Finite-amplitude effects on ultrasound beam patterns in attenuating media

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Some problems relevant to medical ultrasonics are addressed through experimental

measurements of focused, pure-tone beam patterns under quasilinear conditions where significant nonlinearities are manifested. First, measurements in water provide a comparison of the beam patterns of the fundamental and nonlinearly generated harmonics against recent

Karo corn syrup; and 48.9 mℓ isopropyl rubbing alcohol (90% pure). Alcohol was added to the water/phosphate/sugar mixture to reduce the sound speed and attenuation, and to stabilize the medium against bacterial growth. It is known that the water and alcohol undergo a complex interaction. The addition of alcohol to water apparently increases the relative amount of water in the bound versus free state.[23] In general, the B/A of a water/alcohol mixture increases

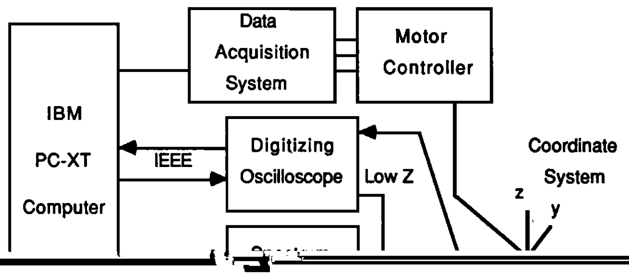


TABLE II. Spatial-average source intensity (I_0).

	Low intensity		High intensity	
Frequency	Generator voltage	I_0(W/cm^2)	Generator voltage	I_0(W/cm^2)
1.75	0.1	0.049	0.55	1.52
2.25	0.1	0.087	0.5	2.24
[redacted]				

[redacted]

al distance was chosen to include some minor lobes of the beam (only part of a sidelobe is evident at 1.75 MHz) while retaining an adequate resolution.

To observe changes in the harmonic content of the field with intensity, scans at "low"- and "high"- power levels were performed. The power spectrum at low power mainly

linear shock at the focus for each frequency, while remaining in the linear operating region of the electronic amplifier and sources. Source intensities are given in Table II. The axis of the transducer was determined from lateral scans in orthogonal planes. Axial scans were then performed at the two intensity levels to determine the focal distance for each har- [redacted] peak amplitude varied by less than − 0.5 dB. Lateral beam patterns were obtained at the focus of the fundamental and [redacted] intensity levels.

In order to distinguish between linear superposition of transmitted harmonics and nonlinearly generated harmonics in the fluid media, waveforms and spectral content at the acoustic source were measured using the hydrophone. The second harmonic at the source was found to be between

III. RESULTS

The axial and lateral harmonic beam patterns (normalized to the peak fundamental amplitude) in water for the 2.25-MHz low and high intensities are given in Figs. 3 and 4.

In Fig. 3 (low power), the magnitudes of the third through fifth harmonics are barely above the noise floor at approximately -55 to -60 dB. In Fig. 4 (high power), the beam patterns of all harmonics are clearly shown with diffractive sidelobes. Since the hydrophone active element has a 1-mm diameter, fine structures such as the fourth and fifth harmonic sidelobes are not resolved.

High-power beam patterns for all four frequencies are shown in Figs. 5–8, where direct comparisons of the results in water and attenuating fluid are made. The attenuation

effects are more significant at higher frequencies and higher

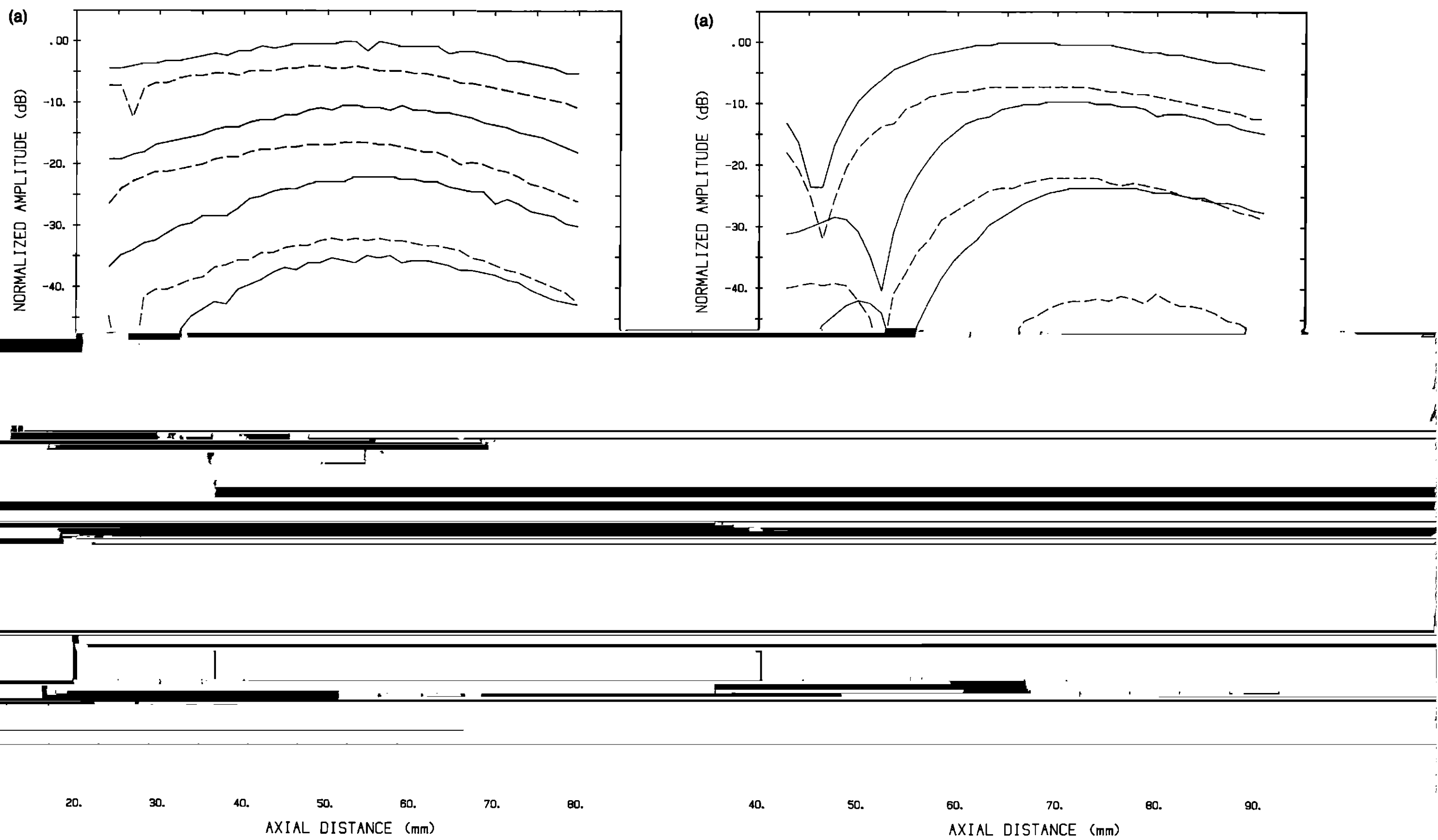
sured at high intensity at the focus, are given in Fig. 9 for water and Fig. 10 for the attenuating fluid. The higher than expected strength of the sixth through tenth harmonics in Fig. 9(b) is related to the "resonance" of the probe-cable-amplifier circuit which increases gain of frequencies above 12 MHz (Ref. 10).

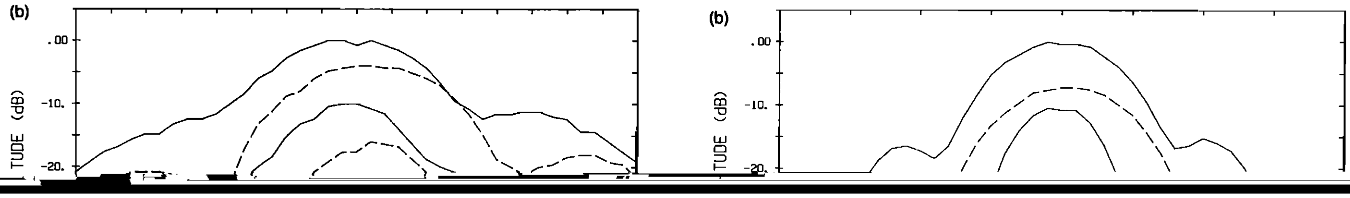
IV. DISCUSSION

A. Radial beamwidths

As a result of their theoretical derivation, Du and Breazeale[8] predicted that the Gaussian beamwidth for the second harmonic is simply $1/\sqrt{2}$ times that of the fundamental

beamwidth, and a $1/\sqrt{n}$ relationship for higher harmonic


(a)
.00
-10.
-20.
-30.
-40.
NORMALIZED AMPLITUDE (dB)
20.
30.
40.
50.
60.
70.
80.
AXIAL DISTANCE (mm)
(a)
.00
-10.
-20.
-30.
-40.
NORMALIZED AMPLITUDE (dB)
40.
50.
60.
70.
80.
90.
AXIAL DISTANCE (mm)


(b)
.00
-10.
-20.
TUDE (dB)
(b)
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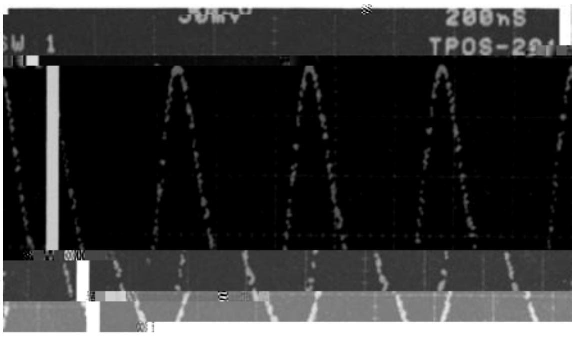
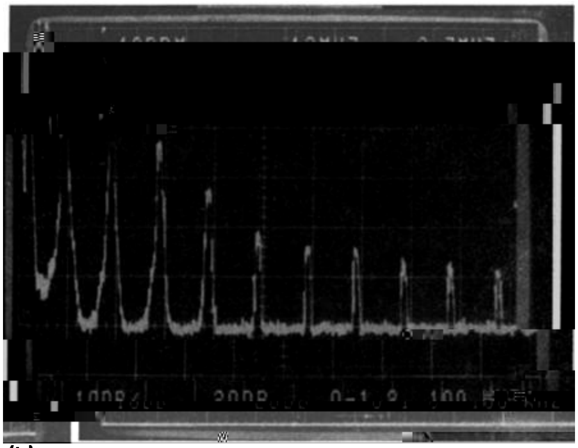
TUDE (dB)

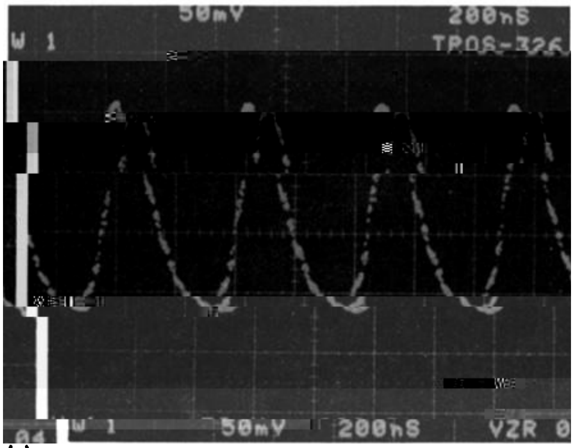


(a)

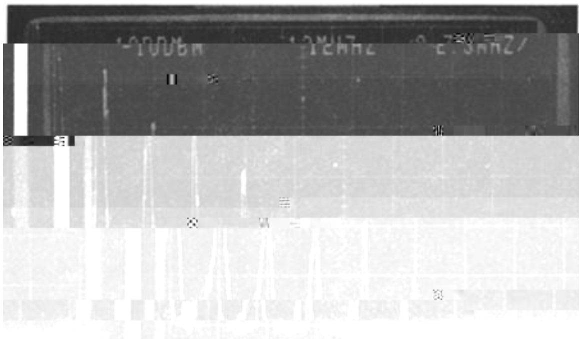


(b)

[illegible]



(a)



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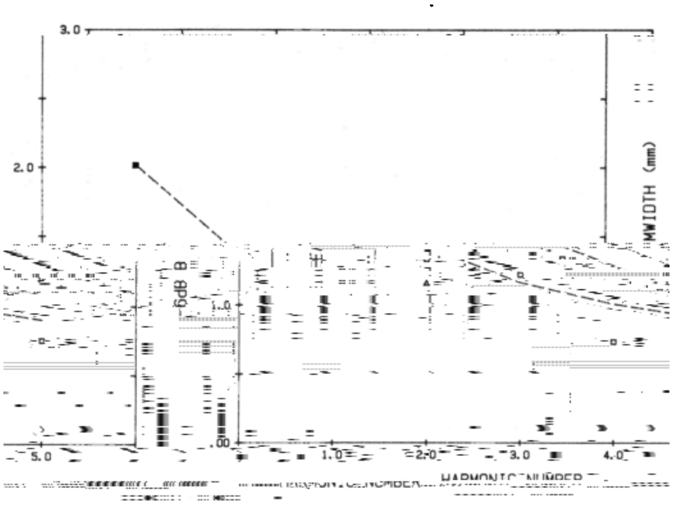


FIG. 12. The − 6-dB harmonic beamwidths for 3.38-MHz source at $I_0 = 1.18$ W/cm^2 compared to $1/\sqrt{n}$ theory in (a) water: experimental (□), theory (---); and (b) absorbing fluid: experimental (△). Since the fundamental beamwidth is the same in the attenuating fluid and in water,

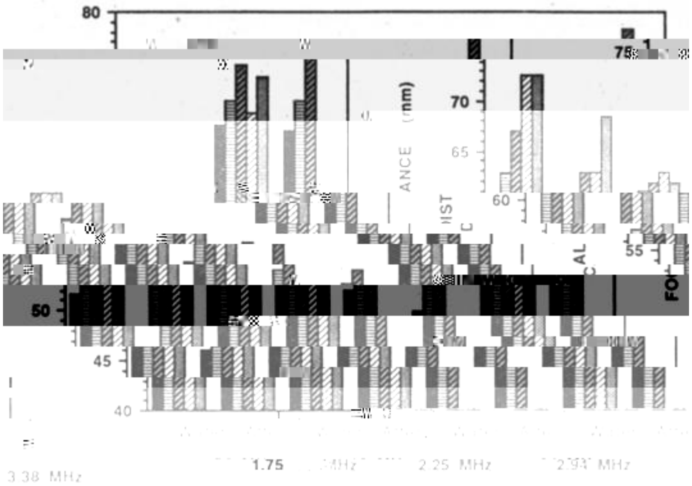


FIG. 13. The location of axial peaks (focal point) for the fundamental and higher harmonics for the four frequencies studied, in water and in the attenuating medium. For each case, shown left to right, are the location of the fundamental (black bar), then the second, third, fourth, and fifth harmon-

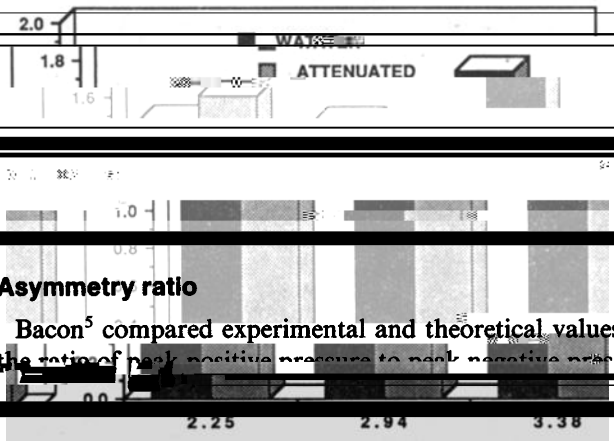
a simple, one-dimensional relation for plane and spherical waves.[32,33] In focused beams, the adaptation of a shock pa-

rameter is questionable because of the rapidly changing har-

and gain measurements to estimate σ using Eq. (2). Next, an *ad hoc* estimate of σ was obtained by comparing the harmon-

ic magnitude ratios at the focus to the theoretical descriply with the fundamental, small axial shifts will produce dif-

TABLE IV. Harmonic attenuation at high intensity.



quency	1st	2nd	3rd	1st	2nd	3rd	1st	2nd	3rd
1.75	2.8	3.9	3.9	1.5	3.0	4.5	1.5	5.6	12.1
2.25	2.8	4.7	7.1	2.7	5.4	8.1	2.7	10.1	21.8

E. Asymmetry ratio

Bacon[5] compared experimental and theoretical values of the ratio of peak positive pressure to peak negative preswater can be used to predict results in tissues, where the small signal attenuation of the fundamental is applied to the fundamental, twice to the second harmonic, and so forth.

As a final note, Saito *et al.*[20] described the ratio of fundamental to second harmonic as being relatively constant beyond the focal region in their study. However, in all cases reported herein, the second and higher harmonics had increasingly steeper slopes (by 1–3 dB/cm) compared to the fundamental falloff beyond the focus.

V. CONCLUSIONS

Focused, radially symmetric, ultrasound beams in the low-MHz medical ultrasound band have been studied to determine finite-amplitude effects in water and in an attenuat- [redacted]

[redacted]

(1) The − 6-dB beamwidths of the harmonics decrease

[redacted]

mated using the results of Sec. IV A, B, and D. The location of axial peaks can be crudely estimated using the results of Sec. IV C. Then, the changes produced by propagation in a lossy medium can be estimated using the simple $a_f n$ results of Sec. IV F. This should be useful in predicting finite-amplitude effects of medical ultrasound equipment in tissues and other related applications.

ACKNOWLEDGMENTS

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