MEASUREMENTS OF ACOUSTIC PRESSURE IN THE NON-LINEAR RANGE IN WATER USING QUANTITATIVE SCHLIEREN

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ABSTRACT

The schlieren method, based on Raman-Nath scattering by ultrasonic waves, is extended to pressures up to $8.8x10^6$ Pa (about $5KW/cm^2$ for 4 MHz CW waves) by capturing up to the 16^{th} order diffraction harmonics in water. Given the high spatial resolution ($\sim 100\ \mu$m), this kind of measurement is not possible with conventional hydrophones. Working under partially applicable Raman-Nath regime (thin grating, $Q \approx 0.016 \ll 2\pi$ but $0 < \nu < 2000$), the theoretical description fails beyond the first few orders. However, we demonstrate that an empirical calibration is possible as long as plane waves are used and the short interaction length is maintained. Examples of beams and measurements are presented and compared with the basic theory.

INTRODUCTION

The acousto-optic method has both the allure of fast measurements and the lack of understanding of the underlying phenomena. Despite significant theoretical work on the subject[1] it has remained for many years an obscure field removed of any practical use to the ultrasound community. Several authors[2-6] have explored acousto-optic methods for acoustic ultrasound measurements, one of these has been even incorporated as a standard method[7], and yet it remains outside the exposimetry mainstream.

One reason for the contradiction between the tantalizing promise of the method and its unavailability is, at least partly, economics: to achieve quantitative capabilities a system must have optical components of extremely high quality, which makes it it very expensive.

Perhaps another reason is the lack of adequate theoretical description, which responds to the complexity of the problem. This complexity is brilliantly discussed in a short article by Korpel[1] and analyzed in depth in one of his most recent works[8].

In this paper we describe an approach that, while based on the basic system description outlined by Brillouin[9] and Raman[10], explores empirically the ability of such system to evaluate acoustic fields at very high intensities, clearly in the non-linear behavior of the medium. Acknowledging that the real situation at high power is beyond the range of applicability of the theories, we show that, whether mathematically understood or not, the method is valid provided some conditions are controlled.

METHODS

The essence of the method consists of using a sensing detector array at the Fourier plane, separating the sidebands by detecting the position in the array and adding the coherent components. The schlieren system used in this work (see figure 1) utilizes refractive optics whose general description has been published previously[11]. When operated in CW mode, the light source is nearly monochromatic

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(650±20nm in air) and the system can operate in the range of 1 to 30 MHz. A set of high quality lenses is used to provide good separation between the diffraction orders, as shown in figure 2 for a 4 MHz acoustic wave.

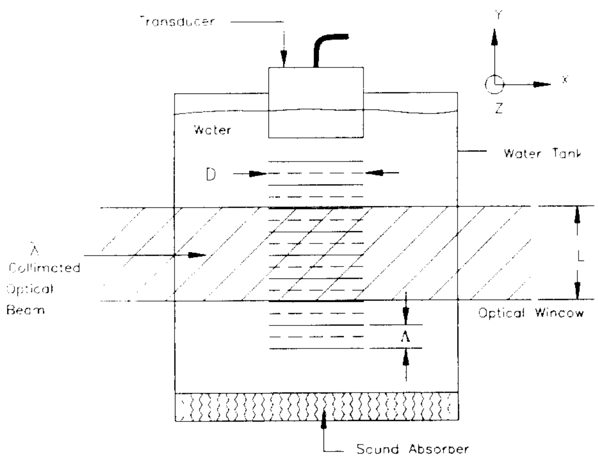

Figure 1. *Geometry in acousto-optical scattering.*

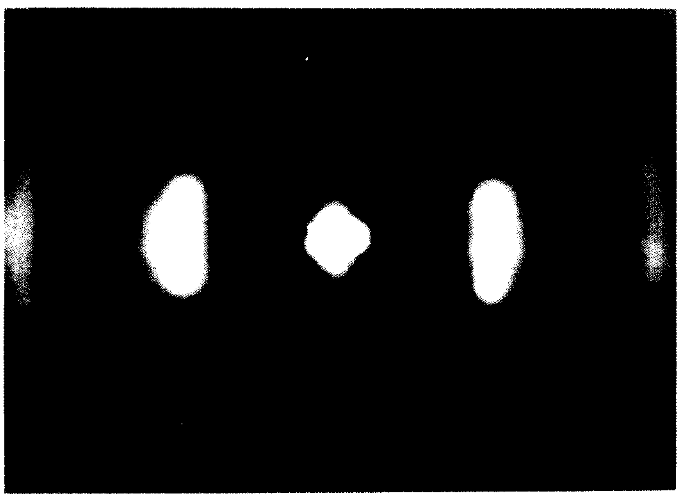

Figure 2. *Diffraction pattern at the focal plane (near field). Zero-th order is at the center, first orders and second orders appear at each side.*

In order to generate high intensity fields we used a 4.0 MHz transducer with a focal distance of 40 mm and an approximate aperture of f/1.3. The transducer was driven in CW mode by a linear amplifier operated below its full capacity to insure that its distortion was negligible (less than 1dB harmonics). The acoustic power generated by the transducer was determined by measuring the RMS driving voltage at the transducer electrodes, and this value (squared) had been verified to be proportional to actual powers using a radiation force balance.

A general description of the data acquisition system is shown in figure 3. The schlieren system generates a video signal corresponding to the image of the beam (figure 4) and a whole frame is captured by the computer equipped with a frame grabber. Because the beam is integrated along the optical path, the values of all the pixels long a vertical column at the focal plane are added to generate the 2-D integral.

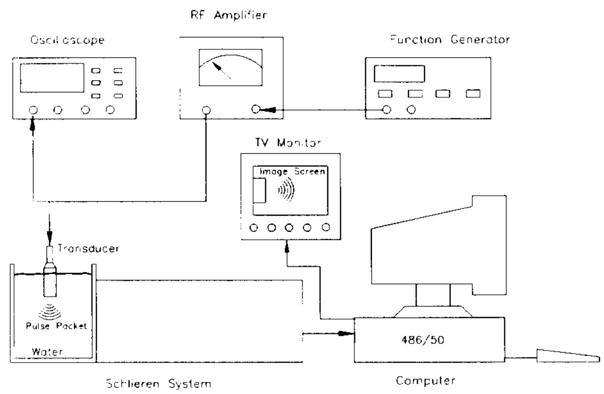

Figure 3. *Setup for data acquisition (see text).*

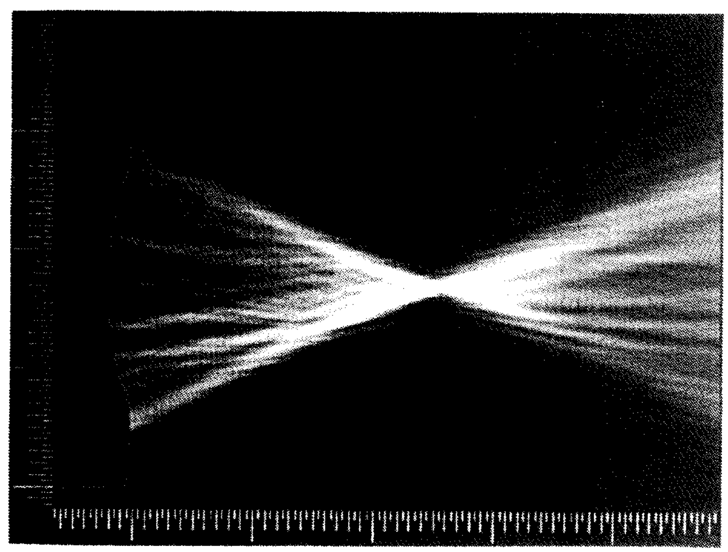

Figure 4. *Schlieren image of CW acoustic beam.*

It is important to perform the integration at the focal point for two reasons: minimal interaction length and plane waves are only met at this location. The transducer, whose beam at the focal plane has a diameter of 0.7 mm, was driven up to 20 Watts, corresponding to a peak intensity of 5.2 KW/cm^2 (equivalent to pressures of 8.8 MPa). Under these conditions, the Klein-Cook parameter $Q = 2\pi D\lambda/\Lambda^2 \approx 0.016$.

Above 5W the image was captured within one second of turning on the amplifier, because the transducer's low efficiency (estimated at 30%) causes it to heat up, subsequently distorting the acoustic beam.

To measure the response of the system, stops of increasing diameter were placed at the optical focal plane. This means that the camera would receive diffraction orders that would miss the stop but still be allowed by the camera lens. At the focal plane the m-th order appears at a distance from the center given by

$$r_m \approx m\, f\, (\lambda / \Lambda) \qquad (1)$$

where f is the focal distance of the focusing lens, λ is the light wavelength, and Λ is the acoustic wavelength. So placing a disk of diameter $(m+½)\, r_1$ allows orders $\geq$ m into the camera for summation, up to the maximum allowed by the camera aperture. In this case, the camera lenss has an effective aperture of 44 mm, and since $\lambda = 0.490 \mu m$ in water, the maximum order accepted is 16 for 4 MHz waves. The camera lens must be well centered on the optical axis to preserve the symmetry of the captured diffracted light.

Three measurements were made for each power setting, to reduce statistical uncertainty, for an overall accuracy estimated at 2%.

RESULTS

The results are shown in figure 5, which contains both the measured values as well as those predicted by the weak interaction model for thin gratings[8], computed numerically in which the diffraction orders are summed coherently up to 16^{th} order.

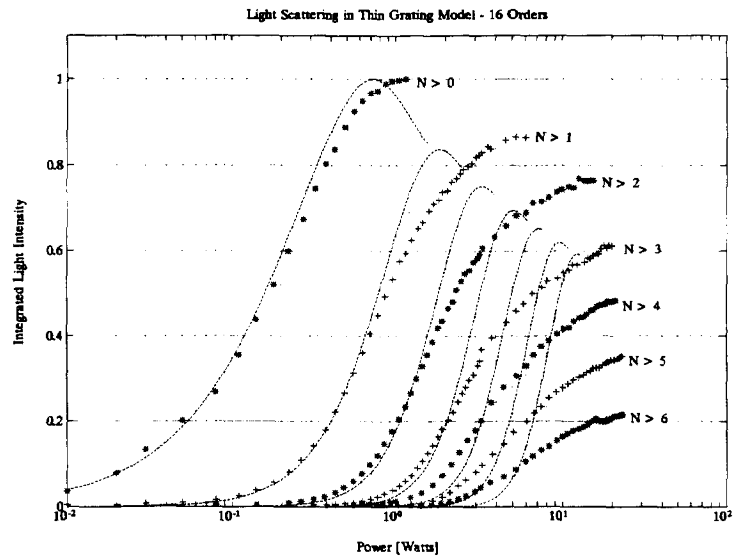

Figure 5. *Measurements of normalized scattering intensity as a function of power. Data overlayed with theoretical prediction by the thin phase grating model.*

It is apparent in figure 5 that the behavior at low intensities matches reasonably well the theory, and this is not surprising since up to about 500 mW the Raman-Nath parameter is below 2. What is surprising, however, is the behavior of the higher orders, which instead of increasing steeply show only a gradual increase. Although this needs further analysis, we think this behavior suggests the presence of higher harmonics in the medium itself caused by the enormous pressures. These wave components, which are odd harmonics of the acoustic fundamental, would diffract the light outside of the acceptance field of the camera lens. This means that for the m-th optical diffraction order there are several diffracted beams, corresponding to the acoustic harmonic distortion:

$$r_{m,k} \approx m\, f\, (k\lambda / \Lambda) \qquad (2)$$

where k is an odd integer. As non-linear distortion increases, the components with higher k contain more energy, but this diffracted beam begins to be miss the detector.

On a practical note, this behavior presents an unexpected advantage, because it provides the capability to measure high intensities over wider ranges than would be allowed by the simple theory. For instance, figure 5 shows that it is possible to measure with reasonable accuracy from 2 to 20 W with a fourth order filter, while the model would indicate that the fourth order would only cover the range of 2 to 4 W.

CONCLUSION

We have shown that the acousto-optic method of ultrasonic exposimetry can be extended, albeit for reasons that are not clear yet, into very high intensity measurements. This new capability may be very important, as hydrophones usually cannot stand high intensity fields for an extended period.

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