LASER-BASED ULTRASONICS ON Gr/EPOXY COMPOSITE

A SYSTEMS ANALYSIS

B.R. Tittmann, R.S. Linebarger and R.C. Addison, Jr.

Rockwell International Science Center
Thousand Oaks, CA 91360

ABSTRACT

Critical issues are examined in the application of laser generation and detection of ultrasound to the inspection of large area air-frame composites. Among these issues are surface roughness, signal-to-noise ratio, insensitivity to the path length between the part and detector, and wide-band versus narrow-band generation. Supporting experiments are reported on broad-band and narrow-band generation in Gr/Epoxy panels and angular reflectance measurements on painted and unpainted Gr/Epoxy. On the basis of these measurements, a laser-in/laser-out systems analysis is carried out for a 10 mm diameter delamination about 1 cm deep. The analysis assumes that a Spherical Fabry-Perot interferometer is used for detection and a 10 nsec laser pulse with a peak power of 13 MW/cm^2 for generation. The estimates indicate a $S/N \approx 20$ dB for a detection probe laser power of about 400 mW.

INTRODUCTION

The laser generation and detection of ultrasound is a well-known and understood phenomenon which has been demonstrated by many researchers [1-8]. The question posed here is whether this technique is feasible for use in the depot inspection of large-area composite airframe structures. Recent reports have been encouraging. For example, Monchalin et al [9] recently observed echos from a corner-shaped 3-mm thick and peel-ply covered, piece of Gr/Epoxy composite and have obtained tri-dimensional images of 2 cm × 2 cm artificial delaminations in 5 mm thick peel-ply covered Gr/Epoxy. The depot inspection system will need to be insensitive to environmental disturbances including mechanical vibration, temperature variations and suspended particulates along the optical path. The system must have sufficient sensitivity to detect flaws of interest without causing surface damage to the part under test.

In this report we examine the critical feasibility issues of an eventual, practical, field usable, concept of source-detector integration. Supporting experimental results are reported on broad-band and narrow-band generation in Gr/Epoxy panels and angular reflectance measurements on painted and unpainted Gr/Epoxy panel surface to determine the effects of surface roughness on the optical detection sensitivity. The measurement results are factored into a laser-in/laser-out systems analysis which estimates the principal losses based on generation with a Q-switched Nd:Yag laser and detection with an actively stabilized spherical Fabry-Perot interferometer.

GENERATION

Broadband Generation

Thermoelastic generation of ultrasound with the aid of a Q-switched laser has been demonstrated before. Here it is discussed primarily in the context of estimating the signal-to-noise ratio of the ultrasonic waves reflected from a 10 mm diameter flaw that is 10-mm deep in a Gr/Epoxy composite panel. In the preliminary experiments described here the spot size of the Q-switched laser beam is 10 mm. The ultrasound generated at powers of about 13 MW/cm^2 is detected by bonding a 2.25 MHz, 0.5 in. diameter longitudinal piezoelectric transducer to an aluminum buffer rod and coupling this rod to Gr/Epoxy with stopcock grease. Figure 1 shows the first and second pulse echo through an 8.3 mm thick sample of unpainted Gr/Epoxy with an attenuation of about 12 dB/cm at 2.25 MHz. The small insert shows the signal with 53 dB gain to prominently display the thermal noise. The measured S/N is about 71 dB. This value must be corrected for the acoustic attenuation in the Gr/Epoxy which is about 10 dB. Other corrections are the noise figure of the receiver amplifier (a model 5052 PR Panametrics pulser/receiver) which, is 3.3 dB, and the one-way insertion loss of the piezoelectric transducer, which is assumed to be 6.7 dB. Taken together, these corrections give a value of 91 dB for the S/N of the acoustic signal at the entry surface of the target material, in a 1 MHz bandwidth.

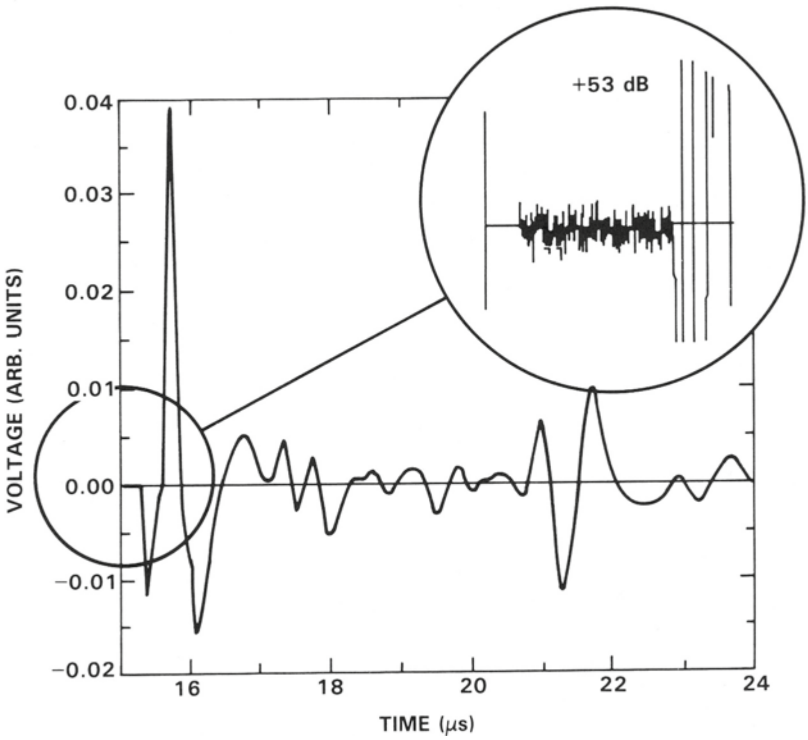

Fig. 1 Laser generation in Gr/Ep. First and second pulse echoes through an 8.3 mm thick sample of unpainted Gr/Ep at 2.25 MHz. The small insert shows the signal with 53 dB gain to display the thermal noise. The measured signal-to-noise ratio is 71 dB.

Narrow-Band Generation

Issues associated with the Q-switched laser generation of ultrasound are the efficiency of the generation process, the ultrasonic bandwidth and the spatial distribution of the ultrasound within the part. To address these issues, we have proposed for this progam an alternate approach which is the modulated cw laser and associated array concept described previously [10] and developed under a Rockwell IR&D Program. By the use of an acousto-optic modulator, the cw laser is modulated at a frequency of several MHz. This allows the elastic energy generated to be confined to a narrow bandwidth in the low MHz range rather than being spread out over the broad bandwidth of over 100 MHz when a Q-switched laser (with a typical 10 nsec pulse width) is employed. By placing the ultrasound into the bandwidth of interest for NDE applications, this approach provides a more efficient conversion process. It also provides better control over the amplitude and phase of the generated elastic pulse, thus opening the possibility of forming an array of sources that can be placed on a curved surface and phased to provide directional control of the elastic beam. The beam can be scanned in a sector and focused with the array to provide more efficient illumination of small flaws than could be obtained from the Q-switched laser source, whose elastic energy is diffracted outward.

To demonstrate the feasibility of achieving narrow bandwidth operation, we used a system, comprising a Nd:YAG cw laser (TEM_{00} mode operation at 12 watt) and a custom made acousto-optic modulator, that was developed under a Rockwell IR&D Program. We have demonstrated that this system can generate a narrow bandwidth acoustic signal at 2.25 MHz in Gr/Epoxy materials. Figure 2 shows the acoustic signals as detected by a piezoelectric transducer through an unpainted 8.3 mm Gr/Epoxy panel with 10 dB attenuation. The excitation spot size diameter was approximatelsy 2 mm. The time delay of the acoustic signal with respect to the laser modulation is associated with the travel time in the Gr/Epoxy. The low S/N of the acoustic signal is due to the current limitation of laser technology. Even with the narrower bandwidth, the S/N is about 60 dB less than that obtained with a Q-switched laser. Since the S/N varies as the square of the laser power, an increase in the modulated laser power by a factor of 1000 is required to have an equivalent S/N for both lasers. An increase of this magnitude appears feasible with long-pulse lasers (pulse widths of 100 μsec) which are currently under development. Also, acousto-optic modulators must be developed to pass optical beams of higher average and peak power.

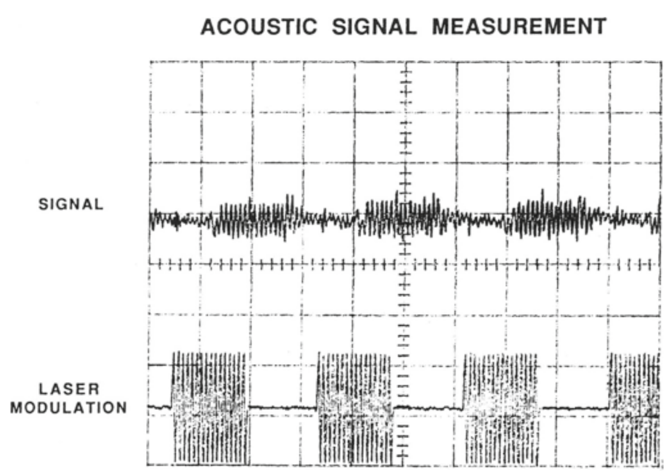

Fig. 2 Narrow-band laser generation in Gr/Ep. 2.2 MHz tone bursts are seen in 8.3 mm thick unpainted Gr/Ep as detected with a piezoelectric transducer. The attenuation in the sample is 10 dB.

DETECTION

Critical issues associated with the optical detection of ultrasound are the ability of the detection system to (1) accept reflected waves from rough surfaces, (2) suppress environmentally caused variations in the optical path between it and the part and (3) to detect the ultrasonically induced surface displacement with high sensitivity.

Surface Reflectance

The nature of the surface reflectance strongly affects the scanning mode that is selected. Practical surfaces are not mirror-like, so the detection system must be able to work with reflected waves that have complex wavefronts. Furthermore, the reflected light will contain speckles due to surface roughness that is larger than an optical wavelength and the coherence of the laser. Interferometers such as the spherical Fabry-Perot (SFP) type have been shown to be suitable for detecting ultrasonic waves reflected from rough surfaces [9]. Whether such an interferometer is to be used with the specular component of the reflection or the diffuse component depends upon the angular reflectance distribution of the surface of the part. More work is needed to characterize the surfaces that are of potential interest. We have made preliminary measurements on flat panels of Gr/Epoxy with varying roughness under both painted and unpainted conditions. Figures 3 and 4 show measurements of the angular reflectance at a wavelength λ = 632.8 nm. Note that in order to reduce detection system interference and saturation effects, and to simplify detection system design and alignment, the probe laser and detection system are typically selected to operate at visible wavelengths, rather than at the 1.06 μm infrared excitation laser wavelength.

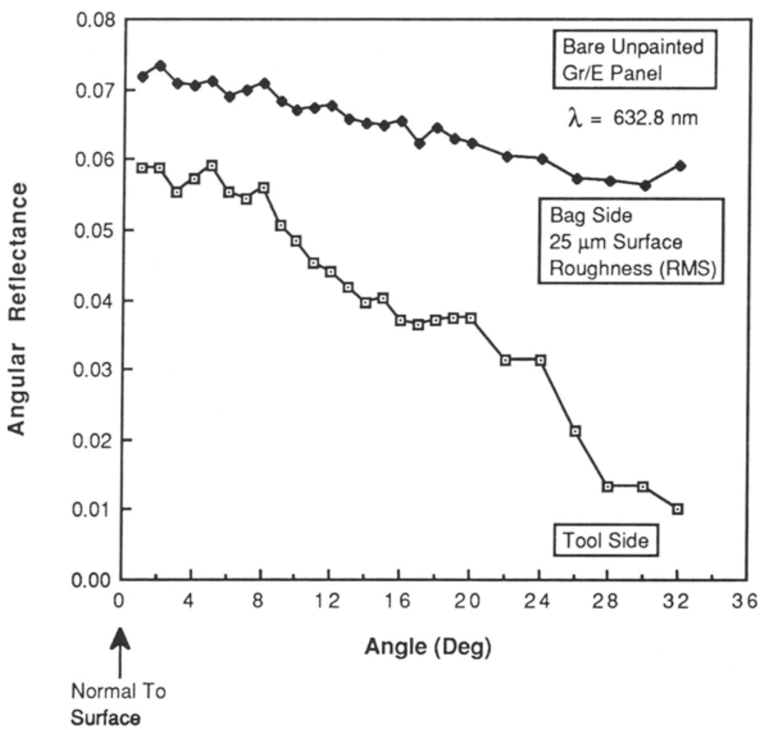

Fig. 3 Angular reflectance measurements on a flat panel of unpainted Gr/Ep. Note that the bag side gives a nearly isotropic reflectance distribution.

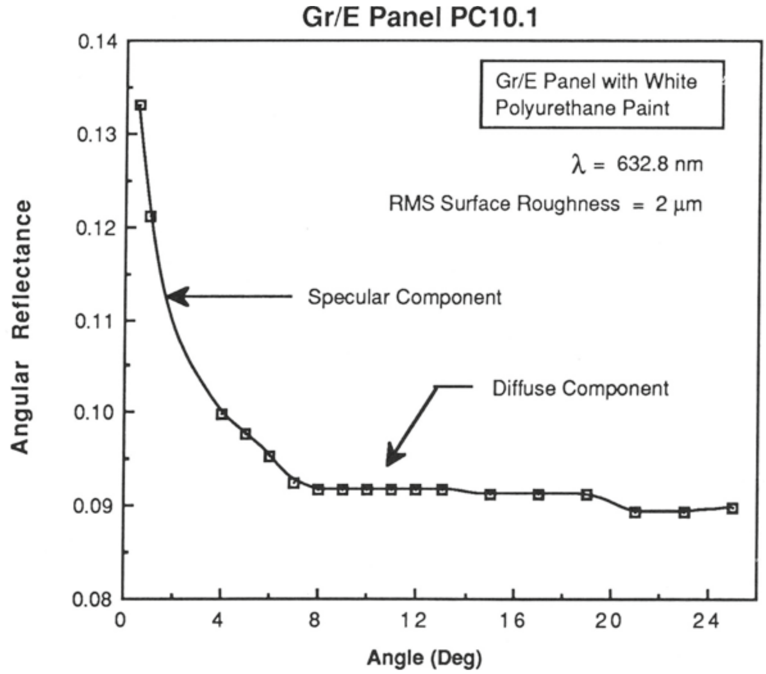

Fig. 4 Angular reflectance measurements on a flat panel of painted Gr/Ep. Note that the reflectance shows well-defined specular and diffuse components.

These angular reflectance measurements were made by recording the stationary, normally incident light diffusely scattered from the flat panels. The detector, whose field-of-view was unrestricted at 2π steradians, was spatially varied at each line-of-sight angle to generate this reflectance data. The bag side of bare unpainted Gr/Epoxy with 25 µm surface roughness gave a nearly isotropic reflectance distribution, as shown in Fig. 3, whereas a painted Gr/Epoxy panel (removed from an airframe structure) showed well-defined specular and diffuse components, as shown in Fig. 4. The on-axis absolute reflectance values were found to be about 7% and 14%, respectively.

Environmental Effects

Since the SFP interferometer causes the wave reflected from the part to interfere with itself, it is insensitive to environmentally-caused disturbances in the optical path between the SFP and the part. Thus, vibration and air currents do not appear to be a problem.

Sensitivity

We have analyzed the sensitivity of SFP etalon detection and calculated the detected ultrasonic displacement as a function of probe laser power for a specular surface and an isotropically scattering diffuse surface with 100% reflectance. The graph of Fig. 5 shows the resultant curves and also identifies the thermal noise-limited and shot noise-limited regimes. Also shown is the limit for piezoelectric detection. The calculations are shown for a bandwidth of 1 MHz. The minimum detectable ultrasonic displacement was calculated by setting the signal-to-noise ratio equal to unity. For low values of the laser power, the dominant source of noise is thermal noise and the minimum detectable ultrasonic displacement decreases as the reciprocal of the laser power squared. For higher values of laser power, the shot noise of the photodetector is dominant and the displacement decreases as the reciprocal of the square root of the laser power.

SYSTEMS ANALYSIS FOR LASER-IN/LASER-OUT OPERATION

Using the information gathered above in calculations and experiments we have analyzed the losses for laser-in/laser-out operation. The results are summarized in Fig. 6. The analysis was prepared for an unpainted Gr/Ep panel having a 10 mm diameter flaw 10 mm deep. The acoustic signals at the entry surface of the target material are assumed to have a power that is 91 dB above the thermal noise in a 1 MHz bandwidth, or a beam intensity corresponding to 7 $\mu W/cm^2$. The acoustic signal is attenuated by 24 dB during the round-trip travel through the Gr/Ep. We assume negligible diffraction loss. This reduces the ultrasonic beam intensity to 2.8×10^{-2} $\mu W/cm^2$. We will further assume that a S/N of 20 dB is desired in the detected optical signal. Thus, the optically detected signal has a power that is 47 dB above that of the thermal noise in 1 MHz bandwidth. This corresponds to an ultrasonic displacement of 4.2×10^{-2}Å or a reflected laser power into the interferometer of 5 mW.

We now assume that the surface is an isotropic scatterer, that the interferometer has an etendue of 0.4 mm^2-sr and that the laser spot has a 1 mm diameter. This causes a decrease in the laser power entering the interferometer of 7.7 dB compared to a specularly reflecting surface. Based on the reflectance measurements of the unpainted Gr/Ep specimen we will assume that the surface has a reflectance of 7%. When these losses are combined, we find that a laser probe power of 4.09×10^{-1} W is required to illuminate the surface of the target. This power level is readily accessible for standard off-the-shelf Ar-ion lasers.

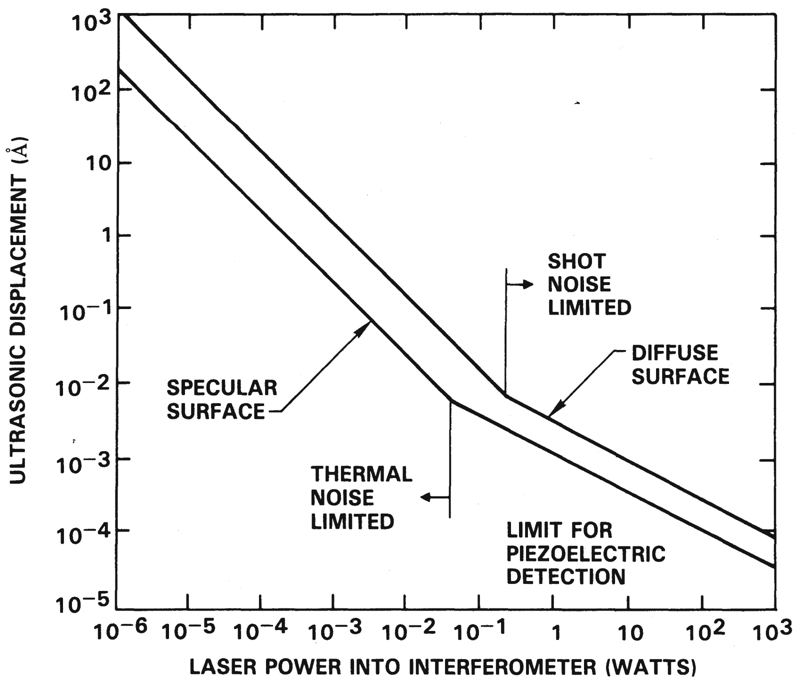

Fig. 5 Sensitivity of SFP etalon detection. The detected ultrasonic displacement is plotted vs the probe laser power for specular and isotropically scattering diffuse surfaces with 100% reflectance.

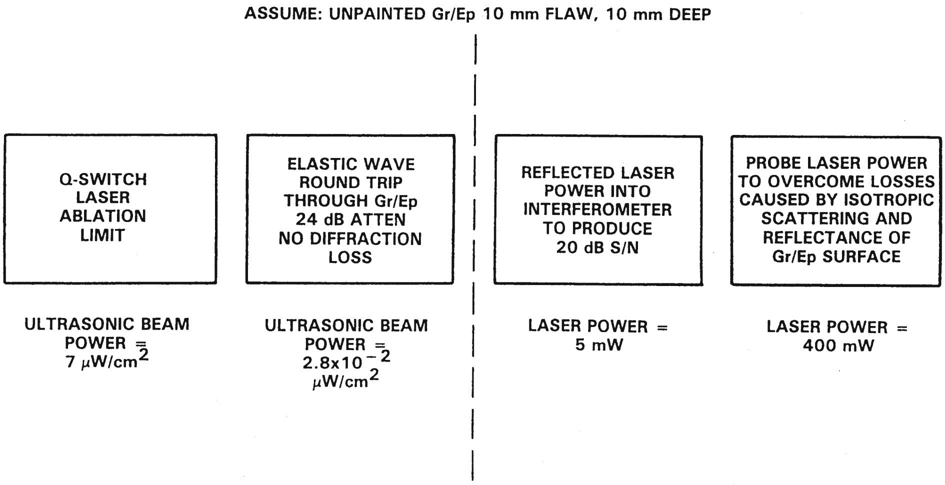

Fig. 6 Laser-based ultrasonics - probe laser requirements for Gr/Ep. This figure summarizes the analysis of a system operating in a laser-in/laser-out configuration. Note that the probe laser requirements are easily met by standard commercial Ar^+ lasers.

CONCLUSIONS

In summary, we have carried out several key experiments and calculations to analyze laser-in/laser-out operation for an application window of flaw detection in Gr/Ep panels. The values of the pertinent parameters in laser generation and laser detection are reasonable and show ready feasibility for stationary bi-static operation.

Not discussed were the various noise sources and our ideas for noise reduction when the rapid scanning operation is required. Several concepts have been developed by us and will be discussed in a subsequent report.

ACKNOWLEDGEMENT

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