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# Nonlinear Acoustics: Periodic Waveguide, Finite Amplitude Propagation in a Medium Having a Distribution of Relaxation Processes, and Production of an Isolated Negative Pulse in Water

**Fifth Annual Summary Report under Grant N00014-89-J-1109**


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Research on nonlinear acoustics has been performed during the 12-month period ending 30 September 1993. The following projects were completed.

(1) Propagation in a periodic waveguide
(2) Finite-amplitude propagation in a medium having a distribution of relaxation processes
(3) Production of an isolated negative pulse in water

Public communication of the research was accomplished through three theses, four oral papers, one journal article published, four journal articles submitted, and one paper in a symposium proceedings.

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# 1. INTRODUCTION

This is the fifth annual report under Grant N00014-89-J-1109, which began 1 October 1988. The research carried out under this grant is primarily in nonlinear acoustics. The broad purpose of the research 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 is for the period 1 October 1992 — 30 September 1993. See the fourth annual report (93-2)* for status of the research at the beginning of the current report period.

The following persons participated in the research during the report period:

### Graduate students

- M. R. Bailey, M.S. student in Mechanical Engineering
- C. E. Bradley, Ph.D. student in Mechanical Engineering. Degree awarded May 1993
- P.-W. Li, Ph.D. student in Physics. Degree awarded August 1993

Bailey and Li had partial support from the IR&D program of ARL:UT. The IR&D support began for Bailey in May 1993, and for Li in June 1993.

### Senior personnel

- W. M. Wright, Consultant, Physics Department, Kalamazoo College, Michigan
- D. T. Blackstock, principal investigator

*Numbers given in this style refer to items in the Chronological Bibliography given at the end of this report, e.g., 93-2 means the second entry in the list for 1993.

# 2. PROJECTS

The following projects were active during the report period:

A. Propagation in a Periodic Waveguide

B. Finite-Amplitude Propagation in a Medium Having a Distribution of Relaxation Processes

C. Production of an Isolated Negative Pulse in Water

D. Miscellaneous

## 2.1 Propagation in a Periodic Waveguide

This was Bradley's project and was completed this year. It was begun by Bradley during his first year, 1987-88, as a graduate student at The University of Texas at Austin. He selected the topic because he was keenly interested in dispersion and in nonlinear effects. Propagation in periodic media seemed to be a subject in which both phenomena could be important. The specific problem he chose to investigate was Bloch wave propagation in a rectangular waveguide that is periodically loaded with rigidly terminated side branches (89-4, 90-3, 90-7, 90-11). As the project developed, however, the scope broadened. The initial study, Bradley's master's thesis research (90-11, 91-4), was ostensibly restricted to small-signal Bloch waves. It was intended that finite-amplitude Bloch waves be the subject of his doctoral research. Indeed nonlinear effects are covered in Bradley's doctoral dissertation (93-1), but the dissertation is much more than just an extension of the master's work. It is a broad generalization of Bloch wave theory. It also contains fundamental work on dispersion in general, not just that associated with Bloch waves. Several journal articles are expected to result from the work. At the time of writing of this report, two articles are in draft form (93-8, 93-9), another will follow the lines of an oral presentation (93-12), and there may be more. Finally, it is worth noting that Bradley has been awarded the F. V. Hunt Postdoctoral Fellowship by the Acoustical Society of America largely because of the outstanding way in which he conducted his research.

The following three (slightly edited) excerpts from Bradley's dissertation provide different views of the research. First is the abstract, which gives a concise overview but does not capture the full spirit of the research. Second is the summary, which is part of the last chapter; here the reader begins to get more of the flavor of the work. The final excerpt is the second part of the last chapter, which I have entitled "Contributions." Here the author, at the insistence of his supervisor, discusses what is new and novel about his work. This section provides the perspective that enables the reader to more fully appreciate the research, even if he is not very familiar with Bloch waves.

### 2.1.1 Abstract

Propagation of acoustic waves in a class of periodically nonuniform waveguides is investigated both theoretically and experimentally. The waveguides under study are rigid, isothermal ducts of arbitrary cross-section that are filled with a thermoviscous fluid. The ducts may have arbitrary periodic boundary deformations and may contain a periodic array of scattering inclusions. It is shown that the solution functions are Bloch wave functions, and the properties of the Bloch waves are investigated theoretically and experimentally. The experiments are carried out in a rigid, air-filled rectangular duct that is loaded with a periodic array of rigidly terminated side branches.

In the investigation of linear, time-harmonic Bloch waves, many features of the band structure found in both the Bloch wave dispersion relation and the Bloch wave functions are derived analytically and verified in measurements. In the problem of linear Bloch wave pulse propagation the standard dispersion integral may be used. It is found that the validity of the solutions of the dispersion integral and hence the concept of group velocity are distance dependent. Both the Bloch wave group velocity and several new dispersive pulse solutions are derived and verified with measurements. A new approach to the problem of nonlinear, time-harmonic Bloch wave propagation is used. It is found that a progressive fundamental Bloch wave gives rise to both forward and backward travelling second harmonic Bloch waves, each of which oscillates in amplitude as it propagates. According to both theory and measurement, the Bloch wave dispersion is able to disrupt the cumulative waveform distortion that is characteristic of nonlinear wave propagation.

### 2.1.2 Summary

This dissertation is composed of four parts. In the first part the problem of linear, time-harmonic wave propagation in a large class of periodic waveguides is addressed. It is shown that the Floquet theorem may be applied to the system in order to determine that the solutions may be expressed in terms of Bloch wave functions. The approach avoids the use of approximate model equations that have been used in the past and accounts for mechanisms of dissipation. Expressions for the parameters that characterize the Bloch waves (the dispersion function $q(\omega)$ and the relative component wave amplitude $g/f(\omega)$) are derived and their band structures investigated. It is found that reciprocity places significant constraints on the allowed Bloch wave solutions. These findings are verified experimentally for both isotropic and anisotropic periodic waveguides.

In the second part, the problem of Bloch wave pulse propagation is addressed. The dispersion integral that governs the propagation of Bloch wave pulses is derived and a straightforward method of solution is found. Several novel pulse propagation solutions that exhibit very unusual behavior are identified and verified experimentally. For example, it is found that in some cases the carrier frequency of the pulse shifts as it propagates, the pulse accelerates, or the pulse propagates at near infinite group velocity. The Bloch wave pulse problem is also considered for the case of asymptotically large propagation distances. Dependent upon how the pulse spectrum is situated with respect to the band structure of the dispersion function, several solutions are found. According to the various solutions, the pulse envelope may or may not remain localized, may distort into its own Fourier transform, or may be trailed by a long oscillating tail. Unfortunately, an experiment to verify these results is not practical.

In the third part, the problem of energy transport by acoustic Bloch waves is addressed. It is found that there are two different but physically relevant energy transport velocities associated with periodic waveguides. One of the energy transport velocities is verified experimentally and the other, which is simply the group velocity, is verified experimentally in Chapter 5.

In the fourth part, the effect of nonlinearity on the propagation of Bloch waves is considered. The approach to the solution of the problem is to first develop and then use a discrete Green's function method. This method does not require the approximate representations of the fundamental and second harmonic fields that have been used in earlier work. It is found that a forward travelling fundamental Bloch wave generates both forward and backward travelling second harmonic Bloch waves, each of which oscillates in amplitude as it propagates. As in the case of conventional nonlinear waves, dispersion disrupts the resonant generation of a second harmonic field. Consequently, the second harmonic field level remains small. In other words, the Bloch wave propagates with very little net distortion. This and other effects predicted by the theory are verified experimentally. The imposition of some sort of periodic structure into an otherwise uniform waveguide is therefore a means of suppressing the waveform distortion caused by nonlinearity.

### 2.1.3 Contributions

In this work a number of contributions are made to the base of knowledge of acoustic Bloch waves in periodic waveguides. In addition, several contributions are made to the field of dispersive wave propagation in general. These contributions, which are both theoretical and experimental, are outlined here.

The contributions in the area of linear, time-harmonic Bloch waves are as follows. As is pointed out in Sec. 1.1, it had previously been shown that the solutions to periodic waveguide problems are Bloch waves only when (1) the system may be modeled by a (necessarily restrictive) ordinary differential equation, and (2) the system is nondissipative. It is found here that the solutions are Bloch wave functions for a very broad class of periodic waveguides that generally cannot be modeled with an ordinary differential equation, and are dissipative as well. To the author's knowledge, it had not before been shown, for ***any*** type of Bloch wave, that the Bloch wave formalism is valid in the presence of dissipation. While the features of the band structure of the Bloch wave dispersion is well known, these features had not been derived for a general system as they are here. The occurrence of a stopband at the resonance frequencies of the scatterer is, to the author's knowledge, a previously unknown phenomenon. While detailed measurements of Bloch wave dispersion have been made in microwave systems, they have not before been made in acoustic systems. The measurements of $g/f$ are certainly the first made for an acoustic Bloch wave system and are believed to be the first made for a Bloch wave system of any kind. The restrictions that reciprocity imposes on the allowed solutions of anisotropic periodic waveguide problems was not previously known.

The contributions of the work on Bloch wave pulse propagation are mainly in the area of narrowband pulse propagation in general. As far as the author is aware, the concept of the characteristic pulse distortion distance was not known before. It was not previously recognized that the key to the determination of the validity of solutions to the dispersion integral is a distance. As a result, the validity of the concept of group velocity was not recognized before as simply being distance dependent. As the large, absorption band group velocities were thought not to be valid, they had not been measured before. Similarly, the new pulse distortion solutions (the shifting carrier solution and the accelerating pulse solution) were neither known of nor verified in measurement. In the general theory of Bloch waves, the Bloch dispersion integral and the recovery operator solutions are also new.

While no previous work had been done on energy transport by acoustic Bloch waves, such work has been done in the context of microwaves. In that discipline, however, the microscopic energy transport velocity had not been recognized. The measurement of the microscopic energy transport velocity here is therefore the first. While in the field of electromagnetic wave propagation in dispersive dielectrics it had been recognized that two different energy transport velocities exist, it was not known before that the same is true of Bloch wave systems.

While a substantial amount of work has been done in the area of nonlinear Bloch waves, the previous work was all done using a weak Bloch wave dispersion approximation. The present work represents an entirely different approach to the problem, one that is valid for arbitrarily strong Bloch wave dispersion. The measurement of the nonlinear effects is the first in an acoustic system.

Two interesting integral relations that did not previously exist were derived for this work. One is the exact dissipative reciprocity relation derived in Appendix A. Dissipative reciprocity relations derived in the past have made use of the lossy Helmholtz equation, which is valid only for irrotational flow and therefore valid only far from boundaries. The reciprocity relation derived here is exact and therefore valid even in the thermoviscous acoustic boundary layer. The other integral relation is the time-averaged energy integral derived in Chapter 7. The integral gives the time-average acoustic energy contained in a volume given the field at the boundary.

## 2.2 Finite-Amplitude Propagation in a Medium Having a Distribution of Relaxation Processes

This project is Li's doctoral research. Initially sponsored by NIH, the work has been supported by ONR since October 1991. Although the intended application is to biomedical ultrasound, the basic problem is one in physical acoustics: How do finite-amplitude waves propagate in a multiply relaxing medium, and what temperature rise is produced in the medium by absorption of the finite-amplitude waves? The research is described below in an edited version of the summary of Li's dissertation (93-8). One oral report has been given (92-4) and another is planned (93-13). Two journal articles are in preparation (93-10, 93-11).

This dissertation has two parts. The first part is devoted to the derivation and analysis of a generalized Burgers equation for propagation of high intensity sound waves in a thermoviscous, multiply relaxing fluid. Of particular interest in this study is the application of the generalized Burgers equation to biomedical ultrasonics. The biomedical profession has not previously had an adequate nonlinear wave equation to model intense ultrasound in tissue.

The generalized Burgers equation is derived from first principles. The fundamental (nonlinear) fluid equations are combined with an equation of state that includes the effect of nonequilibrium thermodynamical processes. The mechanisms of dissipation are viscosity, heat conduction, and relaxation. A fluid having a single relaxation is considered first, then a fluid having multiple but separate relaxations, and finally a fluid having so many, closely spaced relaxations that they may be represented as a continuous distribution. Since it is known from linear theory that the continuous distribution model may be used to explain the (empirical) absorption law $\alpha_0(\omega) \sim \omega^n$ for soft tissue, where $n$ is often in the range 1 to 1.4, our generalized Burgers equation is ideal for usage in biomedical ultrasound. Here is a summary of the assumptions made in the derivation.

- Relaxation effects are small and the relaxational processes are independent of each other. This assumption is valid when the disturbance from equilibrium of each of the relaxation processes is small enough that the linear version of the reaction equation can be used.
- Both thermoviscous and dispersion effects are small.
- The acoustic signals are small in the sense that the particle velocity Mach number $\epsilon$, though small compared with unity, is large enough for quadratic nonlinear effects to be important.
- The various losses are small enough that only their first order interaction with the acoustic signal is considered. If the losses were very large, the acoustic signal would die out before nonlinear propagation effects became significant.

The final form of the generalized Burgers equation is as follows:

$$\frac{\partial p'}{\partial x} - \frac{b}{2\rho_0 c_0^3}\frac{\partial^2 p'}{\partial t'^2} - \frac{m_0}{2c_0}\frac{\ln(\tau_l/\tau_s)}{1-\tau_s/\tau_l}\frac{\partial}{\partial t'}\int_{-\infty}^{t'}\frac{\partial p'}{\partial t''}K(t'-t'')dt'' = \frac{\beta}{2\rho_0 c_0^3}\frac{\partial p'^2}{\partial t'} \quad , \tag{2.1}$$

where $p'$ is acoustic pressure, $x$ is distance from the source, $t' = t - x/c_0$ is retarded time, $\rho_0$ is density of the fluid at rest, $b$ is a constant proportional to the coefficients of viscosity and heat conduction, $\tau_l$ and $\tau_s$ are the largest and the smallest relaxation times in the medium, and $\beta$ is the coefficient of nonlinearity. The strength of dispersion at the reference time $\tau_0$ is defined as $m_0 \equiv 1 - c_\infty^2/c_0^2$ where $c_0$ and $c_\infty$ are the small-signal sound speeds at zero frequency and infinite frequency, respectively. The kernel $K$ in Eq. 2.1 is

$$\begin{aligned} K(t'-t'') &\equiv \frac{1}{\ln(\tau_l/\tau_s)}\int_{\tau_s/\tau_0}^{\tau_l/\tau_0} d\tau\,\frac{1}{\tau}\,e^{-(t'-t'')/\tau} \quad , \\ &= \frac{1}{\ln(\tau_l/\tau_s)}\{E_1[(t'-t'')\tau_0/\tau_l] - E_1[(t'-t'')\tau_0/\tau_s]\} \quad , \end{aligned} \tag{2.2}$$

where $E_1$ is the usual exponential integral of first order

$$E_1(z) = \int_z^\infty \frac{e^{-t}}{t}\,dt \quad .$$

The various terms in Eq. 2.1 have the following physical meaning. The first term on the L.H.S. represents basic propagation, that is, if all other terms were absent, the solution would be $p' = f(t - x/c_0)$. The second term represents thermoviscous effects, the third term molecular relaxation. The term on the R.H.S. is quadratic and represents the nonlinear effects. Omission of this term yields the equation for the propagation of small-signal plane waves in a thermoviscous, relaxing medium. If instead the integral term is dropped, we recover the well-known classical Burgers equation.

The first part of the dissertation concludes with a discussion of the mathematical properties of Eq. 2.1, some asymptotic solutions for certain limiting cases, and numerical solutions for (1) a sinusoidal wave source, and (2) a Gaussian pulse source.

In the second part of the dissertation, the generalized Burgers equation is applied to obtain a prediction of the finite-amplitude absorption coefficient for tissue and the temperature rise in the tissue caused by absorption of the sound energy. When the ultrasound is intense, nonlinear distortion of the wave causes the absorption to be significantly higher than that predicted from linear theory. The maximum value of the absorption coefficient occurs at approximately the shock formation distance.

Conversion of the absorbed acoustic energy into heat causes the temperature of the tissue to rise. At the same time, however, heat is carried away from the tissue by conduction and blood perfusion. The bio-heat equation, which is a commonly used heat transfer model in biomedical studies, is employed here to estimate the temperature increase. The limiting temperature rise is significantly affected by nonlinear effects (which enhance the absorption) and by perfusion. For example, when the ultrasonic source is strong, the temperature rise can be much higher than the value found from linear theory. Particular attention must be paid to points in the neighborhood of the shock formation distance, where the temperature rise is highest. Perfusion is found to have a interesting interplay with the nonlinear effects. When the perfusion length is shorter than the shock formation distance, and the nonlinearity is not too great, two temperature peaks occur along the beam axis. One of the peaks is associated with the perfusion length, the other with the shock formation distance. When the perfusion length becomes comparable to the shock formation distance, however, the two peaks merge into a single peak. This phenomenon has not been previously reported.

## 2.3 Production of an Isolated Negative Pulse in Water

This project, which constitutes Bailey's M.S. research, is based is on the obvious but rarely considered fact that when a wave is incident on an irregular edge, the diffracted wave produced is incoherent. We apply the principle to generate a unipolar negative pressure pulse in water. The method is described in the following abstract of a paper recently presented (93-3).

"An underwater spark, a circular aperture, and an irregularly shaped disk may be used to produce an isolated unipolar negative-pressure pulse. The spark generates a unipolar positive pulse (the accompanying negative tail is often not very noticeable). Forward scattering by the aperture yields the positive-pulse direct wave, followed by the edge wave, which is an inverted replica of the direct wave. We place an irregular disk in the middle of the aperture to block the direct wave. Because the edge wave introduced by the disk is incoherent, and therefore negligible, the only signal left on the axis is the negative-pulse edge wave. Experiments with a corprene aperture and a corprene irregular disk have confirmed the isolation of the negative pulse. Such a pulse may have application in medical ultrasonics and cavitation research."

At the end of the paper some other applications are discussed: "We have considered some other interesting applications of incoherent scattering and have made simple measurements to confirm the basic ideas. First, an aperture with an irregular edge produces a negligible edge wave. An irregular circular mask could thus be fit over the face of a uniform circular piston radiator to de-emphasize the edge wave and thereby reduce minor lobes in the piston directivity pattern. Second, in the use of barriers for road noise control, making the top of the barrier irregular should reduce the noise scattered into the shadow zone." We have made measurements with a barrier having an irregular edge and have confirmed the fact that the irregularity improves the effectiveness of the barrier (92-3, 93-3, 93-14). We have not yet tried fitting an irregular mask over a circular piston transducer but plan to do so.

Bailey will complete his thesis shortly after the report period. The acceptance date recorded by the University will be December 1993 (93-14).

During the latter part of the report period Bailey was able to apply much of the expertise he had developed on pulse generation and measurement. He spent the summer at the Rochester Center for Biomedical Ultrasound, University of Rochester, where, under the direction of E. L. Carstensen, he investigated damage to lung and other tissue involving air bodies by intense pressure pulses in water. In particular he compared the tissue damage caused by unipolar positive pulses to that caused by unipolar negative pulses. The damage is assumed to be due to cavitation. Conventional wisdom is that, because of the more violent bubble collapse caused by a negative pulse, it should produce considerably more damage than a positive pulse. The rather surprising finding of the study is that the tissue damage is about the same for both pulses. The explanation may be that the conventional wisdom is based on free bubble behavior in water, whereas a bubble surrounded by tissue (or other matter different from water) may respond to acoustic excitation in a quite different manner.

## 2.4 Miscellaneous

A "sea stories" paper was given at the Fall 1992 Meeting of the Acoustical Society of America on graduate acoustics under F. V. Hunt at Harvard during the period just before WW II and the postwar period 1946-71 (92-2).

The article by Cotaras and Morfey (see 93-2) has finally been published in *J. Acoust. Soc. Am.* (93-4), followed in the next issue by Ten Cate's account of his measurements of finite-amplitude effects in piston radiation (93-6).

Last year's project on finite-amplitude waves in a three-layer fluid (93-2) had to be at least temporarily postponed because the student working on the project left the program.

# 3. SUMMARY

During the current report period, 1 October 1992 - 30 September 1993, research was done on the following projects (student's name shown in parenthesis):

1. Propagation in a periodic waveguide (Bradley)
2. Finite-amplitude propagation in a medium having a distribution of relaxation processes (Li)
3. Propagation of an isolated negative-pressure pulse in water (Bailey)

Project 1, begun in 1988, was brought to a conclusion. Bradley's dissertation provides a broad general treatment of Bloch wave theory, for both small-signal and finite-amplitude waves, along with a description of experimental measurements. The measurements were done in a rectangular waveguide periodically loaded with rigidly terminated side branches. The dissertation also contains much new material on dispersion in general, that is, not restricted to Bloch waves. Public disclosures over the life of the project include five oral presentations, a paper in a conference proceedings, a master's thesis and related technical report, a doctoral dissertation, and three planned journal articles. Project 2, for which ONR support began two years ago, was also completed this year. Li's research includes the derivation of a model equation for plane, finite-amplitude waves in a thermoviscous, multiply relaxing fluid, some solutions of the model equation, calculation of the absorption of the acoustic energy by the medium, and calculation of the temperature rise due to the absorption. Over the period of ONR support for the project, two oral presentations have been given, one doctoral dissertation has been completed, and two journal articles are planned. Project 3, also brought to a conclusion this year, culminated in Bailey's master's thesis (but follow-on work is anticipated). Principles based on diffraction from regular and irregular edges were applied to develop an apparatus for generating unipolar negative pressure pulses in water. Two oral presentations, a paper in a conference proceedings, and a master's thesis constitute the public disclosures for this project.

# CHRONOLOGICAL BIBLIOGRAPHY
1988-1993

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## 1988–1993
## Grant N00014-89-J-1109
## and
## Predecessor Contract N00014-84-K-0574 (ended 9-30-88)

| | | Code | ONR Grant/Contract | | |
|---|---|---|---|---|---|
| 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 |

### 1988

| ONR Contract | Code | | |
|---|---|---|---|
| 0574 | J | [a]1. | M. F. Hamilton and D. T. Blackstock, "On the coefficient of nonlinearity $\beta$ in nonlinear acoustics," *J. Acoust. Soc. Am.* **83**, 74–77 (1988). |
| 0574 | O | [b,c]2. | D. T. Blackstock, "Shock wave propagation and shape of the waveform," Conference on Lithotripsy (Extra-Corporeal Shock Wave Applications - Technical and Clinical Problems), University of Florida, Gainesville, 12–13 March 1988. |
| 0574 | O | [b]3. | D. T. Blackstock, "Calculation of the intensity and absorption of a finite-amplitude sound wave," Paper B8, 115th Meeting, Acoustical Society of America, Seattle, 16-20 May 1988. ABSTRACT: *J. Acoust. Soc. Am.* **83**, S5 (1988). |
| 0574 | O | [b]4. | D. T. Blackstock, "Physical aspects of lithotripsy," Paper GG1, 115th Meeting, Acoustical Society of America, Seattle, 16-20 May 1988. ABSTRACT: *J. Acoust. Soc. Am.* **83**, S71 (1988). |

[a]Hamilton's support for this work came from Contract N00014-85-K-0708.

[b]Primary support for this work came from University of Rochester, NIH Grant CA 39241.

[c]Partial support for this work came from a grant from Bureau of Engineering Research, College of Engineering, The University of Texas at Austin.

| ONR Contract | Code | | |
|---|---|---|---|
| 0574 | TR | 5. | D. T. Blackstock, "Nonlinear Acoustics: Reflection and Refraction, Scattering of Sound by Sound, and Periodic Media," Fourth Annual Summary Report under Contract N00014-84-K-0574, Technical Report ARL-TR-88-30, Applied Research Laboratories, The University of Texas at Austin, 30 June 1988 (AD A197 614). |
| 0867 | J | 6. | M. F. Hamilton and J. A. Ten Cate, "Finite amplitude sound near cutoff in higher order modes of a rectangular duct," *J. Acoust. Soc. Am.* **84**, 327-334 (1988). |
| Gen§ | O | 7. | D. T. Blackstock, I. J. Busch-Vishniac, M. F. Hamilton, and E. L. Hixson, "Graduate acoustics at The University of Texas at Austin," Paper ZZ9, 116th Meeting, Acoustical Society of America, Honolulu, 14-18 November 1988. ABSTRACT: *J. Acoust. Am.* **84**, S167 (1988). |

§Although no specific grant or contract can be cited, it is appropriate to acknowledge ONR because its support of research in physical acoustics at U. T. Austin has played an important role in the development of the University's graduate acoustics program.

## 1989

| ONR Contract | Code | | |
|---|---|---|---|
| 1109<br>0574 | T,TR | 1. | F. D. Cotaras, "Reflection and Refraction of Finite Amplitude Acoustic Waves at a Fluid-Fluid Interface," Ph.D. dissertation, Electrical and Computer Engineering Department, The University of Texas at Austin, May 1989. Also issued as Technical Report ARL-TR-89-1, Applied Research Laboratories, The University of Texas at Austin (3 January 1989). (AD A209800) ABSTRACT: *J. Acoust. Soc. Am.* **92**, S201 (1991). |
| 1109 | O | [d]2. | D. T. Blackstock, S. Cheng, M. R. Jones, and W. M. Wright, "Focusing of intense sound pulses by an ellipsoidal reflector," Paper BE12, Joint Spring Meeting, Texas Sections of American Association of Physics Teachers and American Physical Society, University of Houston, Houston, 3–4 March 1989. |
| 1109 | O | [d]3. | S. T. W. Cheng, M. R. Jones, D. T. Blackstock, and W. M. Wright, "Focusing of an N wave by an ellipsoidal reflector: An experiment in air," Paper TT12, 117th Meeting, Acoustical Society of America, Syracuse, 22–26 May 1989. ABSTRACT: *J. Acoust. Soc. Am.* **85**, S113 (1989). |
| 1109<br>0574 | O | 4. | C. E. Bradley, "Finite amplitude acoustic propagation in a periodic structure," Paper B12, 117th Meeting, Acoustical Society of America, Syracuse, 22–26 May 1989. ABSTRACT: *J. Acoust. Soc. Am.* **85**, S6 (1989). |
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| 1109 | TR | 6. | D. T. Blackstock, "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, Technical Report ARL-TR-89-38, Applied Research Laboratories, The University of Texas at Austin, 31 July 1989. (AD A211412) |

[d]Primary support for this work came from Applied Research Laboratories IR&D program and Texas Advanced Research Program.

| ONR Contract | Code | | |
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[e]Partial support for this work came from Applied Research Laboratories IR&D program.

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[f]Maynard's support for this work came from an ONR contract at Pennsylvania State University.

[g]Partial support for this work came from NIH Grant CA 49172 and from University of Rochester NIH Grant CA 39241.

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[h]Primary support for this work came from NASA Grant NSG 3198.

[i]Hamilton's support for this work came from Grant N00014-89-J-1003.

[j]Also supported in part by Grant N00014-J-90-1373.

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[k]Also supported in part by Grant NAG-1-1204 and University of Southampton, England.

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[1]Also supported in part by ONR Grant N00014-89-J-1103, Applied Research Laboratories IR&D program, and David and Lucille Packard Foundation.

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[m]Also supported in part by NIH Grant CA 41972.

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24 August 1993

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