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13. ABSTRACT *(Maximum 200 words)*

The two-year research effort was directed at understanding the laser generation of underwater sound at relatively low frequencies (below 1 kHz) by nonlinear expansion of the heated water. Three objectives were pursued: (1) find an upper limit for the maximum efficiency achievable; (2) solve the boundary value problem corresponding to the laser generation of sound by high-repetition rate pulsed lasers; and (3) validate some of the predictions with some experiments. Results show that the efficiency of the optoacoustic conversion process remains very small for practical naval applications in the low frequency range (below 1 kHz) even when the nonlinearity of the thermal expansion mechanism is taken into account, even with high-repetition rate high-power pulsed lasers. More suitable applications would be those where short acoustic pulses (less than a microsecond) are desirable (e.g., medical ultrasonics).

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1. INTRODUCTION

The research carried out under Grant N00014-92-J-1156 (R& T No. 4126957) between December 1, 1991 and November 30, 1993 is summarized in this report. The research topic was the laser generation of underwater sound by nonlinear thermal expansion. The bulk of the grant was used to support a doctoral student, Mr. Thomas C. Wilett, with a research assistantship, some material, supplies, and equipment, and with travel funds to attend the 1992 Physical Acoustics Summer School. Mr. Willett is currently in the final phase of his research and he is expected to graduate during the 1994-95 academic year.

2. RESEARCH GOALS AND APPROACH TAKEN

The main objective of the research was to assess the usefulness of the generation of underwater sound at relatively low frequencies (less than 1 kHz) by absorption of high-power laser beams in the fluid medium. Since the thermal expansion mechanism of sound generation is extremely inefficient in the linear regime[1] , especially with CW lasers, the present research effort concentrated on the nonlinear thermal expansion mechanism by absorption of high-power Q-switched laser pulses. The nonlinear thermal expansion is caused by the dependence on temperature of the coefficient of thermal expansion.

Three goals were pursued. First, we derived an upper limit for the maximum efficiency achievable by with the nonlinear thermal expansion mechanism. Second, we solved numerically the boundary value problem corresponding to the case of laser generation of sound by high-repetition rate pulsed lasers. And third, some experiments were made to validate the predictions. The study was experimental, numerical and analytical.

[1] In water, the efficiency is of the order of $10^{-21} f^2 \mathcal{P}$, where f is the acoustic frequency (in Hertz) and $\mathcal{P}$ is the laser power (in watts).

3. SUMMARY OF ACCOMPLISHMENTS

3.1 The coupled heat transfer / acoustic radiation boundary value problem has been formulated and solved numerically for any arbitrary laser source (spatial and temporal profiles) in the nonlinear thermal expansion regime.

The problem is divided into two regimes: during the laser pulse (thermoacoustic generation), and between two consecutive pulses (temperature diffusion to estimate the initial conditions at the time of the firing of the next laser pulse). The objective is to have a working model of the pressure waveforms generated by high repetition rate pulsed lasers. During the laser pulse, the temperature rises and the coefficient of thermal expansion, β, changes with time from its initial value. This leads to the asymmetric pulse shapes described by Dunina et al., [Sov. Phys. Acoust., 25(4), 353-357 (1979)]. Between two consecutive pulses, the temperature distribution in the fluid is calculated from the diffusion in water and the diffusion at the free water-air surface. The proper diffusion boundary value problem was solved analytically and the temperature distribution in the water at the time of the second pulse was used as an input to calculate the initial conditions of the boundary value problem describing the thermoacoustic generation. Numerical results show that, on the time scale of interest for low frequency sound generation, the diffusion problem between the laser pulses is negligible. Hence, the results of Dunina and others (with single pulses) can be extrapolated to estimate the sound produced by absorption of a high repetition rate pulsed laser.

3.2 The numerical model has been used to predict the pressure waveforms and spectra generated by pulsed lasers with high repetition rates (10 Hz to 1000 Hz), and with various laser intensity modulation schemes.

The results of these simulations confirm that the generation of low frequency sound by laser absorption is very inefficient (see discussion 3.3 below), even in the nonlinear thermal expansion regime, at high repetition rates or with elaborate laser intensity modulation schemes: amplitude and frequency modulation, pulse amplitude and frequency modulation, etc...

3.3 An upper estimate for the maximum efficiency has been derived.

The optoacoustic efficiency η is defined as the ratio of the sound power generated in the fluid to the laser power. An upper bound for the efficiency is

$$\eta = \frac{1}{8\pi\rho_0 c}\left(\frac{\beta_0}{c_p}\right)^2\left(\frac{1}{\tau}\right)^2 \mathcal{P}\ (1+\epsilon)^2 \tag{1}$$

where ρ_0 is the fluid density, β_0 its coefficient of thermal expansion at ambient temperature, c_p its specific heat at constant pressure, τ is the characteristic acoustic time scale, $\mathcal{P}$ the laser power, and ϵ the gain due to the nonlinearity of the thermal expansion. Equation (1) shows that the only way to achieve any reasonable efficiency level is to use Q-switched pulsed lasers, because they are much more powerful than CW lasers. However, the acoustic pulse produced by absorption of a Q-switched laser pulse has typically a characteristic time scale of the order of a few microseconds for an illuminated spot size of a few millimeters. Consequently, it is not an efficient way to generate low frequencies. To lengthen the characteristic time scale of the acoustic pulse, one can illuminate a large area with characteristic dimension $a = c\tau$. For instance, to generate 100 Hz sound, it is more efficient to use a high power Q-switched laser pulse and illuminate the water surface with a spot of radius 15 meters, rather than use a CW laser with intensity modulated at 100 Hz. To achieve the desired periodicity (100 Hz) with the Q-switched laser system, one can either pulsate the laser at a repetition rate of 100 Hz, or alternatively create a spatial array of illuminated spots on the water surface with the proper periodicity.

The question is then to establish what would be the maximum efficiency achievable with such a system. To answer this question, one has to get an estimate of the maximum value of ϵ in Eq. (1). An upper estimate of ϵ (for water) is $\epsilon = 0.06\ e/\rho_0 c_p$, e being the energy absorbed per unit volume. The maximum allowable energy density before boiling is about 2,300 J/cm^3, i.e., the maximum value of ϵ is about 30. Consequently, the upper bound for the efficiency achievable with the nonlinear thermal expansion mechanism is at most 1000 times the efficiency achievable in the linear case. (This is an upper limit, and a more realistic number would probably be 100). The upper bound for the efficiency is therefore at most $\eta = 10^{-18} f^2 \mathcal{P}$. At 100 Hz, with a pulse of 100 mJ over 10 ns, one obtains $\eta = 10^{-7}$. Despite this significant improvement, it hardly makes the thermal expansion mechanism by laser absorption an even moderately efficient way to produce sound in water, especially at low frequencies. The peak pressure amplitude that could be produced by this method would be at most 100 Pa at 1 meter, (about 160 dB re 1 μPa.

It may be argued that the efficiency could be greatly improved by moving the source above the water surface at a velocity greater or equal to the sound speed in water (see

Pierce and Berthelot, *J. Acoust. Soc. Am.*, 83(3), 913-920 (1988)]. However, this so-called parametric pumping is effective only with long laser pulses (at least tens of millisecond in duration); and long pulses cannot deliver the power levels obtained with short Q-switched laser pulses. In addition, diffraction effects that occur below the air-water interface rapidely lead to a saturation of the parametric pumping, making the scanning technique much less attractive than originally thought.

In conclusion, the efficiency of the conversion process remains very small for practical applications in the low frequency range. Q-switched laser pulses are far more powerful than long pulses but they always lead to acoustic pulses with time scales of the order of microseconds unless the illuminated region is spread over a very large area. Therefore, they are not, in general, efficient at generating low frequencies.

At very high frequencies, the optoacoustic efficiency is much improved and the technique may be a viable option for instance to generate shock waves (lithotripsy or atherosclerosis plaque removal) or even as a calibration technique (see below).

3.4 Experiments are still under way to validate the predictions.

Listed below are the on-going experiments. 3.4.1. Pressure waveforms generated in the nonlinear thermal expansion regime.

3.4.2. Pressure waveforms generated in the transition region between the nonlinear thermal expansion regime and the momentum transfer regime (strong surface evaporation with droplet ejection).

3.4.3. Pressure waveforms generated by absorption of a double-pulsed laser source.

3.4.4. Pressure waveforms obtained with an array of laser spots on the water surface.

3.4.5. Pressure waveforms obtained with an air bubble in the vicinity of the illuminated region. This experiment is designed to take advantage of the high Q of a bubble and use it as an efficient mechanism to transfer energy from high frequencies (MHz range of the sound generated by absorption of a Q-switched laser pulse) to low frequencies (kHz range of the resonance frequency of the bubble).

3.5 Proposed application: Ultrasonic calibration device

Laser generation of sound is more efficient at high frequencies than at low frequencies. Hence, laser generation of sound could be used as a calibration device in ultrasonics at frequencies as high as GHz. For convenience, the laser light could be guided in a multimode optical fiber from the laser to the fluid. Another advantage of this system, is that relatively low amplitudes are needed for calibration purposes in a laboratory environment. This idea was summarized in the form of an invention disclosure.

4. CONCLUSIONS

1) The efficiency of the optoacoustic conversion process remains very small for practical naval applications in the low frequency range (below 1 kHz) even when the nonlinearity of the thermal expansion mechanism is taken into account, even with high repetition rate pulsed lasers.
2) More suitable applications would be those where short acoustic pulses (less than a microsecond) are desirable (e.g., medical ultrasonics).
3) Experiments are still in progress to validate some of the predictions.
4) The details of the research will be published in Mr. Willett's dissertation.

5. RESEARCH DISSEMINATION:

- T. C Willett and Y. H. Berthelot, "Experiments on the laser generation of sound in water by nonlinear thermal expansion" in preparation
- Y. Berthelot, "laser ultrasonic calibrator," invention disclosure (1993).
- T. C. Willett, participant at the 1992 Physical Acoustics Summer School, co-sponsored by the Office of Naval Research and the Acoustical Society of America.

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