

**NONLINEAR ACOUSTICS: REFLECTION AND REFRACTION, PROPAGATION IN A PERIODIC WAVEGUIDE, SCATTERING OF SOUND BY SOUND, AND ELLIPSOIDAL FOCUSING  
FIRST ANNUAL SUMMARY REPORT UNDER GRANT N00014-89-J-1109**

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<p>Research on four topics in nonlinear acoustics is described. 1. Reflection and refraction of plane finite-amplitude waves at a plane interface between two fluids. This research is now finished. First, the nonlinear equation for three-dimensional waves in a thermoviscous, relaxing fluid was derived. Second, a second-order perturbation solution was obtained for the reflection-refraction problem for the case of a lossless fluid and an arbitrary source signal. All effects contributing to non-linearity -- including motion of the interface, exact source conditions, and nonlinear relations between various field variables -- were taken into account. Although the reflected and transmitted fields are much more complicated than in the small-signal approximation, Snell's law and the law of specular reflection continue to hold (to second order). 2. Propagation in a periodic waveguide. Propagation has been measured</p>			
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18. scattering of sound by sound                      absorption  
    ellipsoidal focusing
19. in a plane wave tube loaded periodically with reactive branch elements. Experiments with small-signal waves verify in fine detail the dispersion relation that had been derived earlier (and this year modified to include thermoviscous boundary layer effects and the end correction for the branch elements). Stop band and pass band phenomena typical of periodic media are confirmed. Both theoretical and experimental studies of finite-amplitude waves are in progress. 3. Scattering of sound by sound. Primary work this year had been theoretical, in particular, on the role of source and boundary conditions. Development of an experimental facility with which to perform single-beam and crossed-beams experiments in the megahertz range is in progress. 4. Ellipsoidal focusing. This work, which has applications to lithotripsy, is thus far mainly experimental. The experiments are carried out in air. An electric spark located at the near focus of an ellipsoidal reflector generates an N wave. The reflector concentrates the sound at the remote focus. Near the reflector the reflected pulse is N shaped, but strong interaction of nonlinear distortion and focusing (and to some extent diffraction) produces gross changes in the waveform as the pulse travels to the remote focus and beyond. Finally, an extensive upgrade of the experimental facilities of the Nonlinear Acoustics Laboratory is in progress. The goal is to make possible a wide variety of computer controlled experiments. Projects 2 and 4 greatly benefitted from improvements realized this year. One doctoral dissertation (distributed as a technical report), seven oral presentations (two with published four-page summaries), and one summary technical report constitute the dissemination of research during the year.



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## 1. INTRODUCTION

The research carried out under Grant N00014-89-J-1109, which began 1 October 1988 and is the successor to Contract N00014-84-K-0574, is primarily in the field of nonlinear acoustics. The broad goal is to determine the laws of behavior of finite-amplitude sound waves, especially to find generalizations of the known laws of linear acoustics. This report covers the 12-month period ending 30 September 1989 and is the immediate successor to the last report under the predecessor contract:

Fourth Annual Summary Report (88-5)\* 1 October 1987 30 September 1988

The following persons participated in the research:

### Graduate students

C. E. Bradley, M.S. student in Mechanical Engineering

F. D. Cotaras, Ph.D. student in Electrical and Computer Engineering

J. A. Ten Cate, Ph.D. student in Mechanical Engineering

### Undergraduate student

S. T. W. Cheng,<sup>†</sup>

### Senior personnel

M. F. Hamilton,<sup>‡</sup> Mechanical Engineering Department, The University of Texas at Austin

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\*Numbers given in this style refer to items in the Chronological Bibliography given at the end of this report, e.g., 88-5 means the fifth entry in the list for 1988.

<sup>†</sup>Although Cheng received no salary support from the Grant, he worked on the ellipsoidal focusing project, which was supported in part by the Grant.

<sup>‡</sup>Hamilton received no direct support from the Grant. However, he is co-supervisor of Ten Cate's Ph.D. research, which is described in Project C below.

C. L. Morfey, consultant, Institute of Sound and Vibration Research, University of Southampton, England

J. Naze Tjøtta, Research Fellow, on leave from Mathematics Institute, University of Bergen, Norway

S. Tjøtta, Research Fellow, on leave from Mathematics Institute, University of Bergen, Norway

W. M. Wright,<sup>†</sup> Research Fellow, on leave from Physics Department, Kalamazoo College, Michigan. Although Wright received no salary support from the Grant, he was primarily responsible for the ellipsoidal focusing project, which was supported in part by the Grant. He was also heavily involved in the development of a tank facility, which will be used in the scattering of sound by sound.

D. T. Blackstock, principal investigator

## 2. PROJECTS

Projects active during the report period are as follows:

- A. Reflection and Refraction of Finite-Amplitude Sound at a Plane Interface between Two Fluids
- B. Propagation in a Periodic Waveguide
- C. Scattering of Sound by Sound
- D. Ellipsoidal Focusing
- E. Laboratory Upgrade

Project A was concluded during the year, and a major goal was reached in Project B. Project B will continue with a new goal, and Projects C, D, and E will also continue.

### 2.1 Reflection and Refraction of Plane Finite-Amplitude Waves at a Plane Interface between Two Fluids

This project was Cotaras' Ph.D. research topic and was completed during the year (89-1). Substantial assistance was provided by the Tjøttas.

A major goal of the project was to determine whether Snell's law and the law of specular reflection, two of the hallmarks of linear acoustics, must be modified when the incoming sound is of finite amplitude. Our initial attack on the problem was based on a number of simplifying assumptions. The most crucial was that the incoming sound is incident at the angle of intromission (the angle at which no reflected field is generated). For this case the progressive nature of the field on the incident-wave side of the interface makes the analysis very simple. Using these assumptions, we were able to derive the very interesting prediction that Snell's law does indeed need to be modified: at high intensities, the angle of transmission depends not only on the sound speed in each fluid but also on amplitude and on the nonlinearity coefficient of each fluid.<sup>1,2</sup> After a concerted effort to develop an experiment to test the prediction failed (88-5), we decided to return to the theoretical analysis. Nagging questions remained, mainly whether the simplifying assumptions made in the initial analysis are justified.

Might the scale of unknown effects associated with the assumptions be of the same order as the predicted changes in Snell's law?

In order to answer this question, Cotaras mounted a more rigorous attack on the problem, this time leaving out nothing. However, when modeling is made more precise, the difficulty in obtaining any kind of solution becomes severe. He had to settle for a solution that is valid for only weak nonlinearity. Nevertheless, the solution does contain all possible contributions to the nonlinearity, including motion of the interface, exact source conditions, and nonlinear relations between various field variables. Moreover, one can distinguish in the results the contribution of each individual effect neglected in the earlier derivation. The solution is extremely rich and will be a gold mine for future exploitation. One result that stands out is that the reflected and transmitted wave fields are far more complicated than is the case for small-signal waves. Another is that the most crucial assumption in the earlier analysis - that an angle of intromission exists - is so restrictive as to be impractical. Finally, despite the complexity of the reflected and transmitted fields, it appears that Snell's law and the law of specular reflection continue to hold, at least to second order. For more particulars refer to 89-7 (a detailed summary) or to 89-1 (the full report).

As noted in the last year's summary report (88-5), Cotaras also derived a three-dimensional wave equation for finite-amplitude waves in a thermoviscous, relaxing fluid (89-1).

## 2.2 Propagation in a Periodic Waveguide

This is Bradley's project. Reported last year (88-5) was the dispersion relation derived for linear acoustic propagation in an infinite rectangular waveguide loaded periodically with rigidly terminated rectangular side branches,

$$\cos(qh) = \cos(kh) - (S/2S_0) \tan(kd) \sin(kh) \quad (2.1)$$

This function relates the Bloch wave number  $q$  (waves in periodic media are known as Bloch waves<sup>3</sup>) to the free medium wave number  $k$  ( $= \omega/c_0$  for a lossless medium), where  $h$  is the period of the structure,  $d$  is the side branch depth,  $\omega$  is the angular frequency,  $c_0$  is the free medium sound speed, and  $S$  and  $S_0$  are the cross sectional areas of the side branch and the waveguide, respectively. Equation 2.1 is fairly typical of dispersion relations for periodic media in that plots of the real and imaginary parts of  $q$  show a band structure: bands of frequencies associated with propagating waves separated by bands of frequencies associated with attenuated waves. In order to model nonlinear propagation we used Korpel's progressive spectral wave equation,<sup>4</sup> which incorporates the effects of nonlinearity, arbitrary dispersion, and arbitrary dissipation (in order to be physically viable the dispersion and dissipation cannot be independently arbitrary but must be related by the Kramers-Kronig relation). By direct

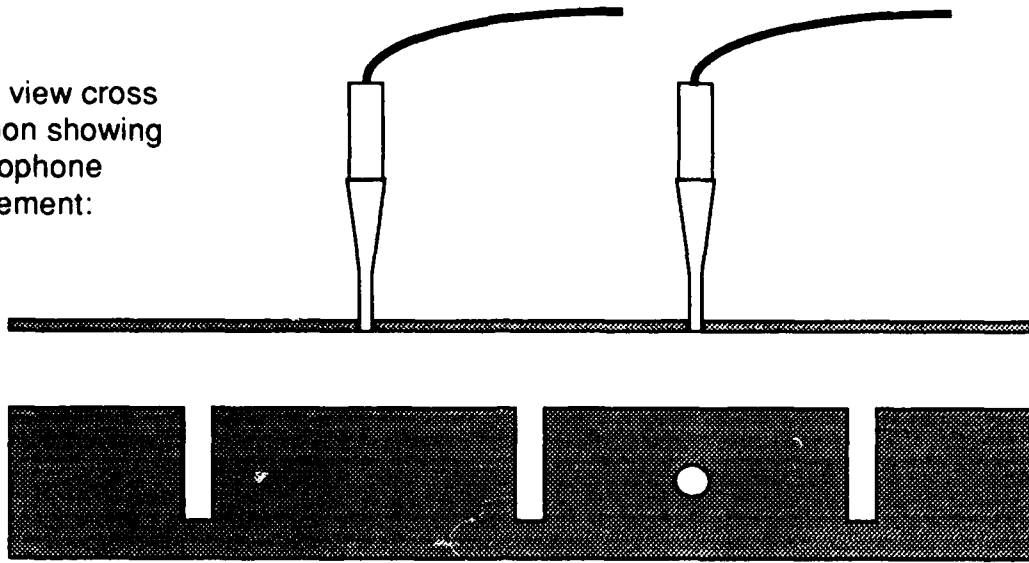
numerical integration of Korpel's equation we found that parametric up-conversion is effectively blocked regardless of whether the second harmonic is located in a passband or a stop band, though the blocking mechanisms are fundamentally different.

This year both the linear and the nonlinear theories have been extended, a periodic waveguide has been constructed, and both linear and nonlinear measurements have been made. The extension of the linear theory began with the generalization of the dispersion relation to include (1) thermoviscous acoustic boundary layer dissipation and dispersion, and (2) the end correction for the side branches where they join the waveguide. Expressions for the acoustic impedance, the Bloch wave function, and the Bloch traveling wave spectrum have been derived. The effect of truncation of the periodic structure has also been investigated and found to cause the generation of additional Bloch waves.

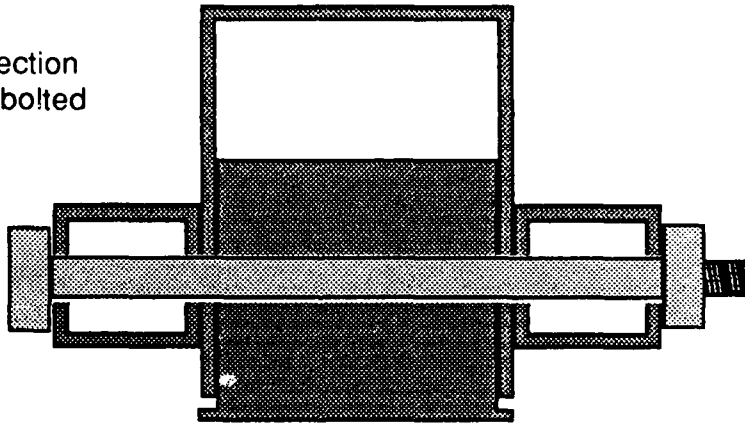
Work on the nonlinear theory has led to two interesting findings. First, a low frequency expansion of Eq. 2.1 yields the Korteweg-deVries dispersion relation. This, in concert with the quadratic nonlinearity typical of acoustics (as in Burgers' equation), implies that the Korteweg-deVries (KdV) equation would be an appropriate low frequency model equation for the periodic waveguide. Because the KdV equation is known to have stationary solutions called cnoidal waves and KdV solitons,<sup>5</sup> which are traveling wave solutions that *do not distort* in spite of the presence of nonlinearity and dispersion, it may be possible to observe waves of this sort in our waveguide. The second interesting finding is that, because of the effective blockage of parametric up-conversion, the efficiency of parametric down-conversion is enhanced. The enhanced efficiency is of interest in parametric acoustic traveling wave amplification and will be investigated further.

The experimental portion of the work began with the design and construction of a periodic waveguide and the development of software to drive a computer controlled data acquisition system. The waveguide's dimensions were chosen to produce relatively strong dispersion, a well defined band structure (the stop band locations can be controlled by the choice of sidebranch depth and structure periodicity), and relatively small thermoviscous losses, all at frequencies for which the analysis is valid. The waveguide is 38.1 mm x 25.4 mm in cross section and is 6 m long. It is loaded at intervals of 0.1 m by side branches 38.1 mm x 9.5 mm in cross section and 38.1 mm in depth. The overall design and some construction details are shown in Fig. 2.1. Propagation curves were measured for about 400 frequencies in the range 100 Hz to 4 kHz. Each propagation curve consisted of 48 measurements of amplitude and phase. Each of these measurements consisted of 2048 waveform samplings and some digital signal processing. All these measurements were combined to construct the (experimental) curves of attenuation and dispersion shown in Fig. 2.2. As can be seen, theory and experiment are in excellent agreement. It should be noted that the experimental work reported here is the first taken with the newly acquired computer

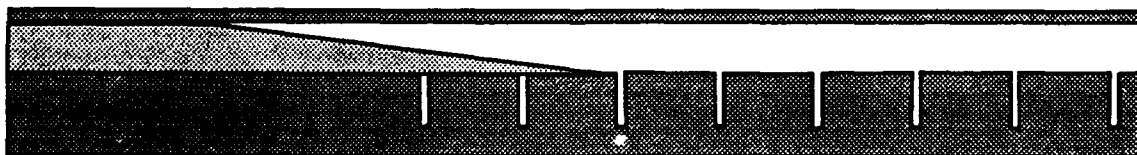
Side view cross section showing microphone placement:



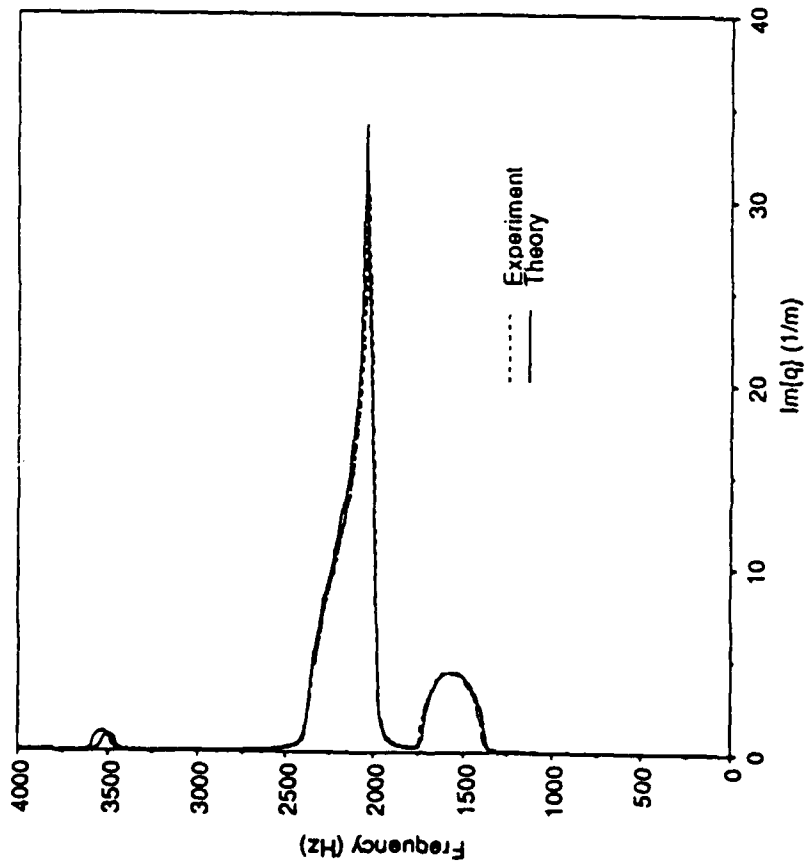
End view cross section showing through-bolted clamp setup:



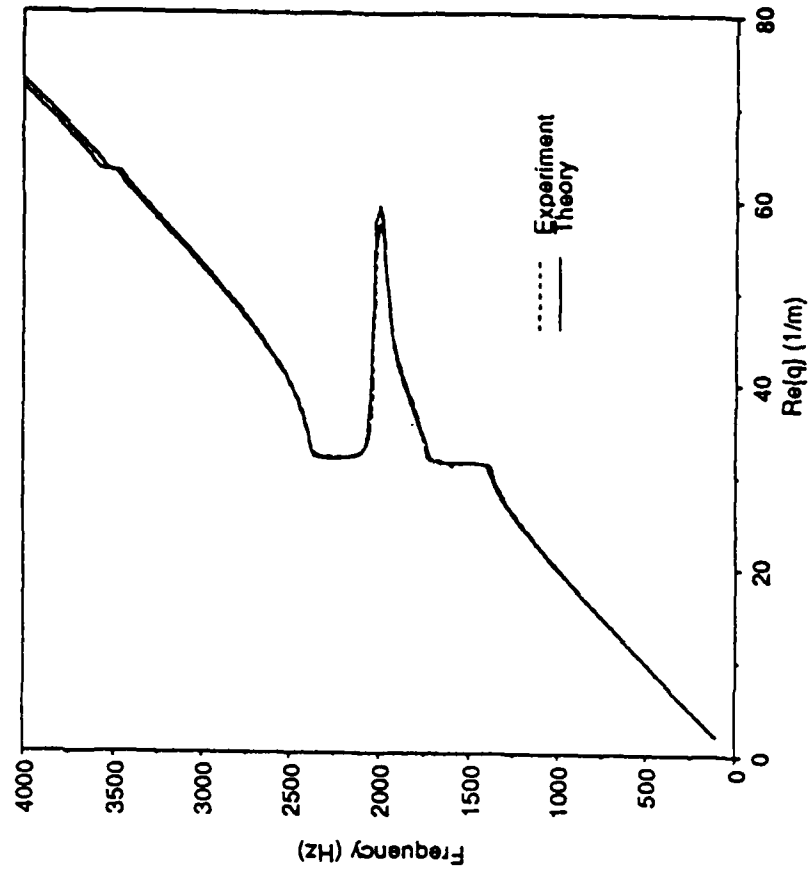
Side view cross section showing anechoic termination:



**FIGURE 2.1  
PERIODIC WAVEGUIDE STRUCTURE.  
GENERAL DESIGN AND CERTAIN CONSTRUCTION DETAILS.**



(a) Attenuation



(b) Dispersion

**FIGURE 2.2**  
**ATTENUATION AND DISPERSION OF SMALL-SIGNAL**  
**WAVES IN THE PERIODIC WAVEGUIDE SHOWN IN FIG.2.1**

controlled data acquisition system (see Sec. 2.5). Figure 2.2 attests to the accuracy and measurement density possible with the new system. Indeed, without the new system, it would have been impossible to obtain experimental curves having the detail (and the accuracy) shown in the figure.

A few high intensity measurements were also made. Measurements of the second harmonic amplitude for the pure tone excitation case in which the second harmonic resides in a passband show the expected spatial beating and are in good agreement with theory. When the second harmonic resides in a stop band its growth is also inhibited, as expected, and agrees fairly well with the theory. The validity of Korpel's equation in the stop band case is currently in question, however, as it does not account for the nondissipative attenuation that is present at stop band frequencies.

The linear and nonlinear experimental and theoretical work were presented recently at the Syracuse meeting of the Acoustical Society of America (89-4).

### 2.3 Scattering of Sound by Sound

The purpose of this project, which is Ten Cate's Ph.D. topic, is to perform an experimental check of the Tjøttas' predictions concerning scattering of sound by sound.<sup>6-9</sup> The need to design and construct a new measurement tank facility this year has delayed any measurements until next year. Besides participating in the design of the new facility and working on other aspects of the experiment, Ten Cate has collaborated with the Tjøttas to extend the theoretical predictions to account for realistic source and boundary conditions.

Although not constructed using funds from the Grant, the new tank facility, which is designed for measurements in the megahertz range, is nevertheless of interest because it will be used for Ten Cate's experiment. The facility is in the Engineering Teaching Center (ETC, the building of the Mechanical Engineering Department) on the main campus of the University. Because the electronic noise level in the frequency range of interest is much lower at ETC than at Applied Research Laboratories (ARL:UT), ETC is a much more favorable location for Ten Cate's experiment. (At ARL:UT one has to contend with severe rf interference from a nearby radio station, which broadcasts at 1.3 MHz.) W. M. Wright has had primary responsibility for the design and construction of the new facility. The following description is taken from his 8 June 1989 report of activities at U.T. Austin during 1988-89: "A glass tank with dimensions 3' x 5' x 3' was designed, constructed, and shown to sustain the water pressure with no leakage. Associated electronic apparatus was purchased and checked out. The assembly of tank, ultrasonic transducers, and electronic instrumentation in ETC 7.156 was found to have substantially less receiving system noise than had been

observed earlier at ARL. Following several changes in proposed approach, an order recently was placed for a custom designed, automated positioning system. This will fit over the tank and permit two megahertz-range transducers to be positioned with four axes under computer control and the remainder manually adjusted. Specifications include positional accuracy of 15 mils ( $375 \mu\text{m}$ ), linear axis resolution of 0.1 mil, and 0.1 degree resolution about a vertical axis of rotation. When the measurement system is complete and its operation fully understood (within the next year, it is hoped), one should have routine opportunity to perform computer controlled measurements and data analysis, e.g., for large-amplitude acoustic fields associated with single transducers and for the interaction of two intense sound fields."

The theoretical work on source and boundary conditions was prompted by the need to know their role in determining the actual scattered field that will be measured. For example, does it make any difference whether the two-frequency excitation at the source is a pressure signal or a particle velocity signal? What about the sum- and difference-frequency pressures  $p_{\pm}$  at the source? Is it appropriate to assume them zero or should their gradients (i.e., the particle velocities) be assumed zero? Does "at the source" mean the rest position of the source, say  $z = 0$ , or the actual position of the source face  $z = \zeta(t)$ , where  $\zeta(t)$  represents the instantaneous displacement of the face? Analysis to answer some of these questions is given in 89-8, where it is concluded that for certain cases, the precise specification of  $p_{\pm}$  at the source is indeed important for experimental observation.

## 2.4 Ellipsoidal Focusing

Motivated by an interest in the physical aspects of lithotripsy, a medical treatment whereby focused shock waves are used to disintegrate kidney stones, we have set up this project to study the interaction of nonlinear distortion, strong focusing, and diffraction. In the lithotripter in most widespread use (manufactured by the West German firm Dornier), the shock wave is generated by an electric spark at the near focus of an ellipsoidal reflector, and the patient is positioned so that the kidney stone is at the remote focus of the reflector. The treatment is carried out in a water bath. Our experimental arrangement is an airborne model of the Dornier device, but our purpose is to measure and understand the intense sound field, not to break stones. The work is a logical continuation of our long-standing practice of using N waves from sparks to try to understand the behavior of finite-amplitude sound.<sup>10</sup> Besides furnishing some input to lithotripsy research, the project may also provide means of testing theoretical treatments of pulse focusing that are being developed by the Tjøttas<sup>11</sup> and by M. F. Hamilton.<sup>12</sup>

Beginning in the summer of 1988, we have been largely occupied with machining

four ellipsoidal reflectors, setting up a data acquisition system that utilizes much of the new equipment described in Sec. 2.5, and making some preliminary measurements (89-2, 89-3). W. M. Wright, assisted by Cheng, has been primarily responsible for the work. Primary funding has come from the Texas Advanced Research Program (TARP) and the ARL:UT IR&D program. Table 2.1 gives information about the four reflectors that have been constructed so far; a and b stand for semi-major axis and semi-minor axis, respectively, and depth means distance from the vertex to the plane of the aperture.

**TABLE 2.1**  
**ELLIPSOIDAL REFLECTORS**

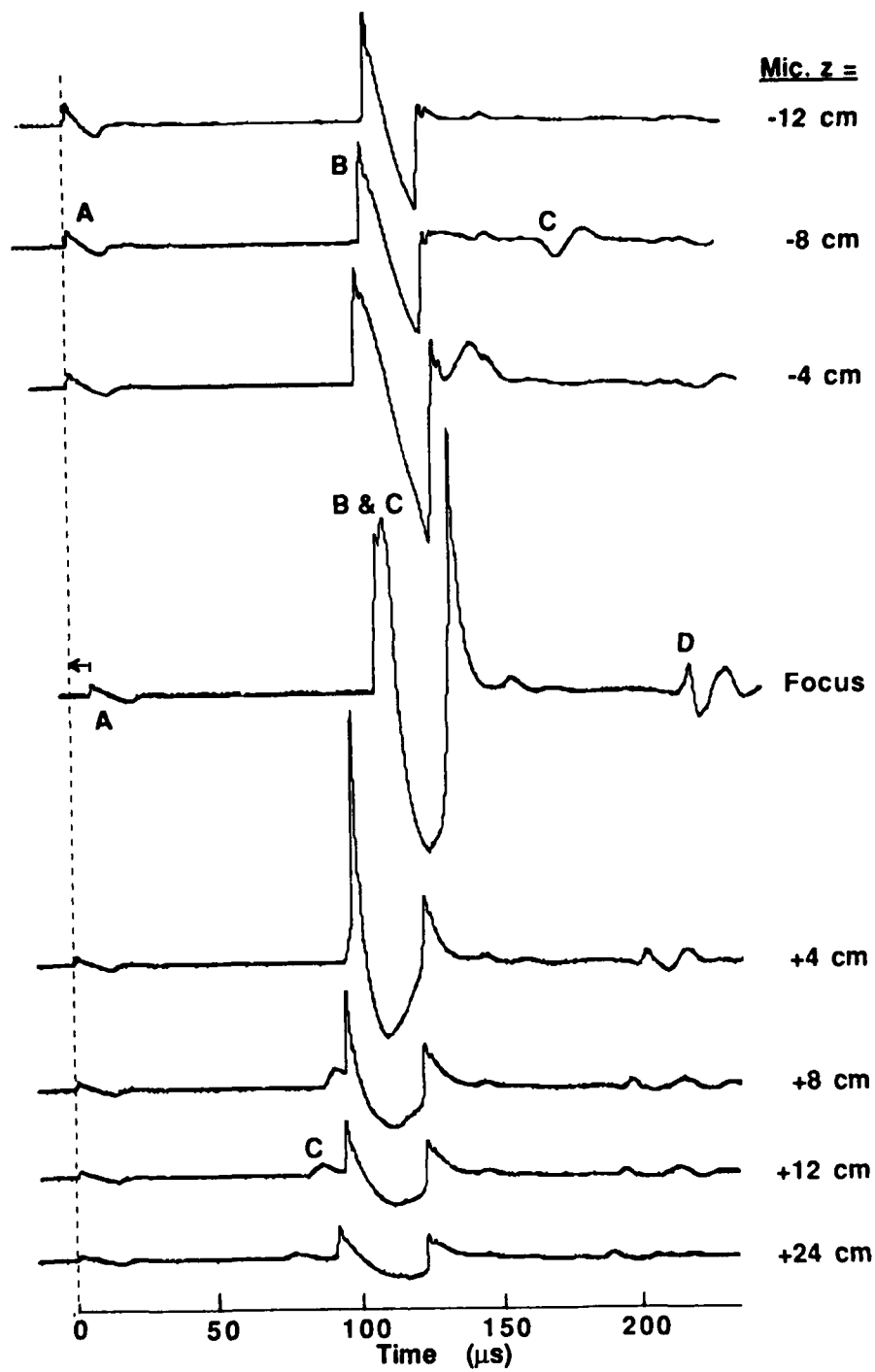
<u>Construction</u>		a	b	Depth
<u>Date</u>	<u>By</u>	<u>(mm)</u>	<u>(mm)</u>	<u>(mm)</u>
7-88	M. R. Jones	140	70	140
4-89	S. Cheng <i>et al.</i>	140	70	59.2
4-89	S. Cheng <i>et al.</i>	140	70	18.8
7-89	P. W. Li	161.2	106.2	40

The second, third, and fourth reflectors were made in order to investigate more fully the role of the diffracted wave.

Figure 2.3 (from 89-3) shows a sequence of axial waveforms obtained when the first reflector was used. "Mic. z" means the position of the microphone relative to the remote focus. The sequence begins with the microphone in the plane of the aperture (Mic. z=12 cm), proceeds to the focus, and ends far beyond the focus. The signal labeled A is the direct (i.e., unreflected) wave produced by the spark, B is the reflected wave, C is the diffracted wave, and D is of unknown origin. The change in waveform as the microphone is moved from the aperture (N-shaped wave) to the focus (U-shaped wave) may be explained qualitatively by using linear theory (strong phase shifts are expected to occur as the focus is approached). However, linear theory seems to fail for the region beyond the focus, where its use (additional phase shifts) would lead one to expect an inverted N to develop. For the post-focal region, the anticipated phase shifts are apparently brushed aside by nonlinear steepening. Each leg of the U-shaped wave becomes (or stays) a shock. The observed phenomena pose an interesting theoretical challenge.

## 2.5 Laboratory Upgrade

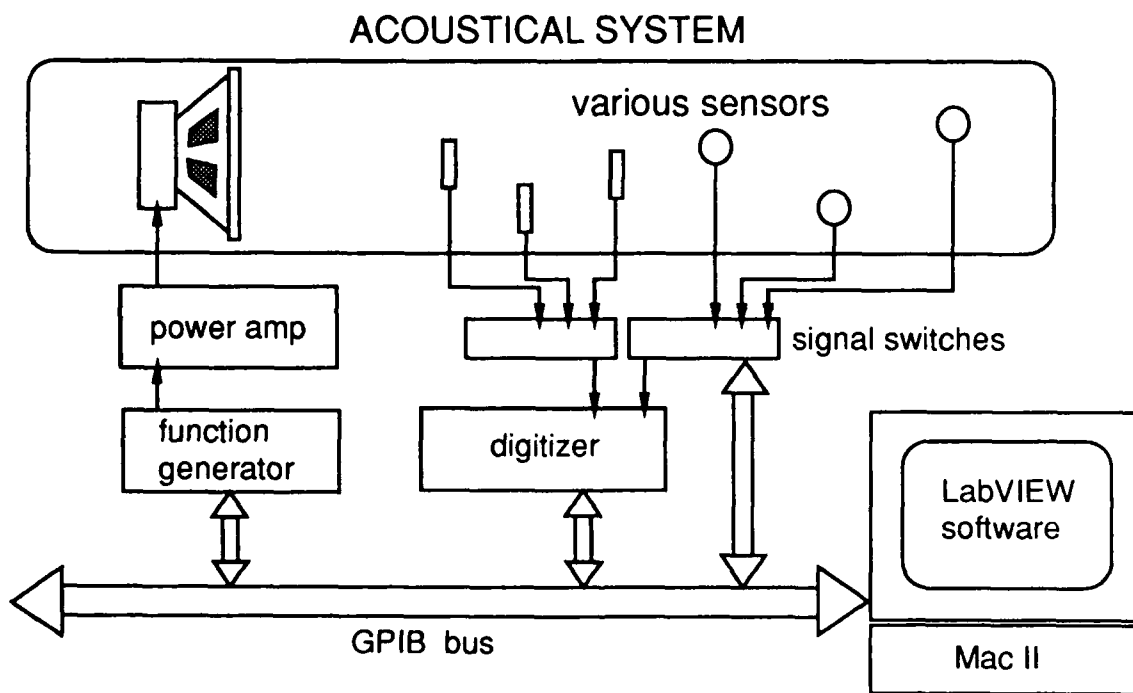
About two years ago it became clear that the Nonlinear Acoustics Laboratory was suffering from obsolescence. Although we were proud of the experimental work that



**FIGURE 2.3**  
**SEQUENCE OF WAVEFORMS FOR A PULSE FOCUSED BY AN**  
**ELLIPSOIDAL REFLECTOR**

had been done under ONR sponsorship in the past, much of the equipment was now outmoded. In particular, our experimental horizon was severely limited because of our inability to make computer controlled measurements. Beginning in late summer 1988, with the combined support of ONR and the ARL:UT IR&D program, we embarked on a two-year project to upgrade the Laboratory.

The first phase of the upgrade has been completed during the present year. We now have a computer controllable data acquisition system, the heart of which is a Tektronix realtime digitizer (RTD 710A), a Wavetek arbitrary function generator (model 275), software (National Instruments LabVIEW), and a general purpose interface bus (GPIB). The latter two items enable our Macintosh II computer to exercise control over the instruments. A typical experiment is shown in Fig. 2.4. The computer con-



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**FIGURE 2.4  
TYPICAL EXPERIMENT UTILIZING THE COMPUTER  
CONTROLLED DATA ACQUISITION SYSTEM**

trols both the source (by virtue of its ability to control the function generator) and the receiver system. The measurements described in Sec. 2.2 were obtained by using an arrangement much like this one. A substantial amount of signal processing was done automatically by the computer to convert signals from two microphones to the attenuation and dispersion data presented in Fig. 2.2. Without the new measurement system, it is doubtful that the experiment would ever have been attempted. A more primitive use of the system was made in the spark experiments (Sec. 2.4).

The spark source was manually controlled. The digitizer-GPIB-LabVIEW-MAC II system did, however, allow a sophisticated processing of the microphone signals. Figure 2.3, the laserwriter output from the computer, is a very useful direct display of the measurements.

The second and final phase of the upgrade will take place in the coming year. The main additions will be a two-channel synthesizer, several more microphones (so that the computer can exercise more control over the acquisition of the received signals), a means of making the spark source computer controllable, and some controllable mechanical positioning apparatus. The latter is needed to allow the microphone to be moved automatically in N wave experiments and similarly to allow automatic movement of a source and/or hydrophone in high frequency underwater experiments in a butterfly tank we have recently acquired.

### 3. SUMMARY

During the current report period, 1 October 1988 - 30 September 1989, we have been occupied primarily with five projects: (1) reflection and refraction at a plane interface, (2) propagation in a periodic waveguide, (3) scattering of sound by sound, (4) ellipsoidal focusing, and (5) an upgrade of the Nonlinear Acoustics Laboratory. In project (1), which is now complete, plane waves of finite amplitude are obliquely incident on a plane, fluid-fluid interface. The analysis has shown that, to second order, Snell's law and the law of specular reflection continue to hold. The reflected and transmitted sound fields are, however, much more complicated than in the small-signal case. A secondary part of the project was the derivation of the nonlinear wave equation for three-dimensional waves in a thermoviscous, relaxing fluid. Project (2) is a combined theoretical and experimental study of plane wave propagation through a tube that is periodically loaded with reactive branch elements. The small-signal study of this system has been completed. Predictions concerning stop bands (frequencies at which the signal is very highly attenuated) and pass bands (little or no attenuation) have been verified by detailed measurements. Work on finite-amplitude waves has begun. Project (3) is mainly experimental and complements very active theoretical work being carried out at The University of Texas at Austin under other sponsorship. Measurements have been delayed this year, however, while a proper tank facility for the experiments has been designed and constructed. In the meantime a theoretical analysis has been done to delineate the role played by source and boundary conditions in the scattering. Although the motivation for project (4) is lithotripsy, the experiments, which have been done with spark-produced N waves in air, also have bearing on recent theoretical studies of focusing of pulses. Dramatic changes in the waveform of an (initially) N shaped pulse have been measured as the pulse propagates toward, through, and beyond the focus. The purpose of project (5) is to make possible a variety of computer controlled experiments - free field in air (e.g., with N waves), airborne sound in waveguides, and free field in water - in nonlinear acoustics. The first phase of the equipment upgrade, the assembly of a flexible and potent computer controlled data acquisition system, has been completed. The new equipment had a powerful effect on projects (2) and (4).

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Grant N00014-89-J-1109

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Predecessor Contract N00014-84-K-0574 (ended 12-31-88)

	<u>Code</u>		<u>ONR Grant/Contract</u>
B	=	chapter in a book	1109 = N00014-89-J-1109,
J	=	journal publication	began 10-1-88
JS	=	submitted for journal publication	0574 = N00014-84-K-0574,
O	=	oral presentation	ended 12-31-88
P	=	paper in a proceedings	
T	=	thesis or dissertation	0867 = N00014-75-C-0867
TR	=	technical report	ended 8-31-84

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<u>Contract</u>	<u>Code</u>	
0574	J *1.	M. F. Hamilton and D. T. Blackstock, "On the coefficient of nonlinearity $\beta$ in nonlinear acoustics," <i>J. Acoust. Soc. Am.</i> <b>83</b> , 74-77 (1988).
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