pulse-echo technique, the time-of-flight for a round trip in a block of PVC was found equal to 25.6 µs. This value corresponds to a thickness of 29.5 mm with a longitudinal wave velocity of 2.3 mm/µs. Figure 5 presents the ultrasonic echoes generated by the microwave source at a power of 100 kW. Although the noise in this waveform could be easily suppressed by averaging, it is presented in this way to estimate the signal to noise ratio.

The time-of-flight of the first echo U_1 is about 12 µs. This measurement is not accurate since the beginning of the echo is not well defined, nevertheless it proves that the source is located near the upper surface of the plate. The measurement of the delay between echoes U_1 and U_2 is more accurate since it is possible to isolate each echo with a temporal window and to measure the delay by a standard cross-correlation procedure. The result, 25.6 µs, is identical to the measure made with the pulse-echo technique.

Another echo L_1 appears between U_1 and U_2. The arrival time of this echo, approximately 25 µs, corresponds to a round trip inside the plate. That means there is an important source of ultrasonic waves located near the lower surface. The delay (12.5 µs) between the echoes U_1 and L_1 is slightly less than the time-of-flight for 1 trip inside the plate. Therefore the sources at upper and lower surfaces are located in a volume with a small thickness. The accurate measurement of the source region depth must be performed with a more precise set-up since its value seems much smaller than in the case of water.

Reflecting Materials.

As for optical waves, metals are almost pure reflectors for electromagnetic waves. To observe the generation of ultrasonic waves in metal, the PVC plate was replaced by a 49.3 mm thick plate made of aluminum. The corresponding waveform is not shown here because the ultrasonic echoes were corrupted by in the ambient electromagnetic noise, but with a better set-up one can imagine producing ultrasonic waves in metals from electromagnetic waves. To enhance the production of ultrasound, a 2-mm thick water layer was poured on the surface. The waveform is presented in Figure 6. The ultrasound amplitude was so important that the gain of the receiver was set to 0 dB. The first arrival time (≈8.2 µs) in the first echo is only slightly larger than one trip in the aluminum plate (≈7.8 µs). There is generation of ultrasound everywhere in the water layer and almost at the water/aluminum interface.

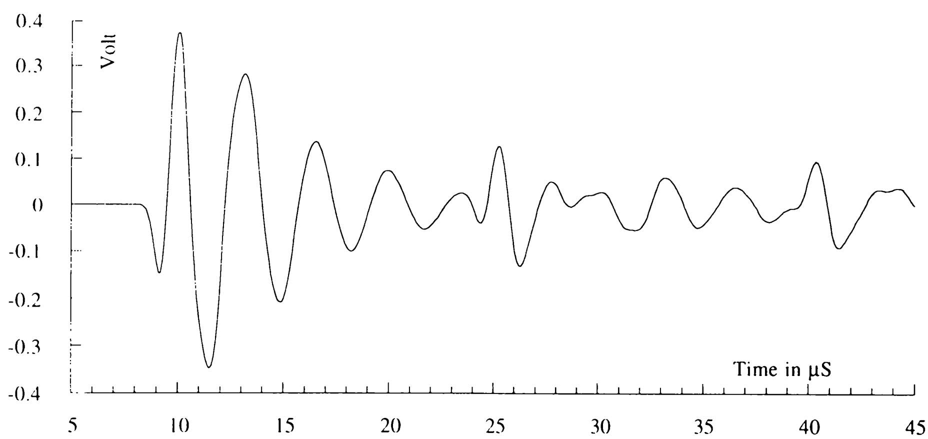

Figure 6 Ultrasonic wave generated at the water/aluminum surface. (Electromagnetic power 100 kW)

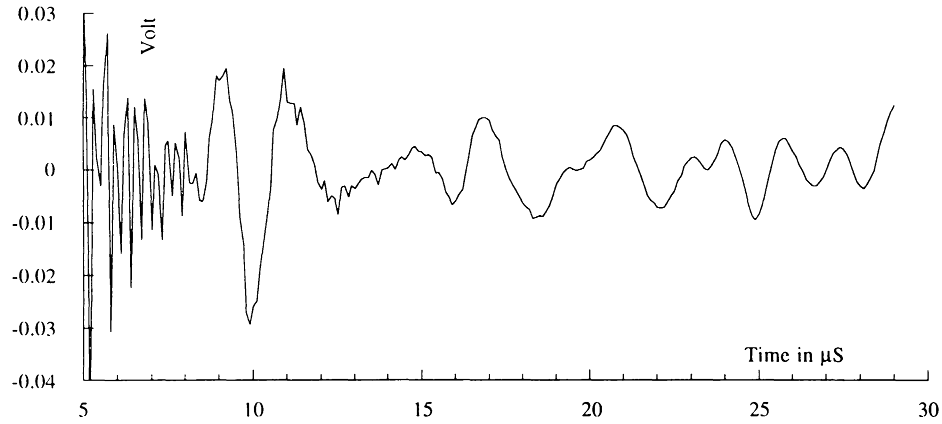

Figure 7. Ultrasonic wave generated at the paint/aluminum surface. (Electromagnetic power 100 kW)

In order to explore the possible application to the in situ non-destructive evaluation of metallic materials, a very thin layer of paint was sprayed on the aluminum surface. The gain of the receiver was again increased to 60 dB. The waveform in Figure 7 shows the noise due to the electromagnetic pulse and a first echo arriving at around 8 µs. This result is promising for NDE applications since structures are often painted.

MODEL

To build a model for the interaction between electromagnetic waves and elastic waves more precise experiments and investigations are necessary. However the following experimental considerations will be useful to develop a model:

- The evolution of the electromagnetic wave power creates elastic waves in a frequency domain imposed by the gate width.

- The transduction is linear and occurs in a zone near the interface.

- The source region depth depends on the material properties and the power of the electromagnetic wave. The higher the power or the higher the absorption of the electromagnetic wave, the deeper the source region. Its depth is much smaller than the penetration depth of the microwave inside the material, since the microwave wavelength is much larger than the source region.

Laser impacts also create elastic waves via several mechanisms: radiation pressure, electrostriction, Brillouin scattering, and thermoelastic expansion. The latter is dominant under normal circumstances. These mechanisms and their applications are completely described in literature and textbooks. [6,7] In addition, the presence of a "precursor" was observed in laser generation and explained with one or two dimensional models, [2,8,9] taking into account the presence of a source buried below the surface. The "precursor" appearance is equivalent to what is observed from the evolution of times-of-flight [Figure 3]. Since the electromagnetic source is large in comparison with the ultrasonic wavelength, it is conceivable that the one-dimensional model would be appropriate. [2,8,9]

As explained in reference 9, a non-focused laser source in the thermoelastic regime generates two waves located at both faces of the plate. A similar analysis would be appropriate for a microwave source. The stress σ induced by a temperature rise ΔT is given by:

$$\sigma(x,t) = C\frac{\partial u(x,t)}{\partial x} - \lambda\Delta T \qquad (1)$$

where u is the normal displacement in the ultrasonic field, C is the diagonal component of the rigidity tensor in the x direction normal to the interface, and λ is the thermal stress coefficient. The interfaces at $x = 0$ and $x = L$ are stress free, then $\sigma(0,t) = 0$ and $\sigma(L,t) = 0$. Equation 1 implies there is a displacement gradient at $x = 0$ and $x = L$. Therefore, two waves are produced at both interfaces if the material does not absorb too much of the electromagnetic energy. If the absorption is negligible, the spatial dependence of ΔT is weak, and the second term on the right hand side in the wave equation

$$\rho\frac{\partial^2 u(x,t)}{\partial t^2} = C\frac{\partial^2 u(x,t)}{\partial x^2} - \lambda\frac{\partial \Delta T}{\partial x} \qquad (2)$$

can be neglected and the waves are produced near the interfaces. If the absorption increases, this term is responsible for the buried sources of ultrasounds and the depth of the generation zone increases.

This model seems even more appropriate for the microwaves than for the optical waves since their wavelengths are much larger. For instance, in this paper the microwave wavelength is larger than the thickness of the tested materials. Comparison between theory and experiment will be presented in a later paper.

CONCLUSIONS

This paper presents the experimental observation of the transformation of energy between electromagnetic waves and elastic waves through the surface of liquid or solid materials.

The results lead to a one-dimension thermoelastic model. More experiments must be conducted to link the electromagnetic and elastic material properties to the elastic waves characteristics. These experimental observations will permit us to model the energy transformation in order to estimate the penetration depth, to predict the response of any material and to consider the applications to the non-destructive evaluation of materials.

Ultrasonic waves can be generated at interface air-solid and also solid-air. If the electromagnetic attenuation is not too significant, the electromagnetic wave can generate ultrasound inside the materials in a zone located near a cavity or a delamination. Clearly, some important applications to the non-destructive testing of material can be accomplished.

There is a very large spectrum of applications since the gate width and shape of the microwave can be controlled to produce lower frequency content. In the other way, ultrasonic waves with very high frequency content can be produced with shorter pulses and even a monocycle pulse source.[10]

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