PULSED LASERS FOR QUANTITATIVE ULTRASONIC NDE

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INTRODUCTION

There has been a lot of recent interest in the use of pulsed lasers for the generation of ultrasound in a range of media [1], due to advantages inherent in the generation process. These include the non-contact nature of the method, and the generation of a wide bandwidth over a small source area. The size and shape of the source can also be changed using suitable optics, as can the generation mechanism itself.

Generation Mechanisms

In general, there are three types of source characteristics that are available. The first uses optical power densities that are below that required for melting of the irradiated solid surface. This results in a transient heating of the substrate, leading to rapid thermal expansion and the radiation of elastic waves. This is the so-called thermooelastic effect and the resulting waveforms and characteristics have been studied widely [e.g. 2,3]. The second type of generation mechanism can be created by removal of material from the surface of the sample. This can be by evaporation of a coating, applied to the surface prior to irradiation, or the ablation of the material itself [4]. In either case, the effect is to create a force due to material departing from the surface. This force tends to be pulse-like, unlike the thermooelastic case where the incoming laser energy is integrated to become a step. Where an applied coating is absent, a mixture of these two mechanisms can lead to a range of waveforms and source characteristics, as the power density at the surface is varied. This is due primarily to the formation of a plasma close to the surface of e.g. a metal, which prolongs ablation at higher power densities.

A third mechanism has recently been identified, which uses the effect of plasma formation close to a surface, but not intimately connected to it as in the case of a metal above. This occurs when there is a relatively high optical reflectivity, such as is present with far infra-red laser radiation (e.g. a CO₂ laser). Here, the reflected energy and incidence pulse can combine to
Types of Detectors

It is evident from the above that a pulsed laser can be a flexible method for the NDE of many materials. However, for it to be a truly useful method, it needs to be combined with a detection system that is itself non-contact and which has a wide bandwidth. The most popular recent choice for detection has been interferometry. This is also an optically-based approach, and leads to good detection sensitivity at a wide range of surfaces. The types of interferometers available have been reviewed by Monchalin [6], and there are now several devices available commercially. Recent advances in both heterodyne and Fabry-Perot designs now give good detection sensitivity, and with a pulsed laser source can lead to an NDE system that is capable of inspecting industrial materials [7]. Interferometry has several limitations - it tends to be expensive, and requires a certain reflectivity at the detection surface. Despite these limitations, it remains an excellent method for detecting wide bandwidth signals generated by the pulsed laser. Other optical methods are also receiving attention, one of them being beam deflection [8]. This is under active investigation in several laboratories for the NDE of materials where conventional interferometry is not viable. This is because it does not require as high a reflectivity at the detection surface as conventional interferometry.
Figure 2. Schematic diagram of apparatus.

To try and remove the problems associated with optical reflectivity, there have been recent experiments that have attempted to use other devices for detection based on piezoelectric devices. These have been specially modified, so as to enhance their reception characteristics when operating in air. There are two basic designs. The first includes those that use conventional piezoelectric ceramic materials, either unmodified [9] or as a 1-3 connectivity composite [10]. In the latter case, waves generated in a range of materials were detected in through-transmission studies. Another design is based on a flexible metallized membrane. Both approaches show promise for NDE applications, especially for the inspection of low reflectivity composites.

In the paper that follows, a series of experiments will be described which use an electromagnetic acoustic transducer (EMAT) as a detector. These devices have been described in several reviews, and the reader is referred to [11] for details.

Radiated Waves

The pulsed laser source has one single characteristic that is not commonly observed in many transduction systems – it can generate a range of wave modes simultaneously. Take, for instance, the irradiation of a thick metallic specimen by a pulsed laser. The result will be the efficient radiation of longitudinal, and shear waves that travel through the bulk of the material, and Rayleigh (surface) waves that propagate along the top surface. In thin materials, the pulsed laser is an excellent method for the generation of guided modes such as Lamb waves. As examples, Fig. 1 shows waveforms generated by a Q-switched laser with a 30 ns pulse length, detected by a Michelson interferometer. It can be seen that longitudinal and shear modes can be generated and detected in aluminium with none of the resonance effects associated with conventional piezoelectric devices.
The rest of this paper will be devoted to the use of EMAT detectors for the NDE of various metallic materials, chiefly aluminium. It will be shown that the combination of a pulsed laser source and an EMAT detector can lead to a range of interesting testing configurations. The processing of signals required for the extraction of useful data will also be described.

![Figure 3. Recorded waveforms, (a) as received and (b) filtered.](image)

**EXPERIMENTAL ARRANGEMENT**

A schematic diagram of the apparatus used in the experiments to be described is shown in Figure 2. The generating laser source was a Q-switched ruby laser, operating at an optical wavelength of 693.4 nm in the red, with a pulse duration of about 30 ns and a maximum energy of 1.5 Joules. The beam of the ruby laser was directed normally onto the surface of the sample using two dielectric mirrors. It was apertured, and focused with a lens through the center of an annular EMAT detector, so that the laser source and EMAT detector were concentric.

The EMAT detector constructed for this set of experiments was an annular EMAT, consisting of an annular spiral pancake coil and a hollow cylindrical CoSm rare earth permanent magnet. The inner and outer diameters of the magnet were 10.9 mm and 19.1 mm, respectively, with the magnetic field lines perpendicular to its flat face. The coil was wire-wound, fabricated by hand, and had the same radial dimensions as those of the permanent magnet.
Figure 4. Experiments in a sample (above), showing received waveforms as a function of position (below).

The above configuration is a type of pulse-echo arrangement, although as we will show later, there are some complications introduced by using a relatively wide annular EMAT. A typical waveform recorded in a 25mm thick aluminium sample is shown in Figure 3(a). The longitudinal (L) and shear (S) modes are visible, together with a mode-converted signal (L-S). Note also a large initial signal (R). This is the Rayleigh wave, generated by the pulsed laser source and passing beneath the EMAT detector. It is a low frequency signal, and it can thus be filtered out, using a band-pass filter over 1-3 MHz, leading to a signal (Figure 3(b)) with more visible bulk arrivals. Note that the transduction system could be used for Rayleigh wave experiments, and Lamb wave studies in thin materials; some of these are reported later.

ULTRASONIC IMAGING

The geometry of the system shown schematically in Figure 2 is similar to that used in conventional pulse-echo testing, and hence imaging is possible. The aim of the first set of measurements was to undertake trial experiments on artificial defects, to determine the properties of the transduction system in such applications.
The image reconstruction technique used to process data will depend upon the method of scanning used. In the present case, the Synthetic Aperture Focusing Technique (SAFT) was chosen. A sample of aluminum plate containing artificial defects in the form of cylindrical holes was used in this experiment. This was of thickness 100 mm, with 5-mm and 10-mm diameter defects displaced 40 mm horizontally at distances of 26 mm and 66 mm, respectively, from the surface. The axis of the holes was parallel to the scanned surface.

A set of waveforms were recorded at 1-mm intervals, with oil on the surface to produce a normal force source, providing the data shown in Figure 4. There are several points of interest. First, hyperbolic variations in delay time are clearly visible. These are due to a longitudinal reflection (L), a longitudinal to shear wave mode conversion (L-S) on reflection from the defect, and a shear reflection (S). The form of the longitudinal reflection in each figure appears to be composed of two hyperbolae which meet immediately at the position above the defect. This is due to the different path delays from the central source to each side of the finite-sized EMAT coil, when the transducer assembly is off-epicenter with respect to the defect.

Initially, an assumption was made that the source and receiver were coincident. This led to the SAFT reconstructions of Figure 5(a). Note that because L, L-S and waveforms were all visible, processing could be performed on any of these modes. In the images that result, a two-lobed location was obtained. This is due, in fact, to the wide EMAT annulus, and can be corrected by removing the effect of different path lengths to two sides of the EMAT when the defect is not directly below the laser source. The results are shown in Figure 5(b), where an improvement is evident.
TESTING OF ADHESIVE BONDS

An interesting application would be to use non-contact ultrasonic NDE for the testing of bonds, due to either adhesive bonding or by other processes such as diffusion bonding. The latter application is covered in more detail elsewhere [13]. Here we will concentrate on adhesive bonds. In this case, the metal being bonded is thin (0.77 mm thick), with a 1.6mm thick layer of epoxy bonding it to a similar aluminium sheet. In this material, Lamb waves will be generated by the transduction system of Figure 2, and the technique will be to study the propagation of Lamb waves in the upper metal layer, in both the presence and absence of a proper adhesive bond.

Lamb waves can exist in a variety of modes, which can be classified as being of one of two types: asymmetric, where the whole plate moves in a flexural motion, and symmetric, where the center of the plate does not move. A series of modes are possible, depending upon the frequency of interest and the thickness of the plate. In general, propagation is in directions parallel to the plate faces, and is dispersive, i.e., the phase and group velocities are frequency dependent.

The two lowest order modes, denoted \( a_0 \) and \( s_0 \), can exist at all frequencies. Higher order modes have cut-off frequencies, below which they do not exist. These cut-off frequencies \( (f_C) \) depend on the plate thickness \( (2h) \), and the longitudinal and transverse velocities in the bulk plate material. In
the 0.77mm thick aluminium plate used, several modes would be expected to exist over the bandwidth of interest. These are most conveniently displayed in frequency spectra. The lowest order $s_0$ and $a_0$ modes cover a wide bandwidth, whereas the higher order modes exhibit a much narrower bandwidth, showing up as distinct peaks in the frequency spectrum. This is illustrated in Figures 6(a) and (b) which show results over a disbonded sample, and over a good bond respectively. Each spectrum shows three distinct higher order peaks, due to the $a_1$, $s_1$ and $s_2$ modes in increasing order of frequency. Note, however, that over a disbond the $s_1/s_2$ double peak is of higher amplitude than that due to the $a_1$ mode at lower frequency, whereas this is reversed for the bonded sample. This is a result of higher attenuation of higher frequencies in the bonded case, and illustrates how such a system may be used to detect anomalous regions in bonded samples.

CONCLUSIONS

The characteristics of an ultrasonic source generated by a pulsed laser have been described briefly, and the types of detector useful to result in a completely non-contact NDE system have been reviewed. Details of one type of transduction combination, using a concentric EMAT annular detector, have been given, and selected NDE applications discussed.

REFERENCES