OF TEXAS
AUSTIN

DEPARTMENT OF MECHANICAL ENGINEERING

PROBLEMS IN NONLINEAR ACOUSTICS:

PARAMETRIC RECEIVING ARRAYS,
FOCUSED FINITE AMPLITUDE SOUND,
AND DISPERSIVE NONLINEAR INTERACTIONS

First Annual Summary Report under ONR
Contract N00014-85-K-0708 (April, 1986)

Mark F. Hamilton

DTIC
ELECTE
MAY 1 3 1986
S   D
B

86 5 12 161

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER	2. GOVT ACCESSION NO. AD-A16731	3. RECIPIENT'S CATALOG NUMBER
4. TITLE *(and Subtitle)* Problems in Nonlinear Acoustics: Parametric Receiving Arrays, Focused Finite Amplitude Sound, and Dispersive Nonlinear Interactions. First Annual Summary Report under Contract N00014-85-K-0708		5. TYPE OF REPORT & PERIOD COVERED Annual Summary Report 1 Sept. 1985 - 30 April 1986
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Mark F. Hamilton		8. CONTRACT OR GRANT NUMBER(s) N00014-85-K-0708
9. PERFORMING ORGANIZATION NAME AND ADDRESS Department of Mechanical Engineering The University of Texas at Austin Austin, TX 78712-1063		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 61153N 11 4126943
11. CONTROLLING OFFICE NAME AND ADDRESS Office of Naval Research Department of the Navy Arlington, Virginia 22217		12. REPORT DATE 30 April 1986
		13. NUMBER OF PAGES 29
14. MONITORING AGENCY NAME & ADDRESS(*if different from Controlling Office*)		15. SECURITY CLASS. *(of this report)* UNCLASSIFIED
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE
16. DISTRIBUTION STATEMENT *(of this Report)* Approved for public release; distribution unlimited		
17. DISTRIBUTION STATEMENT *(of the abstract entered in Block 20, if different from Report)*		
18. SUPPLEMENTARY NOTES		
19. KEY WORDS *(Continue on reverse side if necessary and identify by block number)* nonlinear acoustics parametric array focused sound dispersive interactions		

20. ABSTRACT *(Continue on reverse side if necessary and identify by block number)*
Three projects are discussed in this report. (1) Use of a parametric receiving array to measure ship noise. The possibility of using a parametric receiving array (parray) for eliminating multipath components in measurements of ship noise was investigated theoretically. A model based on the non-collinear interaction of two diffracting Gaussian beams has been developed. Results were obtained for the specific case of a parray whose pump is located

(continued on back)

DD FORM
1 JAN 73 1473   EDITION OF 1 NOV 65 IS OBSOLETE

S/N 0102-LF-014-6601

on the sound source. Predicted parametric measurements of beam patterns radiated by the source are shown to be in reasonable agreement with conventional results when the receiving hydrophone is beyond about 10 Rayleigh distances from the source. Inversion formulas were derived that determine the noise source distribution from nearfield measurements obtained with a parray. (2) <u>Focused finite amplitude sound</u>. An existing computer program has been modified for application to focused sound fields radiated by real sources. The program accounts simultaneously for the effects of nonlinearity, diffraction, and absorption. Results computed with the program compare very well with analytic linear models for focused sound that is strongly affected by diffraction. Analysis of low amplitude focused sound fields was performed before using the program to investigate finite amplitude effects at high amplitudes. (3) <u>Dispersive nonlinear wave interactions in a rectangular duct</u>. Preliminary experimental work was performed in preparation for an investigation of finite amplitude noise that propagates in higher order modes of a rectangular duct.

PER CALL JC

A-1

INTRODUCTION

Work discussed in this Annual Summary Report was supported by ONR Contract N00014-85-K-0708. The contract began 1 September 1985 and terminates 31 August 1986, but this report covers research performed only up to 30 APR 1986. The personnel involved with the research effort are as follows.

Senior Personnel

M. F. Hamilton, principal investigator

J. Naze Tjøtta and S. Tjøtta, visiting scientists,
    University of Bergen, Norway

Graduate Students

C. Darvennes, Ph.D. student in Mechanical Engineering

T. S. Hart, M.S. student in Electrical Engineering

S. J. Lind, M.S. student in Architectural Engineering

It must be pointed out that the research performed by J. Naze Tjøtta and S. Tjøtta on problems outlined in the proposal for Contract N00014-85-K-0708 was accomplished from June through August of 1985 and therefore just prior to the start of the present contract. The Tjøttas' work was supported by the Independent Research and Development program of Applied Research Laboratories, The University of Texas at Austin (ARL:UT). Their collaborative effort with Hamilton during that period yielded substantial progress on the proposed use of a parametric receiving array to measure ship noise. The results of that work are therefore discussed in the present report.

Contract N00014-85-K-0708 provides for basic research on nonlinear acoustics. The three projects currently supported by the contract are as follows:

1. Use of a Parametric Receiving Array to Measure Ship Noise

2. Focused Finite Amplitude Sound

3. Dispersive Nonlinear Wave Interactions in a Rectangular Duct.

The first project is the primary research effort supported by the contract, and the investigation is predominantly theoretical. The second involves computational analysis, the third experimental. Each project is discussed separately in the following sections.

2

I. USE OF A PARAMETRIC RECEIVING ARRAY TO MEASURE SHIP NOISE

1. Personnel

Research on this project began during the months just prior to the start of the present contract on 1 September 1985. Substantial contributions were made by J. Naze Tjøtta and S. Tjøtta from June through August of 1985. The Tjøttas were on leave from the University of Bergen, Norway, and spent the summer months at ARL:UT, where they were supported by internal funds. Together with Hamilton, the Tjøttas submitted for publication in the Journal of the Acoustical Society of America a manuscript that discusses a mathematical model of the parametric receiving array, for use in measuring ship noise, that is based on Gaussian beam theory.[1] It seems appropriate to report here the results contained in that manuscript. C. Darvennes has worked on this project since 1 September 1985.

2. Background

The task of accurately measuring the radiated noise from large ships underway is complicated by two factors[2] resulting from the phenomenon referred to as multipath. A hydrophone used to detect the acoustic radiation may receive not only the noise propagating directly from the ship but also reflected signals from both the surface of the water and the ocean floor. One problem arises when the ship is underway, because the Doppler shift associated with each multipath component will in general be different.[3] The resulting differential Doppler shift alters the frequency distribution of acoustic energy in the received signal. To avoid differential Doppler shift, a highly directional hydrophone array capable of discriminating against the multipath components is desirable. The second complication resulting from multipath concerns the determination of transmission loss necessary for calculating source levels. In a recent investigation by Wright and Cybulski,[4] sonobouys were used to measure

3

the low frequency noise radiated by large merchant ships underway. Although the water was approximately 4 km deep, an inability to adequately account for bottom reflections significantly reduced the amount of usable data. Because of its relative insensitivity to differential Doppler shift and its potentially high directivity, an end-fire array presents itself as a viable means of discriminating against the undesirable multipath components.

Chotiros[2] has suggested the use of a parametric receiving array (parray) for measuring noise radiated by a ship underway. A parray consists of only two components. One is a source, referred to as the pump, capable of radiating a collimated, high intensity sound beam. The other is a hydrophone located along the acoustic axis of the pump. Because of its high intensity, the pump wave interacts nonlinearly with, and thus modulates, any noise signal propagating through its path. The resulting intermodulation components detected by the hydrophone provide information about the noise signal. The differential elements that form a continuous end-fire array are thus synthesized by the nonlinear response of the fluid to the pump wave. When the pump wave and noise signal are each a pure tone of different frequency, the interaction effects of interest are the sum and difference frequency signals.

A unique advantage associated with using a parray to monitor noise radiated by a ship underway is the ability to attach one end of the parray, specifically the pump, to the ship itself, with the hydrophone placed at a fixed location some distance away (see Fig. 1). Navigation data provided by the ship may be employed to continuously direct the pump toward the hydrophone. In this way the parray can maintain optimal orientation for eliminating multipath components from the noise signal radiated by the passing ship. Other engineering details associated with this parray configuration are discussed by Chotiros.[2]

The remaining, unresolved fundamental problem involves determining the acoustic radiation pattern in the farfield of the ship when the parray itself may be predominantly within the nearfield. At frequencies below 100 Hz, the nearfield of large ships can extend from hundreds to thousands
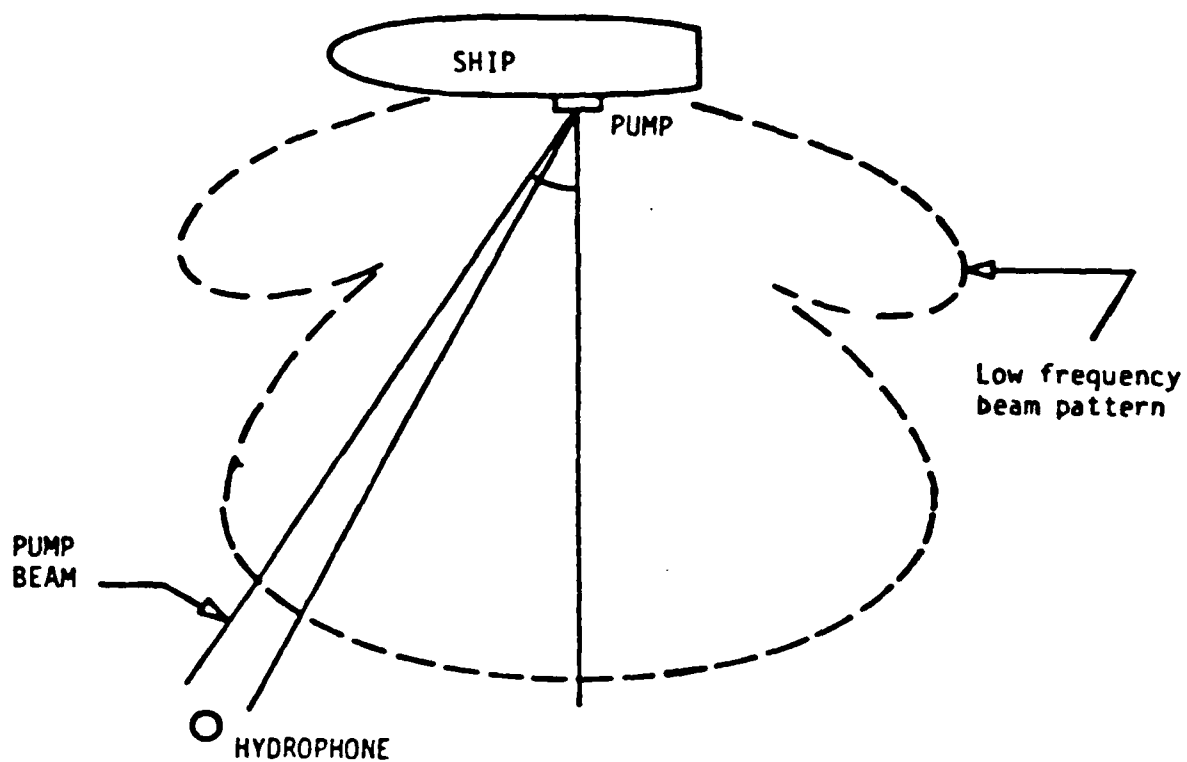
Figure 1

Proposed configuration for a parametric receiving array
used to measure ship noise

of meters. An upper bound on the length of the parray is governed primarily by the maximum range at which the intensity of the pump wave is capable of maintaining sufficiently strong nonlinear interaction with the noise signal. Maximum parray lengths are typically on the order of hundreds of meters, although design parameters for parrays tens of kilometers in length have been discussed by McDonough.[5] In any event, interaction in the nearfield of both the pump and noise source must be fully accounted for. Specifically, methods must be developed with which the noise source distribution (and therefore the farfield directivity, which is determined by the Fourier transform of the source distribution) can be determined from measurements in the nearfield. None of the theoretical models of parrays previously reported in the literature accounts for nearfield diffraction of both the pump wave and noise signal.

Preliminary experiments modeling the proposed application of a parray for measuring ship noise have been performed at ARL:UT.[6] The experiments consisted of employing the method described above to measure low frequency radiation of a pure tone from a large circular source. The small, high frequency pump was located in the center of the source and was rotated to scan the pump wave through the entire sound field (as in Fig. 2 but with $\underline{b}$, the displacement of the pump from the center of the source, equal to zero). Measurements of the sound field were made with the hydrophone both within and beyond the nearfield of the source. Beam patterns for the radiated sound were thus obtained with the parray and compared with beam patterns obtained by conventional measurement of the field. Excellent agreement was obtained when the hydrophone was located well in the farfield, but as the hydrophone was moved into the nearfield the beam patterns measured with the parray increasingly overestimated the beamwidths measured by conventional means. Discrimination of the parray against multipath was also demonstrated in the experiments by placing a reflector parallel to the acoustic axis of the noise source. Although beam patterns measured conventionally in the presence of the reflector were significantly altered relative to the free field patterns, those measured with the parray closely resembled beam patterns obtained in the absence of the reflector. The experiments clearly established the viability of using a parray to
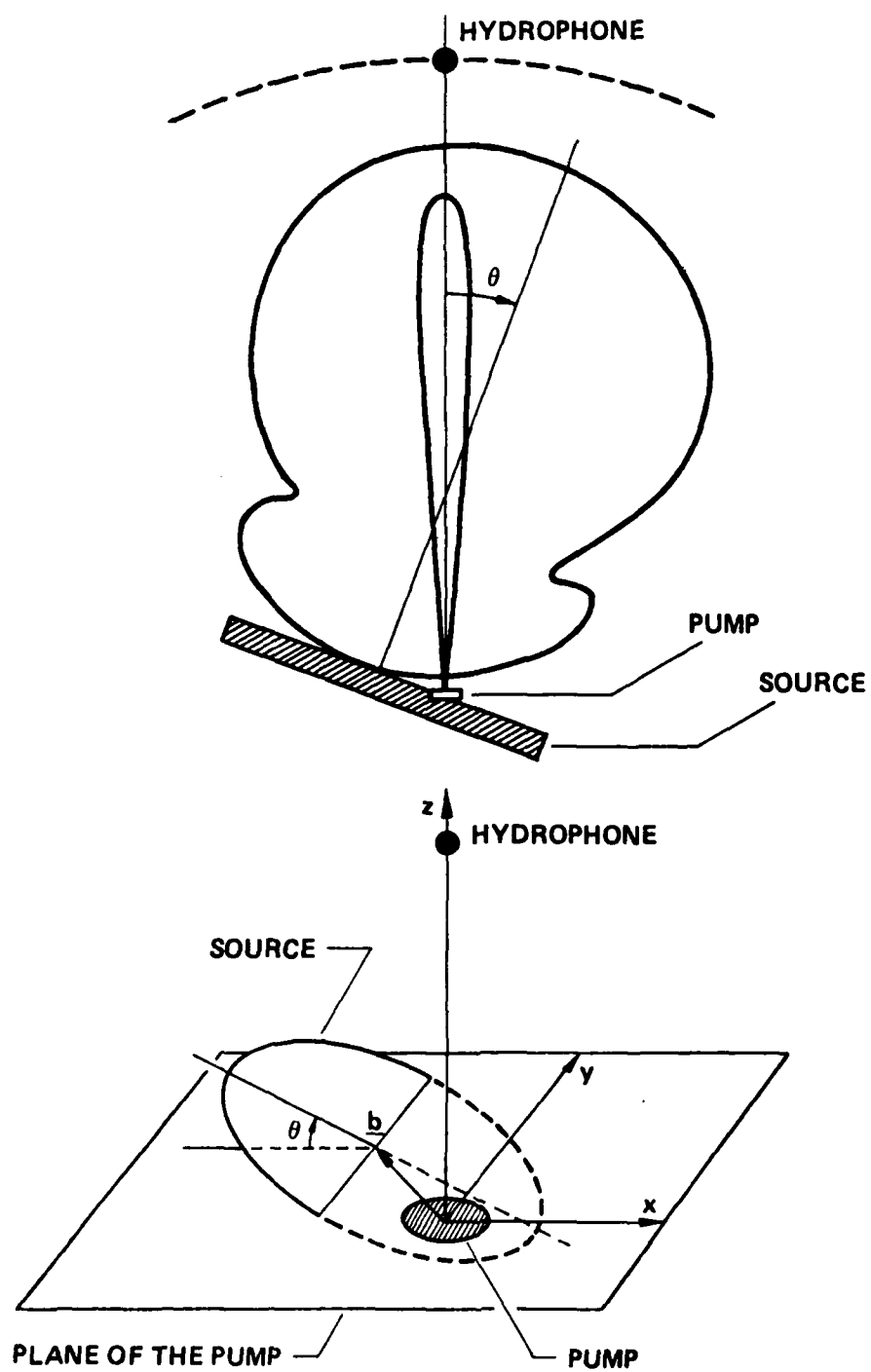
Figure 2

Geometry

separate the beam patterns due to direct radiation from the contributions due to multipath components.

3. Results

In what follows are discussions and results taken directly from a manuscript submitted to the Journal of the Acoustical Society of America by Hamilton, Naze Tjøtta and Tjøtta.[1]

A model was developed that describes the noncollinear interaction in a nondissipative fluid of two sound beams generated by Gaussian shaded sources. The sources may possess linear phase shading and different spot sizes, and their centers may be displaced relative to each other (see Fig. 2). The analysis is based on the fundamental theory developed in earlier papers by the authors.[7,8] Numerical results were obtained for the specific case of a parray whose pump is located on the sound source. The results show the effect of the pump's position, size, and frequency on parametric measurements when diffraction of both interacting waves is important. Asymptotic results were derived for the case where the receiving hydrophone is located in the farfield of the source.

The geometry is as shown in Fig. 2. Gaussian shading of the form $\exp\{-(|x|/e_i)^2\}$ is assumed for the amplitude of both the pump (i=1) and source (i=2), where x is a vector in the plane of the pump. A phase term is introduced to steer the source relative to the pump. Solutions for the sum and difference frequency waves received at the hydrophone are obtained from a parabolic approximation of the nonlinear wave equation.[7,8] The hydrophone is located on the acoustic axis of the pump. Thermoviscous losses in the fluid are ignored, with the result that the solutions reduce to functions of the exponential integral that are easily evaluated. In the figures that follow it is assumed that the radius of the source is 20 times that of the pump, i.e. $e_2/e_1=20$. The size of the pump measured in wavelengths of its radiated sound is fixed by setting $k_1 e_1=15$, where k_1 is the wavenumber of the pump wave. The frequency of the

source is then determined by the ratio k_1/k_2. Parametrically measured beam patterns are calculated at ranges given by $\sigma_2 = z/z_2$, where $z_2 = k_2 e_2^2/2$ is the collimation length of the beam formed by the source waves. The transition region between the near and far fields of the source is therefore located around $\sigma_2 = 1$.

In Fig. 3 the solid curves are numerical results for beam patterns of the difference frequency wave, referred to here as parametric beam patterns, measured by the hydrophone when the pump is located in the center of the source. The parametric beam patterns are calculated for σ_2 equal to 1, 10, and 100, and for source frequencies determined by k_1/k_2 equal to 3, 10, and 30. The dashed lines in Fig. 3 are the linear farfield directivity patterns for the source waves, which are given by $\exp\{-(k_2 e_2 \sin\theta)^2/4\}$. It is seen that for each source frequency, the parametric pattern approaches the desired linear farfield pattern as the hydrophone is moved farther from the source. Beyond $\sigma_2 = 10$, the parametric patterns are within 1 dB of the linear farfield patterns between the -3 dB points of the latter. In all cases the parametric patterns are broader than the linear farfield patterns, in agreement with experiment.[6]

The effect of displacing the pump relative to the center of the source is shown in Fig. 4. The pump is located at the edge of the source (i.e., at $|x| = e_2$), with the translation being in the same plane as that in which the source is rotated. It is seen that displacement of the pump significantly affects the parametric beam patterns only when the hydrophone is on the order of one Rayleigh distance from the source. Other results, not shown here, demonstrate that focusing of the pump wave on the receiver and variation in the size of the pump have no appreciable effect on the measured beam patterns.

Finally, an inversion formula was derived that permits evaluation of the source function if the difference frequency pressure is known at a sufficient number of points at any given range. The inversion formula is
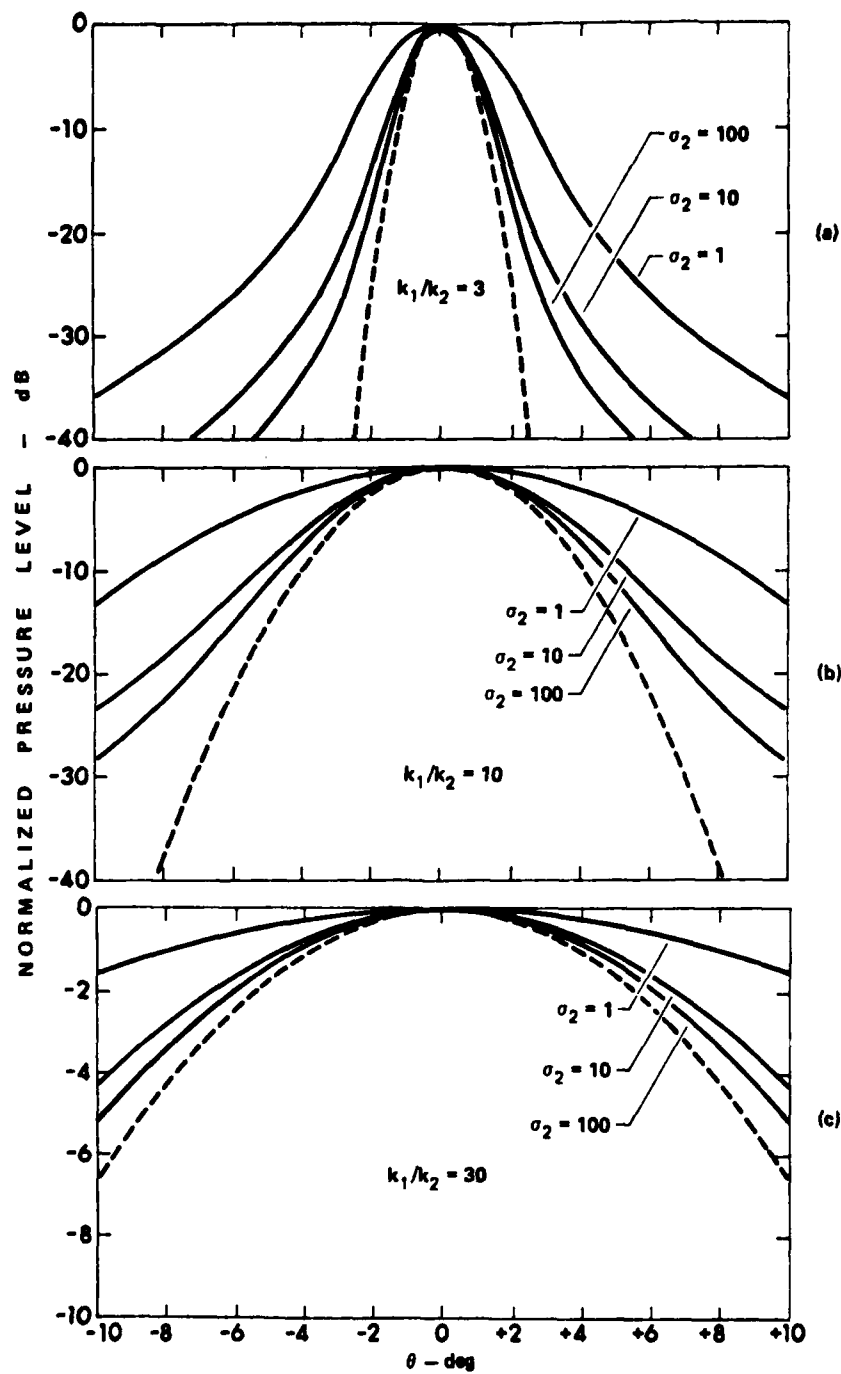
Figure 3

Comparison of parametrically measured beam patterns (solid lines) with
the linear farfield directivity patterns (broken lines). The pump is
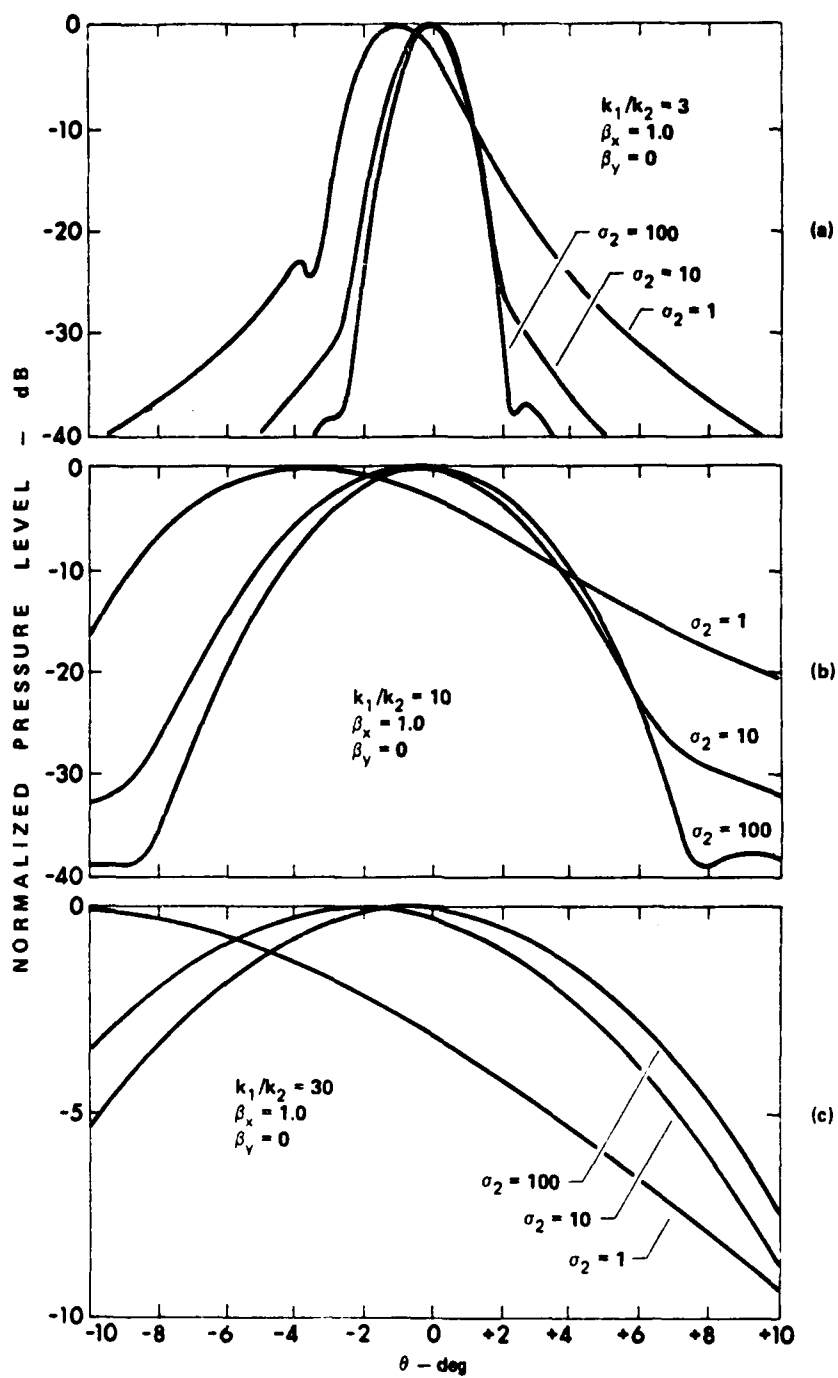located in the center of the source.

Figure 4

Beam patterns measured parametrically when the pump is located on the edge of the source.

essentially the spatial Fourier transform of the parametrically measured beam pattern, with a normalization factor that depends on range, frequency, and the shape of the pump. Once the source function is determined, the linear farfield directivity of the source is given simply by a second Fourier transform. In theory, therefore, parametric measurements made in the nearfield of the source can be used to determine the desired farfield directivity pattern. The distance between the pump and hydrophone need only be so long as to eliminate unwanted multipath components. However, difference frequency measurements must be made over a surface, not just a line, and both amplitude and phase must be measured.

On 1 September 1985, C. Darvennes began research on the use of a parray near reflecting surfaces. One envisioned use of the parray is for the measurement of noise radiated by surface ships. It is therefore important to understand the extent to which sound reflected from the surface of the water affects the response of the parray. Her analysis begins with research by Novikov et al.[9] on the use of a parametric transmitting array located adjacent to a reflecting surface. She is now in the process of verifying their analysis and attempting to modify the results for application to parametric receiving arrays.

II. FOCUSED FINITE AMPLITUDE SOUND

1. Personnel

Work on this project was performed by T. S. Hart since 1 September 1985.

2. Background

In a recent investigation of acoustic microscopy, where focused sound is used for imaging, questions were raised concerning the improved resolution achieved at finite amplitudes.[10,11] Rugar[10] observed that at sufficiently high sound power levels, resolution beyond the linear diffraction limit can be attained. His conclusion is that the nonlinear generation of higher harmonics provides signals with shorter wavelengths than are originally transmitted. Despite the fact that it is the fundamental transmitted frequency that is monitored and not the higher harmonics, improved resolution occurs nevertheless. Rugar suggests that after sound passes through a focal region, the resulting phase shifts cause energy in higher harmonics to be returned to the fundamental. As a result, the information content in the higher harmonic waves is ultimately imparted to the wave at the fundamental frequency. Rugar's theoretical investigation of this phenomenon is based on a quasilinear analysis of the second harmonic component formed by a focused Gaussian beam. Conclusions drawn from the analysis are therefore necessarily incomplete. First, a quasilinear analysis can lead only to indirect information about the fundamental component. Second, the assumption of a Gaussian source excitation obscures the intricate effects of diffraction that critically affect the nonlinear distortion of real sound beams.

A review of published work on focused finite amplitude sound reveals that the effects of nonlinearity and diffraction have not been considered simultaneously when both effects are strong. Within the focal region,

however, both effects can be quite significant. An early analysis of spherical finite amplitude waves by Naugol'nykh, Soluyan, and Khokhlov[12] was compared with experiment by Smith and Beyer.[13] The spherical cap radiator used in the experiments gives rise to strong diffraction effects, namely, a highly oscillatory axial field. Because the spherical wave theory does not account for diffraction, it is shown to provide only crude agreement with experiment in the prefocal region, and it is of no use within the focal region. Ostrovskii and Sutin[14,15] use a spherical wave model to describe propagation up to just before the focal region. Within the focal region they neglect nonlinearity and consider only diffraction effects. Consequently, the analysis does not properly account for the nonlinear losses in the focal region discussed previously by Naugol'nykh and Romanenko.[16]

Quasilinear models have been developed for systems where diffraction effects are strong but finite amplitude effects are weak. The linear (fundamental) and quasilinear (second harmonic) fields have been investigated both theoretically and experimentally by Lucas and Muir.[17,18] The theory is based on a parabolic approximation of the nonlinear wave equation, and agreement with experiment is very good. Similar quasilinear theories have been developed for focused sum and difference frequency sound.[19-21]

Only Bakhvalov, Zhileikin, and Zabolotskaya[22] account simultaneously for diffraction and nonlinearity in focusing systems where amplitudes are sufficiently high that the quasilinear models are inapplicable. Their analysis is based on numerical solutions of the parabolic nonlinear wave equation, and it is apparently valid for arbitrary source excitations. Curiously, however, the authors investigate only systems where diffraction is of moderate importance. Specifically, cases involving highly oscillatory sound fields that arise in practical applications[13,17,18] are not considered.

3. Results

A numerical investigation of focused finite amplitude sound based on Aanonsen's finite difference solution[23] of the nonlinear parabolic wave equation is currently in progress. Aanonsen's algorithm accounts simultaneously for nonlinearity, diffraction, and absorption, but practical considerations of computation time limit its use to the nearfield of directive sound sources.[24] However, an appropriate transformation was subsequently applied[25] that facilitates computations in the farfield, and excellent agreement was found between theory and experiment. The transformation introduces a coordinate system that follows the eventual divergence of sound beams in the farfield. In the present investigation, a similar transformation is introduced that is more suitable for describing the convergent geometry of a focused system.

The geometry of the system is shown in Fig. 5, where d is the location of the focal plane along the z axis. The system is uniquely defined by three dimensionless parameters, the linear focusing gain G, the source strength B, and the thermoviscous absorption A. In what follows, thermoviscous absorption is ignored. The linear focusing gain G is given by[17] $G = z_0/d$, where z_0 is the Rayleigh distance of the source. We define the source strength $B = d/z_s$ as the ratio of the focal length to the plane wave shock formation distance $z_s = 1/\beta \epsilon k$, where β is the coefficient of nonlinearity, ϵ the acoustic Mach number at the source, and k the wavenumber. All pressure amplitudes are normalized to the amplitude of the fundamental on the source. For a linear system with no thermoviscous losses, the behavior of the radiated sound field is determined solely by the gain G.

We first consider a source whose amplitude is uniform within a circle of radius a and zero elsewhere. In Fig. 6 the solid lines are linear solutions obtained numerically for parameters similar to those of the experiments performed by Lucas and Muir,[17,18] i.e., $G = 40.3$ and $B = 0.11$. The broken lines are the corresponding analytical solutions of the parabolic wave equation. The top curve is the amplitude of the fundamental
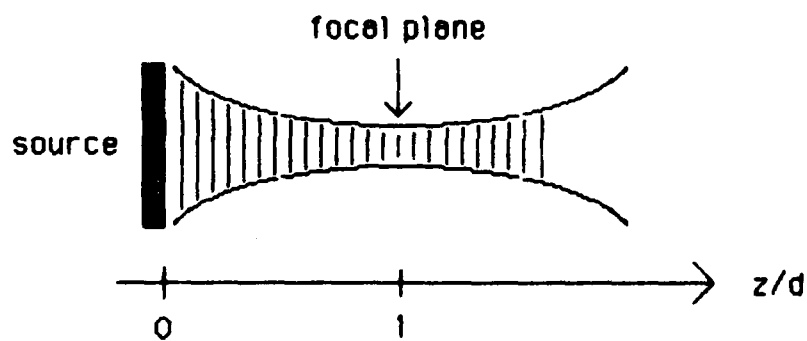
11

Figure 5

Geometry of focusing system.

component along the z axis, and the middle curve is the corresponding phase. Agreement between the numerical and analytical solutions is seen to be very good in the focal region, where the amplitudes differ by less than 0.2 dB. In the bottom curve is shown the beam pattern in the focal plane, where again the numerical and analytical solutions are very close (the label on the abscissa should read $2G(r/a)$, where r is the radial coordinate perpendicular to the z axis). Of particular significance is the fact that the analytical solutions are shown by Lucas and Muir[17] to be in very good agreement with experiment.

In Fig. 7 are quasilinear solutions obtained numerically for the second harmonic component that is generated by the sound field modeled in Fig. 6. Whereas the maximum normalized amplitude of the fundamental component depends only on (and is approximately equal to) G, that of the second harmonic also depends on the amplitude of the fundamental. In this case the second harmonic signal attains an amplitude of about 13 times that of the fundamental component at the source. In addition, the beam pattern in the focal plane is significantly narrower than that of the fundamental.

Finally, in Figs. 8 and 9 are shown results for the fundamental and second harmonic component generated by a focused source whose amplitude varies as $[1-(r/a)^2]^2$ when $r \leq a$, and which is zero when $r > a$. This source condition was used by Bakhvalov et al.[22] to investigate diffraction in their numerical analysis of focused finite amplitude sound. The values of G and B are the same as those used in Figs. 6 and 7. Comparison with Figs. 6 and 7 reveals that the highly oscillatory field structure that characterizes real uniform circular sources is all but absent in the present model. Although the effects of diffraction in the focal region increase with the linear focusing gain, the parameter G used here is more than 5 times the maximum value considered by Bakhvalov et al. As a result, continuation of the present investigation would yield the first theoretical results for focused sound beams where the effects of both nonlinearity and diffraction are strong.
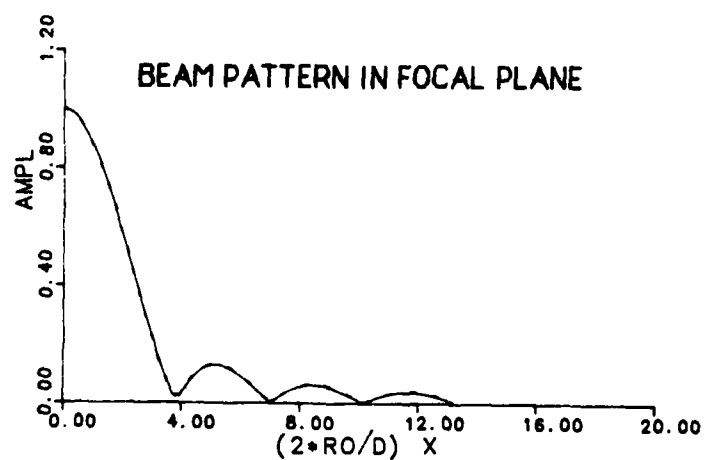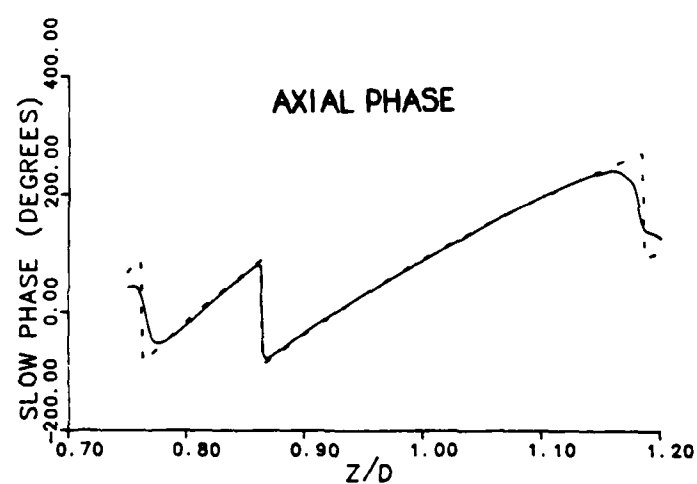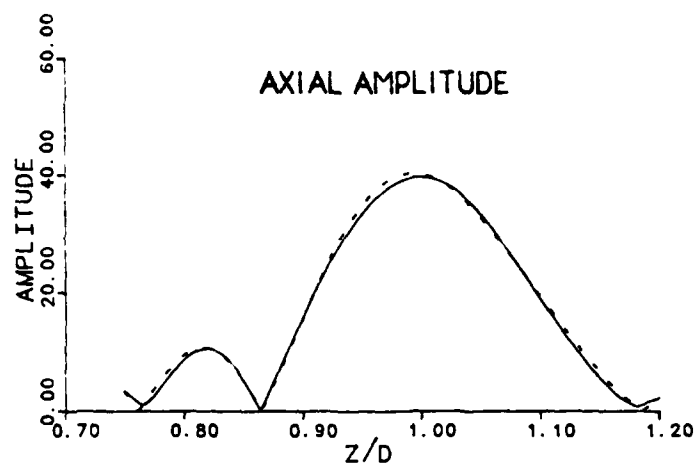
12

Figure 6

Linear sound field generated by a uniform circular focused source.

Figure 7

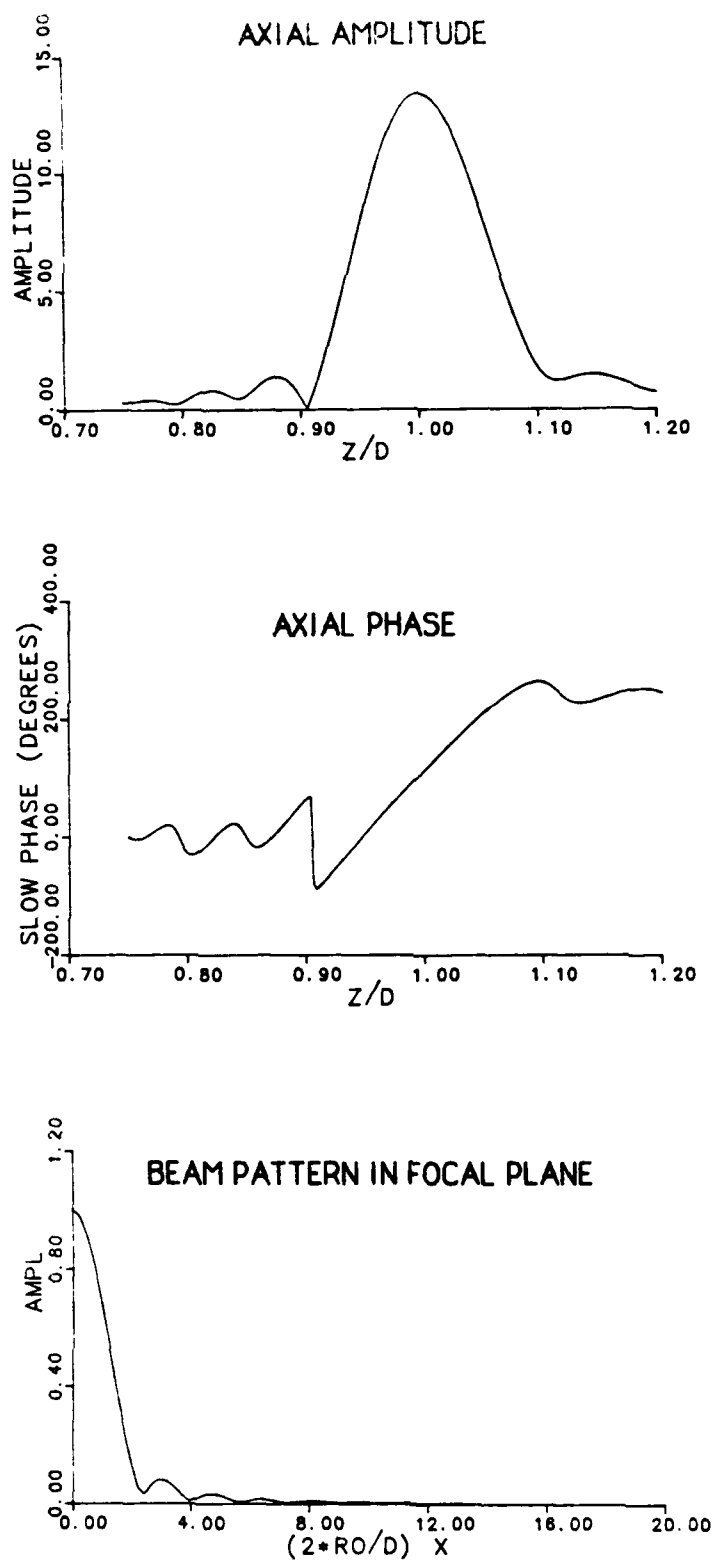Quasilinear second harmonic sound field generated by a
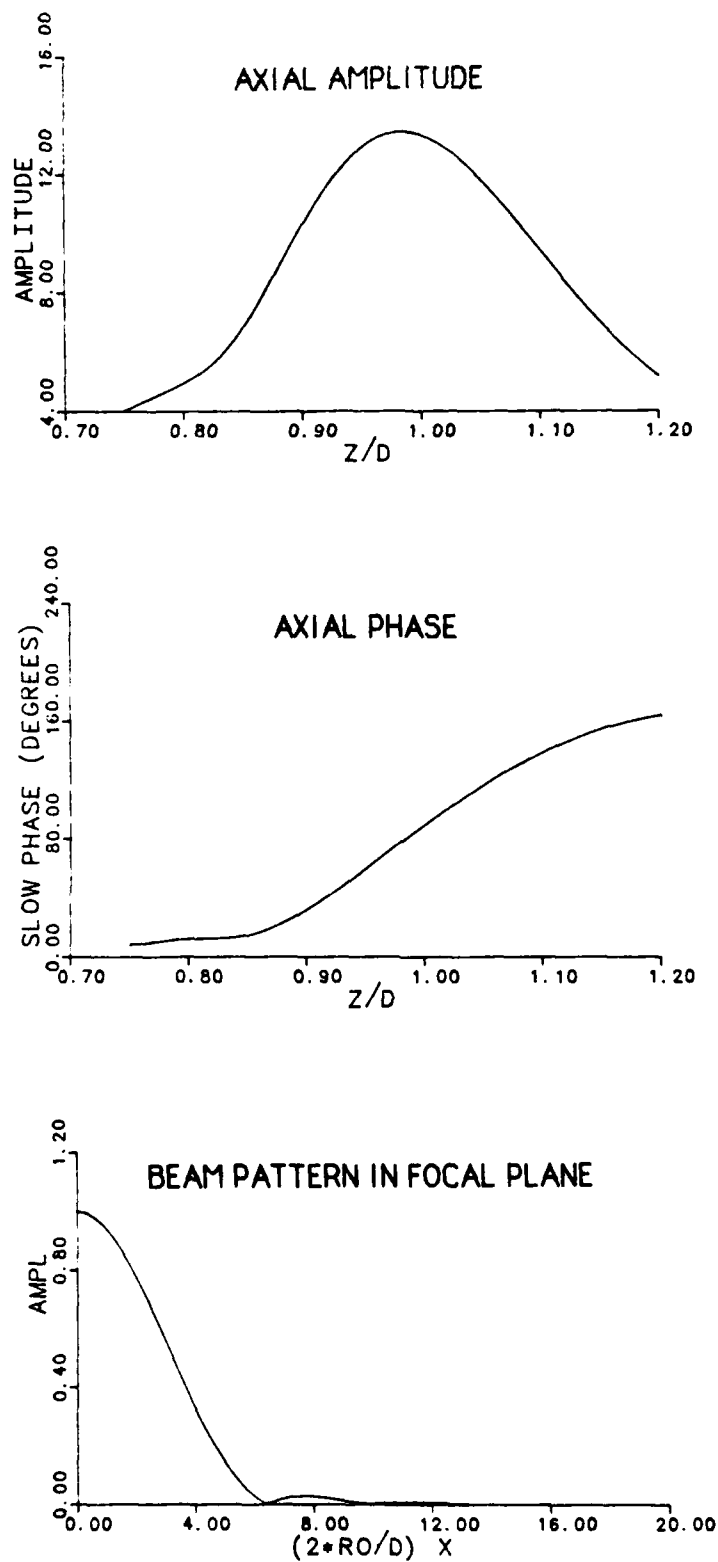uniform circular focused source.

Figure 8

Linear sound field generated by a focused source whose amplitude
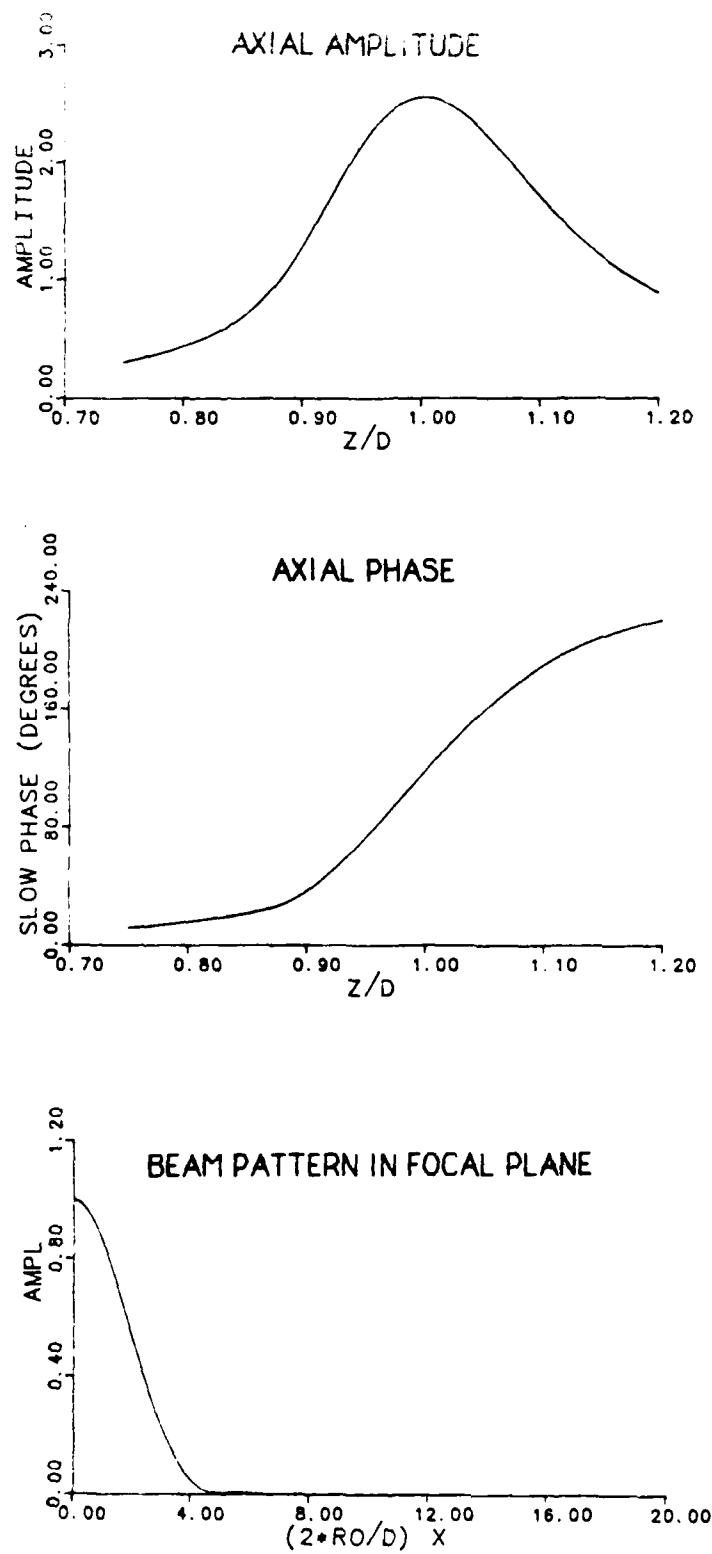varies as $[1-(r/a)^2]^2$ when $r \leq a$ and which is zero when $r > a$.

AXIAL AMPLITUDE

BEAM PATTERN IN FOCAL PLANE

AXIAL PHASE

Figure 9

Quasilinear second harmonic sound field generated
by the linear sound field shown in Fig. 8.

III. DISPERSIVE NONLINEAR WAVE INTERACTIONS IN A RECTANGULAR DUCT

1. Personnel

This research is to be an extension of work currently supported by ONR Contract N00014-84-K-0574. As discussed by D. T. Blackstock,[26] principal investigator under that contract, the project currently involves an investigation of finite amplitude pure tones that interact in higher order modes of a rectangular duct. Since 1 January 1986, S. J. Lind has assisted with the completion of that work. Beginning 1 June 1986, Lind will extend the research to include bands of random noise that interact in higher order modes.

2. Background

Guided acoustic wave propagation is of interest in a wide variety of physical systems that involve the transmission of sound in bounded or layered media. Of the many examples that may be cited include the propagation of sound in pipes, ducts, shallow water channels, and surface acoustic wave devices. Inherent to all waveguide systems is the property of dispersion, the phenomenon whereby the phase speed of a wave depends on frequency. At the cutoff frequency, which is the lowest frequency at which sound can propagate in any given mode, the phase speed of sound down the waveguide is infinite. As the frequency is increased, the phase speed decreases asymptotically toward the speed of sound in unbounded media. Waveguides therefore constitute systems that are very highly dispersive.

Whereas the propagation of low amplitude sound in higher order modes of waveguides is well understood, that of high amplitude sound is not. Specifically, dispersion induced by the boundaries of a waveguide critically affects the distortion of finite amplitude sound. Sound waves in the lowest order mode, or plane wave mode, are practically

nondispersive, and their behavior at finite amplitudes is well understood. Although a number of papers[27-35] consider guided waves of finite amplitude in higher order modes, it is significant that none of the analyses accounts consistently for the combined effects of nonlinearity, dispersion, and absorption. Even more remarkable is the complete absence of any published experimental work, particularly when one considers the various approximations made in the theoretical work.

Substantial progress, both theoretical and experimental, has been made at ARL:UT on the problem of finite amplitude sound propagation in higher order modes of ducts. An eight meter rectangular duct was used that allows the simultaneous generation of finite amplitude sound in the plane wave mode and first higher order mode (see Fig. 10). Two cases of nonlinear wave propagation have been investigated.[26]

The first case involves the weak nonlinear interaction of a pure tone in the plane wave mode (0,0) with a pure tone of another frequency in the first higher order mode (1,0). A quasilinear theory[36] was developed that accurately predicts the amplitudes of the waves generated nonlinearly at the sum and difference frequencies. Of particular significance is that the experiment demonstrated, for the first time, dispersion induced spatial oscillations in a nonlinearly generated wave field. The oscillations had been predicted by researchers in nonlinear optics, but the shorter optical wavelengths involved prevent similar measurements from being made.

The second case involves the strong nonlinear distortion of a single pure tone in the (1,0) mode. Three frequency ranges may be identified. One, very near cutoff, is characterized by standing waves formed across the duct. Very little energy is propagated down the duct. A second, at frequencies far above cutoff, is characterized by moderate dispersion. All components of the nonlinearly distorted wave propagate down the duct with approximately equal phase speeds. Although a set of coupled differential equations has been derived for this frequency range, it is not amenable to numerical solution. The third is in a mid-frequency range where dispersion is sufficiently strong that only waves propagating with identical phase speeds are strongly coupled. In this range considerable
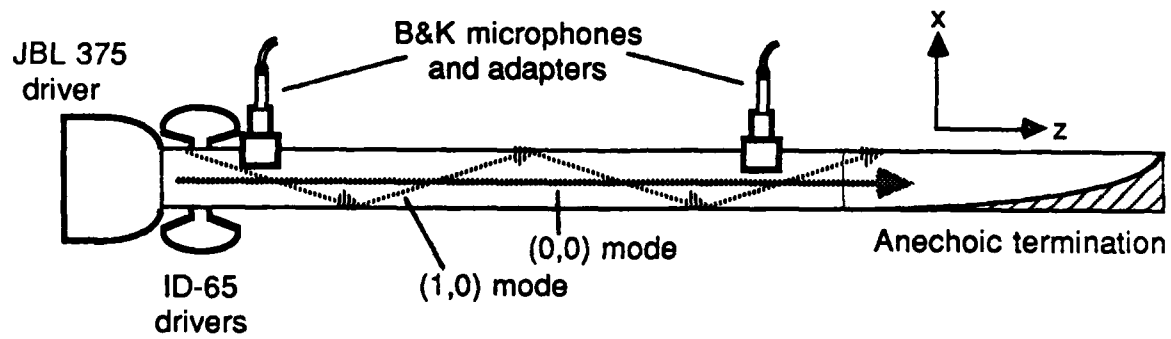
14

Figure 10

Waveguide apparatus.

simplification of the set of coupled equations is possible, and agreement between theory and experiment is good all the way through the fifth nonlinearly generated harmonic.[36]

Two observations may be made regarding the research underway at ARL:UT. First, results from similar experiments have never before been published. Second, the previously published theories provide inadequate models of the experiments. The analyses developed at ARL:UT, which account for the combined effects of nonlinearity, dispersion, and absorption, are in a number of cases in excellent agreement with experiment.[36]

3. Results

Since 1 January 1986, Lind has assisted J. A. TenCate, who is supported by ONR Contract N00014-84-K-0574, in the completion of work on pure tones that interact in higher order modes of a rectangular duct.[26] Through collaboration with TenCate, Lind has acquired experience with the same experimental apparatus that he will use beginning 1 June 1986 to extend the work on pure tones to bands of random noise.

REFERENCES

1. M. F. Hamilton, J. Naze Tjøtta, and S. Tjøtta, "Noncollinear interaction of two sound beams from displaced Gaussian sources, with application to parametric receiving arrays," submitted on 19 November 1985 for publication in J. Acoust. Soc. Am.

2. N. P. Chotiros, "Noise measurement in the presence of multipath propagation," Prog. Rep. No. 6, Contract No. AT/2027/0114 ARL, Dept. of Electronic and Electrical Engineering, University of Birmingham (1981).

3. J. G. Clark, R. P. Flanagan, and N. L. Weinberg, "Multipath acoustic propagation with a moving source in a bounded deep ocean channel," J. Acoust. Soc. Am. 60, 1274-1284(1976).

4. E. B. Wright and J. Cybulski, "Low-frequency acoustic source levels of large merchant ships," NRL Report 8677, Naval Research Laboratory, Washington, D. C. (1983).

5. R. N. McDonough, "Long-aperture parametric receiving arrays," J. Acoust. Soc. Am. 57, 1150-1155(1975).

6. A. L. Garcia and N. P. Chotiros, private communication.

7. G. S. Garrett, J. Naze Tjøtta, and S. Tjøtta, "Nearfield of a large acoustic transducer, Part III: General results," J. Acoust. Soc. Am. 75, 769-779(1984).

8. M. F. Hamilton, "Effects of noncollinear interaction on parametric acoustic arrays in dispersive fluids," J. Acoust. Soc. Am. 76, 1493-1504 (1984).

9. B. K. Novikov, V. I. Tarasov, and V. I. Timoshenko, "Behavior of the characteristics of a parametric radiator near a reflecting boundary," Sov. Phys. Acoust. 29, 138-142(1983).

10. D. Rugar, "Resolution beyond the diffraction limit in the acoustic microscope: A nonlinear effect," J. Appl. Phys. 56, 1338-1346(1984).

11. C. F. Quate, "Acoustic microscopy," Physics Today 38, 34-42 (1985).

12. K. A. Naugol'nykh, S. I. Soluyan, and R. V. Khokholv, "Spherical waves of finite amplitude in a viscous thermally conducting medium," Sov. Phys. Acoust. 9, 42-46 (1963).

13. C. W. Smith and R. T. Beyer, "Ultrasonic radiation field of a focusing spherical source at finite amplitudes," J. Acoust. Soc. Am. 46, 806-813 (1969).

14. L. A. Ostrovskii and A. M. Sutin, "Focusing of finite-amplitude acoustic waves," Sov. Phys. Dokl. 20, 275-277 (1975).

15. A. M. Sutin, "Influence of nonlinear effects on the properties of acoustic focusing systems," Sov. Phys. Acoust. 24, 334-339 (1979).

16. K. A. Naugol'nykh and E. V. Romanenko, "Amplification factor of a focusing system as a function of sound intensity," Sov. Phys. Acoust. 5, 191-195(1959).

17. B. G. Lucas and T. G. Muir, "The field of a focusing source," J. Acoust. Soc. Am. 72, 1289-1296(1982).

18. B. G. Lucas and T. G. Muir, "Field of a finite-amplitude focusing source," J. Acoust. Soc. Am. 74, 1522-1528(1983).

19. P. Y. Hennion, "Study of parametric radiation in the nearfield by Fourier analysis: Application to a focused source," J. Phys. (Paris) 40, C8-126 to C8-130(1979).

20. B. G. Lucas, J. Naze Tjøtta, and T. G. Muir, "Field of a parametric focusing source," J. Acoust. Soc. Am. 73, 1966-1971(1983).

17

21. J. Naze Tjøtta and S. Tjøtta, "Sound field of a parametric focusing source," J. Acoust. Soc. Am. 75, 1392-1394(1984).

22. N. S. Bakhvalov, Ya. M. Zhileikin, and E. A. Zabolotskaya, Nonlinear Theory of Sound Beams (in Russian), Nauka, Moscow (1982).

23. S. I. Aanonsen, "Numerical computation of the nearfield of a finite amplitude sound beam," Rep. No. 73, Department of Mathematics, University of Bergen, Bergen, Norway (1983).

24. S. I. Aanonsen, T. Barkve, J. Naze Tjøtta, and S. Tjøtta, "Distortion and harmonic generation in the nearfield of a finite amplitude sound beam," J. Acoust. Soc. Am. 75, 749-768 (1984).

25. M. F. Hamilton, J. Naze Tjøtta, and S. Tjøtta, "Nonlinear effects in the farfield of a directive sound source," J. Acoust. Soc. Am. 78, 202-216 (1985).

26. D. T. Blackstock, "Nonlinear acoustics: Long range underwater propagation, air-filled porous materials, and noncollinear interaction in a waveguide," First annual summary report under ONR Contract N00014-84-K-0574, Tech. Rep. ARL-TR-85-36, Applied Research Laboratories, The University of Texas at Austin, October 1985.

27. J. B. Keller and M. H. Millman, "Finite-amplitude sound-wave propagation in a waveguide," J. Acoust. Soc. Am. 49, 329-333(1971).

28. L. A. Ostrovskii and I. A. Papilova, "Nonlinear mode interaction and parametric amplification in acoustic waveguides," Sov. Phys. Acoust. 19, 45-50(1973).

29. A. H. Nayfeh and M.-S. Tsai, "Nonlinear wave propagation in acoustically lined circular ducts," J. Sound Vib. 35, 77-89 (1974).

30. A. H. Nayfeh and M.-S. Tsai, "Nonlinear acoustic propagation in two-dimensional ducts," J. Acoust. Soc. Am. 55, 1166-1172 (1974).

31. A. H. Nayfeh, "Nonlinear propagation of a wave packet in a hard-walled circular duct," J. Acoust. Soc. Am. 57, 803-809 (1975).

32. P. G. Vaidya and K. S. Wang, "Non-linear propagation of complex sound fields in rectangular ducts, Part I: The self-excitation phenomenon," J. Sound Vib. 50, 29-42 (1977).

33. V. V. Kaner and O. V. Rudenko, ""Propagation of finite amplitude modes in acoustic waveguides," 19, 78-85 (1978) (in Russian).

34. L. A. Ostrovsky, I. A. Soustova, and A. M. Sutin, "Nonlinear and parametric phenomena in dispersive acoustic systems," Acustica 39, 298-306 (1978).

35. J. H. Ginsberg, "Finite amplitude two-dimensional waves in a rectangular duct induced by arbitrary periodic excitation," J. Acoust. Soc. Am. 65, 1127-1133 (1979).

36. J. A. TenCate and M. F. Hamilton, "Dispersive nonlinear wave interactions in a rectangular duct," in Proceedings of the 12th International Congress on Acoustics, Toronto, Canada, July 1986.

END
FILMED

6-86

DTIC