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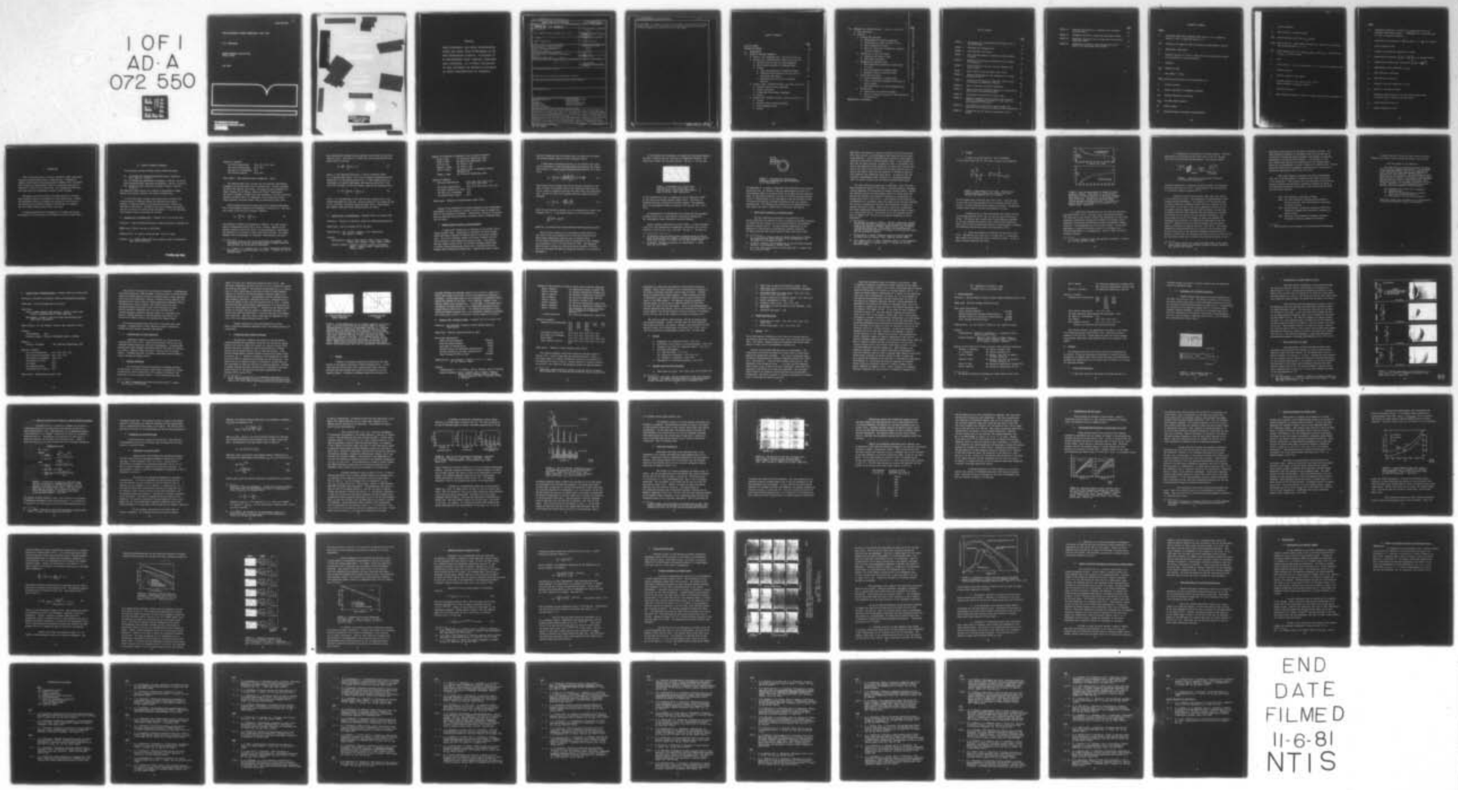

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HIGH INTENSITY SOUND RESEARCH, 1961- 1978

D. T. Blackstock

Applied Research Laboratories
Austin, Texas

June 1979

U.S. Department of Commerce
National Technical Information Service
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OUTDOOR PROPAGATION

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This is the final report on Contract F44620-76-C-0040, under which research on high-intensity acoustic waves was done. Although the contract covers only ~~the~~ a three-year period, ~~1 November~~ 1975 to 31 October 1978, research on high-intensity sound was continuously supported by AFOSR for 17 years, that is, since 1961. For completeness, therefore, work done under four predecessor contracts is also reviewed. Throughout the 17-year period, the primary goal was to investigate nonlinear effects in the behavior of very intense sound. Despite its fundamental nature, the research was carried out with a view toward applications in national defense

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and technology, for example, the sonic boom, intense aircraft noise, and sonar. A complete chronological bibliography of all papers and reports pertaining to all five contracts is included at the end of this report.

Unclassified

TABLE OF CONTENTS

LIST OF FIGURES

GLOSSARY OF SYMBOLS

Roman

a	coefficient whose value signifies plane waves ($a = 0$), cylindrical waves ($a = 1/2$), or spherical waves ($a = 1$)
B/A	coefficient of quadratic term in isentropic pressure-density relation
c_o	small-signal sound speed
D	hydraulic diameter of a duct (4 times the cross sectional area divided by the perimeter of the cross section)
f	frequency
f_{kHz}	frequency in kHz
k	wave number ($= 2\pi f/c_o$)
$OASPL_{1m}$	overall sound pressure level extrapolated to 1 m
p	acoustic pressure
p_1	pressure amplitude of fundamental component
p_{10}	pressure amplitude at the source
p_{rms}	root mean square pressure
Pr	Prandtl number
R_o	Rayleigh distance (transducer area/wavelength)

r	radial coordinate
r_o	source radius or reference radius
SFL	source-frequency level (dB re p_{ref}-m-kHz)
SL_{1m}	source level for a spherically spreading wave, defined as the farfield SPL extrapolated back to $r = 1$ m
SPL	sound pressure level (= $20 \log_{10} p_{rms}/p_{ref}$, where $p_{ref} = 20$ μPa for air and $p_{ref} = 1$ μPa for water)
t	time
t'	delay time (= $t - x/c_o$ for plane waves, = $t - (r-r_o)/c_o$ for spherical wave
u	particle velocity
u_o	particle velocity at the source
V	viscosity number (= $4/3 + \mu_B/\mu$) in Eqs. 1 and 3 reduced pressure (= $pr/p_{so}r_o$) in Fig. 9
x	rectilinear distance
$\bar{x}$	shock formation distance (= $1/\beta\epsilon k$ for a plane wave of source frequency f)

Greek

α	attenuation coefficient ($= \delta\omega^2/c_o^3$ for a sinusoidal wave in an unbounded thermoviscous medium; $= 2\sqrt{\delta'\omega}/c_o D$ for a sinusoidal wave in a duct of hydraulic diameter D
β	coefficient of nonlinearity ($= \frac{\gamma+1}{2}$ for gases; $= 1 + \frac{B}{2A}$ for liquids)
γ	ratio of specific heats
Γ	strength of nonlinearity coefficient ($= \beta\varepsilon k/\alpha$)
δ	thermoviscous coefficient $\left[= \frac{\nu}{2}\left(V + \frac{\gamma-1}{Pr}\right)\right]$ for an unbounded medium
δ'	thermoviscous boundary layer coefficient $\left[= \frac{\nu}{2}\left(1 + \frac{\gamma-1}{\sqrt{Pr}}\right)^2\right]$
ε	dimensionless source amplitude ($= u_o/c_o$)
μ	shear viscosity coefficient
μ_B	bulk viscosity coefficient
ν	kinematic viscosity coefficient ($= \mu/\rho_o$)
ρ_o	density of the ambient medium
σ	distortion range variable ($= x/\bar{x}$ for plane periodic waves, $= \beta\varepsilon k r_o \ln(r/r_o)$ for spherical periodic waves)
τ_o	initial decay time (Fig. 9)
ω	angular frequency ($= 2\pi f$)

I. INTRODUCTION

This is the final report on Contract F44620-76-C-0040, under which research on high-intensity acoustic waves was done. Although the contract covers only the three-year period 1 November 1975 to 31 October 1978, research on high-intensity sound was continuously supported by AFOSR for 17 years, that is, since 1961. For completeness, therefore, work done under four predecessor contracts is also reviewed.

Throughout the 17-year period, the primary goal was to investigate nonlinear effects in the behavior of very intense sound. Despite its fundamental nature, the research was carried out with a view toward applications in national defense and technology, for example, the sonic boom, intense aircraft noise, and sonar.

A complete chronological bibliography of all papers and reports pertaining to all five contracts is included at the end of this report.

II. REVIEW OF PREVIOUS CONTRACTS

The following contracts preceded Contract F44620-76-C-0040:

(I) AF 49(638)-1118, General Dynamics/Electronics (Rochester, NY), 1 Nov 61 - 31 Oct 63

(II) AF 49(638)-1320, University of Rochester, 1 Nov 63 - 31 Oct 68

(III) F44620-69-C-0044, University of Rochester, 1 Nov 68 - 31 Oct 70

(IV) F44620-71-C-0015, University of Texas at Austin, 1 Nov 70 - 31 Oct 75

For simplicity these contracts are referred to hereinafter by Roman numeral; for instance, Contract (II) means AF 49(638)-1320.

In the review below, projects whose details may be found in published articles or technical reports are described only briefly. Projects or items not backed up by published articles or reports are described in more detail. Included in the latter category are projects that for one reason or another proved unsuccessful. It is felt important that failures as well as successes be recorded.

A. <u>Contract (I)</u>, <u>AF 49(638)-1118</u>, 1 November 1961 to 31 October 1963

Contractor: General Dynamics/Electronics (Research Division), Rochester, NY.

AFOSR funds: $35,823 (matched by GD/E funds)

AFOSR monitors: Lt. Hyman H. Album and Capt. Lucius P. Gregg

Students: T. J. Tepper (summer 1963 only, graduate student in mathematics, Wayne State University)

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Reports of research*

Four oral presentations: 62-1, 62-2, 63-1, 64-4
Two journal publications: 64-1, 64-2
One paper in a proceedings: 62-3
Two technical reports: 63-2, 63-3

Final report: "High intensity sound propagation" (63-3)

The research began with a project that was primarily experimental, propagation of periodic waves in an air-filled tube. By later standards the waves used were not very strong. We wanted to find out whether the famous "missing 3 dB of Thuras, Jenkins and O'Neil"[1] constitutes a real lack of agreement between theory and experiment or is just an artifact. Finding no missing 3 dB in our experiment, we concluded that conventional nonlinear acoustical theory needs no modification (62-2, 62-3).

Later projects during the two-year period were entirely theoretical. Two of these together constitute the highlight of Contract (I). The first was a study of the solution of Burgers' equation,

$$u_x - \frac{\beta}{c_o^2} u u_{t'} = \frac{\delta}{c_o^3} u_{t't'} \qquad (1)$$

(see Glossary of Symbols for definition of symbols), for plane periodic waves in thermoviscous fluids (63-1, 64-2). Burgers' equation is the simplest equation in which the effects of wave propagation, nonlinearity, and dissipation are included; it has a known exact solution. The second highlight was the development of coordinate transformations that allow

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* The numbers refer to items in the Chronological Bibliography. The attribution of an item to a particular contract is based on when the work was done, not on the date of publication.

[1] A. L. Thuras, R. T. Jenkins, and H. T. O'Neil, "Extraneous frequencies generated in air carrying intense sound waves," J. Acoust. Soc. Am. 6, 173-180 (1935).

many spherical and cylindrical wave problems to be treated by plane wave analysis (64-1). The trick is to reduce the lossless equations for non-planar waves to the form

$$u_r + \frac{au}{r} - \frac{\beta}{c_o^2} uu_{t'} = 0 , \qquad (2)$$

where a = 1 for spherical waves and a = 1/2 for cylindrical waves (a = 0 implies plane waves). Use of the coordinate transformations then reduces Eq. 2 to the lossless form of Eq. 1. Other projects were the development of a general approximate wave equation system (63-1, 63-2, 64-4) and an attempt to solve the Burgers' equation for spherical waves,

$$u_r + \frac{u}{r} - \frac{\beta}{c_o^2} uu_{t'} = \frac{\delta}{c_o^3} u_{t't'} , \qquad (3)$$

(63-3). It is interesting to note that the full solution of Eq. 3 has eluded investigators to this day. We have returned to the problem off and on over the years, frustration being the usual result. Some progress was, however, made much later, during Contract (V) (78-6).

B. Contract (II), AF 49(638)-1320, 1 November 1963 to 31 October 1968

Contractor: University of Rochester (Electrical Engineering Department)

AFOSR funds: $121,393 (average $24,277 per year)

AFOSR monitors: Capt. Lucius P. Gregg, Lt. Col. George Stalk,
Maj. Donald L. Calvert

Students:

Undergraduates: Bruce A. Davy, David T. Deihl, Jerome T. Dijak, David M. Ryon, Kenneth A. Small, James T. Walton

Graduate Students: Michael S. Cosgrove, Donald B. Cruikshank, James C. Lockwood, James L. McKittrick, and Thomas L. Szabo

Degrees (at University of Rochester unless otherwise indicated)

Bruce A. Davy	BS, Electrical Engineering, 1968
David T. Deihl	BS, Electrical Engineering, 1967
David M. Ryon	BS, Physics, 1967
Kenneth A. Small	BS, Physics, 1967
James T. Walton	BS, Physics, 1965, at Kalamazoo College , Kalamazoo, MI
Thomas L. Szabo	MS, Electrical Engineering, 1967

Reports of research

Nine oral presentations:	64-3, 65-1, 65-3, 66-4, 67-1, 67-3, 67-4, 68-2, 69-2
Six journal publications:	66-1, 66-2, 66-3, 67-2, 68-1, 69-1
One paper reprinted in a book:	72-8
One paper in a proceedings:	65-2
One administrative report:	68-3

Final report: "Research on high-intensity sound" (68-3)

Because of the availability of student assistants, both undergraduate and graduate, it was possible to broaden the effort when the program was moved to the University of Rochester. Research was carried out on periodic waves in tubes and along boundaries, on periodic waves in unbounded media, and on N waves.

1. Periodic waves in tubes or along boundaries

A strong early interest was in stability of the acoustic (oscillating) boundary layer. Experiments at relatively low sound pressure levels had *always confirmed* the laminar model of the acoustic boundary layer. We tried to determine whether the acoustic boundary layer becomes turbulent at high enough sound pressure levels. This project had some limited success (67-4), but acoustic streaming always became so severe at high sound pressure levels that it interfered with the boundary layer visualization method used. Although the project finally had to be abandoned, much was learned about the effect of the viscous and thermal boundary layers on sound propagation (68-2).

A particularly interesting byproduct of the boundary layer study was the development of the following Burgers-like equation for intense sound subject to boundary-layer attenuation and dispersion (67-3, 69-5, 72-1):

$$u_x - \frac{\beta}{c_o^2} u u_{t'} = \frac{\sqrt{\delta'}}{c_o D/2}\sqrt{\frac{2}{\pi}}\int_0^\infty u_{t'}(x,t'-\xi)\,\frac{d\xi}{\sqrt{\xi}} \ . \qquad (4)$$

This equation has the proper form (and the correct solutions) in the limit as either the nonlinear term or the dissipation term drops out. So far, however, no general solutions have been found, only approximate ones. Earlier (in 1965) the following equivalent equation had been developed

$$u_x - \frac{\beta}{c_o^2} u u_{t'} = -\frac{\sqrt{2\delta'}}{c_o D/2}\,\frac{\partial^{\frac{1}{2}} u}{\partial t'^{\frac{1}{2}}} \ , \qquad (4')$$

where the half-derivative operator is to be interpreted in terms of the integral in Eq. 4. A convenient property of the half-derivative,

$$\frac{\partial^{\frac{1}{2}}}{\partial x^{\frac{1}{2}}}\left(e^{mx}\right) = \sqrt{m}\, e^{mx} \ ,$$

makes Eq. 4' attractive for solving problems involving periodic waves.

The work under Contract (I) on distortion of plane waves in a tube (62-2, 62-3) was extended, both for weak waves (66-3) and for waves strong enough that a sawtooth wave is produced (67-3). For the latter study McKittrick, with the assistance of Davy, designed and constructed a 29 m, 5 cm diam plane wave tube. This apparatus, which replaced a similar one constructed during Contract (I) (62-3), was to be used again and again by subsequent students, for a variety of experiments.

In the sawtooth wave experiment, an especially interesting discovery was that a sawtooth wave in a tube has an asymmetrical waveform: the shocks have rounded tops but sharp bottoms. See Fig. 1. We were able to show qualitatively that the asymmetry is due to dispersion caused by the viscous and thermal boundary layers (67-3). The effect of dispersion had been overlooked in previous studies.[2] The asymmetry was to be investigated further in Contracts (IV) and (V) (e.g., 73-9, 77-9).

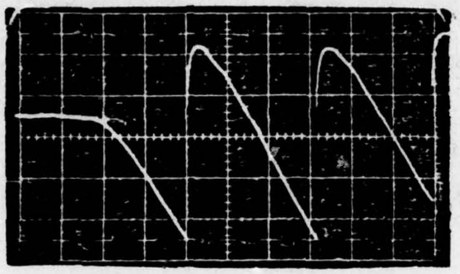

FIGURE 1. Oscillogram of a sawtooth wave (tone burst) in an air-filled tube, 3.6 m from the source. Source level and frequency about 154 dB and 3 kHz, respectively.

An investigation of standing waves in a closed end tube was begun. A primary object was to check Chester's theoretical predictions.[3] The investigation became Cruikshank's doctoral research.

Another resonance experiment was tried briefly. In this experiment a tube in a ring configuration (resembling a cyclotron), with a source attached to the ring via a port, was used. See Fig. 2. The object of

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[2] An excellent review of earlier work on sawtooth waves in tubes is given in the article by H. Medwin, "Attenuation of guided, repeated shock waves in gases," J. Acoust. Soc. Am. 36, 870-877 (1964).

[3] W. Chester, "Resonant oscillations in closed tubes," J. Fluid Mech. 18, 44-64 (1964).

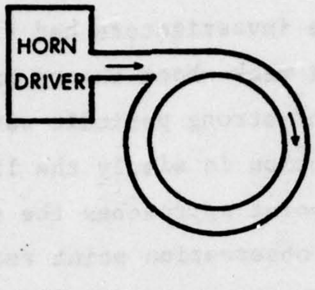

FIGURE 2. Traveling wave resonance tube. Resonance is expected when the circumference of the ring equals nλ.

the experiment is to excite a progressive wave traveling in one direction around the ring. At resonance, when the circumference is equal to nλ, the excitation added by the source should be in phase with the traveling wave. In this way we expected to be able to build up very high pressure levels.[4] Unfortunately, in our experiments it was not possible to keep the source from exciting a backward traveling as well as a forward traveling wave. The resonance was therefore not the progressive-wave type sought, and after a limited effort the project was shelved.

2. Waves (mostly periodic) in unbounded media

The most significant contribution during Contract (II) was the application of weak-shock theory to problems in nonlinear acoustics and indeed the advertisement of the weak-shock method to the nonlinear acoustics community (64-3). The most important application of the method was to the problem of connecting two classical solutions, the Fubini solution[5] and the Fay solution[6] (65-1, 65-2, 66-2, 72-8).

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[4] H. E. von Gierke, Aerospace Medical Research Laboratories, W-PAFB, OH, originated this device and calls it the "acousticron." He described it to the author in 1960.

[5] E. Fubini, "Anomalie nella propagazione di onde acustiche di grande ampiezza," Alta Frequenza 4, 530-581 (1935).

[6] R. D. Fay, "Plane sound waves of finite amplitude," J. Acoust. Soc. Am. 3, 222-241 (1931).

Heretofore, the relation of these two solutions to each other had not been clear; in fact, some investigators had viewed the two solutions as contradictory. Use of weak-shock theory provided a simple general solution of the problem of strong periodic waves. It was possible to show that the Fubini solution is simply the limit of the general solution as the observation point approaches the source while the Fay solution is the limit as the observation point recedes from the source.* Another very useful result was the extension of weak-shock theory to cover spherical and cylindrical waves (66-2). It turns out that the coordinate transformation used previously for continuous waveforms (64-1) is equally fruitful when the waveform contains weak shocks.

Two other theoretical studies may be mentioned. First, the Keck-Beyer perturbation solution[7] was shown to converge because it represents a series expansion of the solution of Burgers' equation (66-1). Second, the transient solution for small-signal sound in a viscous fluid was obtained and applied to the problem of turning on a sinusoidally vibrating source (65-3, 66-4, 67-2). A novel feature of the solution is the prediction of a precursor, which runs ahead of the classical wavefront. The solution, including the precursor, was confirmed by an analog experiment performed by Szabo. Szabo built an electrical transmission line whose mathematical characteristics are the same as those of sound in a viscous fluid (69-1). The solution was later confirmed directly by M. B. Moffett, who carried out an acoustical experiment at Brown University.[8]

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* The operable word here is "simple." Earlier it had become possible to show that the Fubini solution and the Fay solution are limiting forms of the solution of Burgers' equation (64-2), but the latter is extremely complicated. In particular, the Burgers' equation solution is much more difficult to evaluate in the transition region than the weak-shock solution.

[7] W. Keck and R. T. Beyer, "Frequency spectrum of finite amplitude ultrasonic waves in liquids," Phys. Fluids 3, 346-352 (1960).

[8] M. B. Moffett and R. T. Beyer, "Transient effects in the propagation of a sound pulse in a viscous liquid," J. Acoust. Soc. Am. 47, 1241-1249 (1970).

3. N waves

N waves, so called because of their resemblance to the letter N (see Fig. 3), are common in nature and technology.

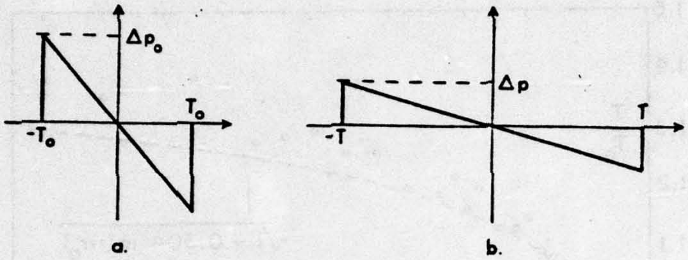

FIGURE 3. Time waveform of an N wave. Because of nonlinear propagation effects, the initial N (a) loses amplitude and elongates (b) as it travels.

The wave begins with a shock and ends with a shock. The sonic boom is an N wave, as is the disturbance from a supersonic bullet or projectile. An ideal bursting balloon produces an N wave. The farfield pressure signal from an explosion approximates an N wave.

Although one of our early experiments with N waves was done with bursting balloons (68-1), all the rest were done with electric sparks. The motives were to model sonic boom propagation phenomena, to test and calibrate microphones used to measure finite-amplitude waves, and to study nonlinear wave behavior of high-intensity transients. The following projects were worked on during Contract (II).

a. Decay and elongation of spherical N waves (64-3, 67-1, 70-2). Experimental data taken by W. M. Wright and J. L. McKittrick were compared with predictions based on weak-shock theory. As Fig. 4 shows, excellent agreement was found.

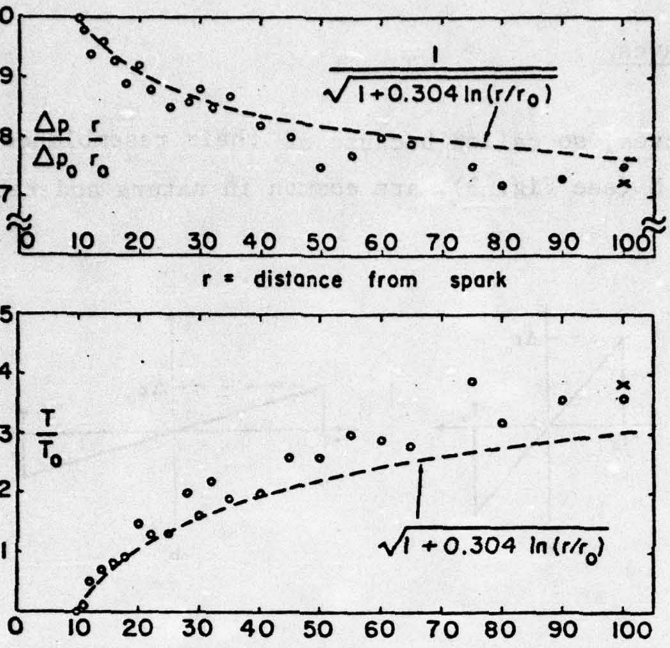

FIGURE 4. Data from measurements of spherical N waves produced by sparks. Upper graph is for the pressure amplitude of the wave, corrected for spherical spreading. Lower graph is for the duration T of the positive half cycle of the wave. Dashed lines represent theory; circles represent experimental points. The slight consistent deviation is probably due to microphone calibration error. (From 67-1)

b. Diffraction and refraction of an N wave by a gas-filled soap bubble (69-2, 71-1). This was a sonic boom modeling project. The object was to test Pierce's theory[9] that variability of sonic boom signatures, particularly peaking and rounding of the shocks, can be explained by refraction and diffraction caused by atmospheric inhomogeneities. The inhomogeneities act as acoustic lenses. In the model experiments an argon-filled bubble served as a converging lens, a helium-filled bubble as a diverging lens. Pierce's theory was qualitatively confirmed.

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[9] A. D. Pierce, "Spikes on sonic boom pressure waveforms," J. Acoust. Soc. Am. 44, 1052-1061 (1968).

c. Diffraction of an N wave by a circular aperture. See Fig. 5. Subsitution of an aperture (a plate with a hole in it) for the soap bubble led to some interesting measurements. The aperture project

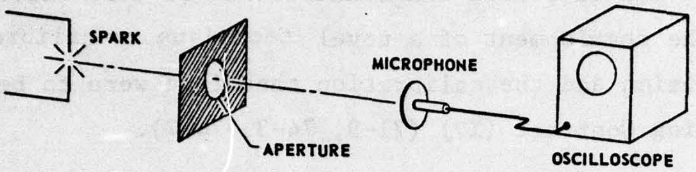

FIGURE 5. Apparatus for studying the diffraction of an N wave by an aperture.

eventually became part of Lockwood's doctoral research, which spanned Contracts (III) and (IV) (71-5). During Contract (IV) the topic was to be studied further by Anderson (74-7).

Besides the three formal projects there were other aspects of the research on N waves. The measurement of spark-produced N waves requires special microphones. At a distance of 10 cm from the spark a typical N wave has a duration of about 25 μsec, a risetime (at the front shock) of less than 1 μsec, and an amplitude of about 0.01 atm. To properly record a signal that has these properties, one must have microphones with much wider bandwidth than are commerically available. We therefore had to construct our own condenser microphones. The basic design is that of W. M. Wright, to whom we are indebted for teaching us his techniques for producing and measuring N waves from sparks.[10] McKittrick built our first microphones and used them to measure the waveform of sawtooth waves in a tube (67-3). The unusual bandwidth of the microphones led us to develop a new microphone calibration method based on the nonlinear propagation characteristics of N waves, in particular, the elongation and extra decay of an N wave (71-1). The calibration method may be crudely illustrated by referring to Fig. 4.

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[10] W. M. Wright, "Studies of N waves from weak sparks in air," Final Report under Contract Nonr-3932(00), Kalamazoo College, Kalamazoo, MI, June 1971 (AD 725 865).

The numeric 0.304 contains the microphone calibration constant. The small consistent deviation of the dashed curves from the data may be corrected by altering the numeric slightly; this amounts to using the measurements to calibrate the microphone. A side benefit of the N wave research was therefore the construction of very wideband microphones and the development of a novel technique to calibrate them. Both the microphone design and the calibration technique were to be materially improved during Contract (IV) (71-9, 74-3, 74-7).

The N wave research, particularly the sonic boom modeling work, led to the development of a popular lecture "Mini Sonic Booms in the Laboratory." This lecture, which was sponsored by the Acoustical Society of America and the National Academy of Sciences, was given at the following universities during 1968-71, when the SST and the sonic boom were lively issues:*

1968 - Ohio University, University of Akron
1969 - St. Louis University, Oklahoma State University, Baylor University, Texas A&M University, University of Texas at Austin
1970 - Rice University, University of Houston, Utah State University, Brigham Young University, University of Nevada at Reno
1971 - University of Southwestern Louisiana, Louisiana Polytechnic Institute, Vanderbilt University

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* These lectures are not included in the Chronological Bibliography.

A typical abstract of the talk, which serves as a brief summary of our work on N waves during the period, is as follows:

Mini Sonic Booms in the Laboratory

The sonic boom is a propagating pressure disturbance whose wave shape resembles the letter N. Its wavelength is too long (the spatial extent of the N generally exceeds 100 feet) for direct experimental studies to be carried out in the laboratory. Thus experiments on sonic booms have been done mainly in the field, at great expense. Model studies can, however, be performed in the laboratory. Electric sparks are used to produce "minibooms" whose wavelength is about 1 cm and whose time duration is about 25 μsec. Among the interesting phenomena that can be observed with these minibooms are the following:

(1) Lengthening of the wave as it propagates.
(2) Anomalous decay.
(3) Refraction and diffraction by an acoustic lens (a gas-filled soap bubble).
(4) Diffraction by a disk and by an aperture.

These model studies have contributed to our understanding of sonic-boom propagation through the atmosphere.

C. Contract (III), F44620-69-C-0044, 1 November 1968 to 31 October 1970

Contractor: University of Rochester (Electrical Engineering Department)

AFOSR funds: $47,554 (average $23,777 per year)

Other funds

Office of Naval Research (CNA contract): $5,681 -- used in the project on standing waves of finite amplitude.

NASA (grant): $2,488 -- used in the sonic boom modeling study (soap bubble experiments).

AFOSR monitors: Lt. Col. Donald L. Calvert, Capt. Westcott H. Smith

Students

Undergraduates: none

Graduate Students: Donald B. Cruikshank, James C. Lockwood

Degrees

Donald B. Cruikshank	PhD, Electrical Engineering, 1969

Reports of research

Four oral presentations:	69-4, 69-5, 70-1, 70-4
Three journal publications:	69-6, 71-1, 72-5
Two papers in proceedings:	70-2, 70-5
One chapter in a book:	72-1
One thesis:	69-3
One technical report:	69-3
One administrative report:	70-3

Final report: "High intensity sound" (70-3)

The period of Contract (III) was marked by transition. Cruikshank completed his doctorate in 1969 and began a teaching career at Cornell College, where he continued some of his work on standing waves of finite amplitude. (He is now in the Department of Physics, Anderson College, Anderson, IN.) Blackstock took a year's leave of absence beginning in September 1969 at The University of Texas at Austin, and Lockwood joined him there. Eventually Blackstock decided to stay at The University of Texas, and the contract at Rochester came to an end in October 1970. Lockwood remained a Rochester doctoral student but in September 1970 became a research assistant at Applied Research Laboratories, The University of Texas at Austin, and continued his research there.

The research during Contract (III) may be classified under these headings: standing waves of finite amplitude, acoustic saturation, N waves and other intense transients, and general.

1. Standing waves of finite amplitude

Cruikshank's research on standing waves in a closed tube was completed (69-3, 69-4, 72-5). Chester's predictions[3] were by and large confirmed although there were some minor discrepancies. Cruikshank also modified some shock strength calculations Temkin[11] had made for standing wave fields. Temkin's method represents a shortcut based on energy balance. Cruikshank was able to rectify a discrepancy between Temkin's results and those of Chester (69-6).

2. Acoustic saturation

One of the most interesting phenomena in nonlinear acoustics is saturation: No matter how much acoustic power is emitted by a source, the amount that can be transmitted a given distance is limited. The limitation is set by nonlinear effects. In 1970 saturation was mainly

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[11] S. Temkin, "Propagating and standing sawtooth waves," J. Acoust. Soc. Am. 45, 224-227 (1969).

known, if at all, as a theoretical prediction (64-2, 66-2). Some laboratory experiments had been done (see 74-1 for an historical review) but were not well known.[12] We therefore collaborated with J. A. Shooter and T. G. Muir (whose support came from an Office of Naval Research contract) to carry out a field experiment to determine whether saturation does in fact occur. The experiment was done underwater with a high frequency, spherically spreading sound beam. Saturation was observed and indeed at about the level predicted (70-2, 70-4). A second discovery was that the directivity characteristics of a sound beam are altered by finite-amplitude effects.[12] Because only the intense center section of the major lobe was subject to saturation, the major lobe became blunt and flat-topped while at the same time minor lobe suppression became poor. This work, which constitutes the highlight of Contract (III), was completed during Contract (IV).

Further discussion of saturation appears on pp. 39-40, where a plane-wave saturation experiment done in air during Contract (V) is described.

3. N waves and other intense transients

One task was to complete the analysis of the soap bubble refraction-diffraction experiments, which had been carried out during Contract (II), and to report the research in a journal article (71-1). Another task was to continue the work on diffraction by a circular aperture and by similar objects, such as disks and spheres. A comparison between signals received through an aperture and around a disk is shown in Fig. 6. Finally, an analysis of the propagation of a weak shock followed by an exponentially decaying tail was carried out. The application was to explosive sounds, in particular, to some 19th century experiments in which the velocity of sound was measured. Although a complete solution was found, the work was not published at the time. During Contract (V) the work was resurrected, generalized, and reported (78-5); see pp 29-30.

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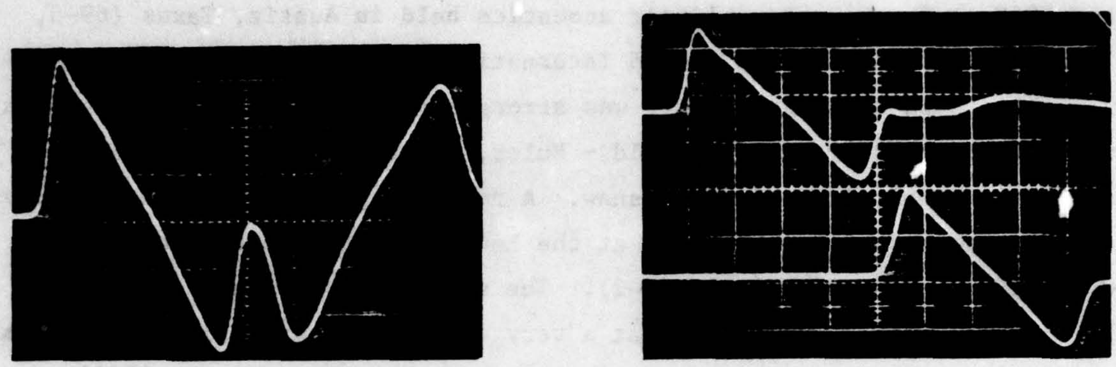
[12] At the time we were ignorant of the remarkable experiments of C. H. Allen, "Finite amplitude distortion in a spherically diverging sound wave in air," Ph.D. thesis, The Pennsylvania State University (1950).



a. N WAVE DIFFRACTED BY A LARGE APERTURE

b. DIFFRACTION BY A DISK

FIGURE 6. N wave diffraction (a) by a circular aperture, and (b) by a disk. In (a) the first N wave is the incident signal; it travels straight through the hole to the microphone (see Fig. 5). Following close behind is an upside down N wave, which represents the signal scattered from the circular edge of the aperture. In (b) the upper trace is the incident signal; it was taken with the disk absent. The lower trace, taken with the disk in place, represents the signal scattered by the edge of the disk. It is delayed relative to the upper trace because of its longer travel path. Notice that the diffracted signals from the aperture and the disk are inverses of each other. Their relation illustrates Babinet's principle that complementary diffracting objects give rise to complementary diffracted waves.

4. General

A chapter on nonlinear acoustics was written for the third edition of the American Institute of Physics Handbook (72-1). In previous editions (first edition 1957, second edition 1963) nonlinear acoustics had been included only briefly and incidentally, not as a separate chapter. A history of nonlinear acoustics was written for

the 1969 conference on nonlinear acoustics held in Austin, Texas (69-5, 70-5), later known as the Second International Symposium on Nonlinear Acoustics. In this paper there was strong emphasis on relatively unknown work of the pioneers of the field - Euler, Lagrange, Poisson, Blake, Challis, Stokes, Airy, and Earnshaw. A review paper on weak-shock theory and Burgers' equation was given at the Loughborough Symposium on Aerodynamic Noise in 1970 (70-1, 70-2). The various review papers of this period are tangible evidence that a very substantial expansion of national and international activity in nonlinear acoustics began in the 1960's.

D. Contract (IV), F44620-71-C-0015, 1 November 1970 to 31 October 1975

Contractor: The University of Texas at Austin (Applied Research Laboratories)

AFOSR funds: $146,189 (average $29,238 per year)

Other funds (approximate)

Office of Naval Research:	$110,000
Naval Sea Systems Command:	30,000
Department of Transportation:	18,000
National Oceanic and Atmospheric Administration:	4,000
National Aeronautics and Space Administration:	8,000
Total (average $34,000 per year):	$170,000

AFOSR monitors: Capt. Westcott H. Smith, Lt. Col. G. S. Lewis, Lt. Col. Robert C. Smith

Students

Undergraduates: A. J. Gregorcyk, Mark E. Schaffer, Solon B. Williams

Graduate Students: Mark O. Anderson, Mary B. Bennett, Edward P. Cornet, David R. Kleeman, James C. Lockwood, F. Michael Pestorius, Mark E. Schaffer, William L. Willshire

Degrees (at The University of Texas at Austin unless otherwise indicated)

Mark E. Schaffer	BS, Engineering Science, December 1973
Solon B. Williams	BS, Chemical Engineering, December 1973
Mark O. Anderson	MS, Mechanical Engineering, August 1974
Mary B. Bennett	MS, Electrical Engineering, May 1973
Edward P. Cornet	MS, Physics, December 1971
David R. Kleeman*	MS, Electrical Engineering, August 1976
Mark E. Schaffer*	MS, Mechanical Engineering, December 1975
James C. Lockwood	PhD, Mechanical and Aerospace Sciences, 1971, at University of Rochester, Rochester, NY
F. Michael Pestorius	PhD, Electrical Engineering, August 1973

Reports of research

Eighteen oral presentations:

71-2	72-3	73-2	74-3	75-2
71-3	72-4	73-5	74-4	75-3
71-4	72-6	73-6		
71-6	72-7	73-7		
71-8		73-10		

Six journal publications: 73-4, 73-8, 74-1, 74-6, 75-1, JS-1

Six papers in proceedings: 71-7, 72-2, 73-3, 74-2, 74-5, 75-4

Seven theses: 71-5, 71-9, 73-1, 73-9, 74-7, 75-5, 76-6

Eight technical reports: 71-5, 71-9, 73-1, 73-9, 74-7, 75-5, 76-3, 76-6

Final report: "Research in high intensity sound" (76-3)

The research expanded a great deal during the five-year period of Contract (IV). Several things made the expansion possible. First, a much larger number of students interested in acoustics are available at The University of Texas at Austin. Second, Austin is a center of acoustical activity, both industrial and government sponsored; Applied Research

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* Degree was received during the period of Contract (V) but is listed here because most of the work was done during the time of Contract (IV).

Laboratories in particular has excellent facilities for acoustical research. Third, there continued to be a strong growth of interest in the field of nonlinear acoustics itself during the 1970's. Finally, greatly increased funds became available. AFOSR increased its level of sponsorship, and cosponsors together added an amount slightly in excess of the AFOSR support.* The expansion produced a greatly increased output, as can be seen by comparing figures for Contracts (II) and (IV) (both ran for five years). There are 18 bibliographical entries associated with Contract (II) but 45 associated with Contract (IV). As for degrees, five BS and one MS are listed for Contract (II) whereas two BS, five MS, and two PhD degrees are listed for Contract (IV).

The projects worked on during Contract (IV) may be grouped under the following headings: N waves, periodic waves of finite amplitude, finite-amplitude noise, and general. Because a good description of each project is given in the final report for Contract (IV) (76-3), only a list with appropriate bibliographical entries cited is given here.

1. N waves
   - a. Propagation of a spherical N wave: 71-9, 74-7
   - b. Diffraction of an N wave by a circular aperture: 71-5, 74-7
   - c. Focusing of an N wave by a spherical mirror: 71-9, 72-4
   - d. Microphone developments
     - (1) Improved design: 71-9, 74-7
     - (2) Calibration technique: 71-9, 74-3, 74-7
     - (3) Response to transients: 71-8, 76-3
   - e. Development of a schlieren apparatus: 76-3, 76-6
2. Periodic waves of finite amplitude
   - a. Plane waves in a tube: 72-7, 73-2, 73-3, 73-9, 73-10, 74-2

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* It should be noted that inflation accounted for much of the increase in funding. For example, the base salary for a beginning graduate student increased 32% from September 1970 to September 1975.

b. Upper limit on the use of weak-shock theory: 74-6

c. Plane waves in horns and in the (stratified) atmosphere: 72-6, 73-7, 76-3

d. Directional beams of intense sound: 71-2, 71-3, 71-4, 71-5, 71-6, 71-7, 72-2, 73-4

e. Acoustic saturation of spherical waves: 71-2, 72-2, 74-1

f. Outdoor propagation of tones: 76-3

g. Parametric array in air: 73-1, 73-5, 75-1

h. Suppression of sound by sound of lower frequency: 75-2, 75-5, JS-1

i. Acoustical convolutor: 73-8

3. <u>Finite-amplitude noise</u>

a. Plane waves in a tube: 72-7, 73-2, 73-3, 73-6, 73-9, 73-10, 74-2

b. Noise in open media: 74-4, 74-5, 75-3, 75-4

4. <u>General</u>: 72-3

Two of the projects, diffraction of an N wave by a circular aperture and acoustic saturation of spherical waves, were continued from Contract (III). Two others, schlieren apparatus development and outdoor propagation of tones, were to be completed in Contract (V).

Contract (IV) had more highlights than its predecessors. The significance of acoustic saturation as an upper limit on sound transmission has already been discussed. The study of directional beams provided an understanding of nonlinear propagation effects for a whole new -- and practical -- class of high-intensity sound sources. The experiment on the parametric array in air proved that the parametric effect occurs in air as well as in water (previously, doubt about the existence of the effect in air had been expressed). The successful first attack on the problem of finite-amplitude noise constituted a breakthrough. Heretofore, despite its potential importance for aircraft noise, the problem had seemed intractable.

Some basic information about the students is as follows. James C. Lockwood, University of Rochester student, finished his PhD degree in 1971 after writing a thesis on two topics, directional beams of intense sound and diffraction of an N wave by a circular aperture (71-5). He stayed at Applied Research Laboratories for a time as a staff member and then took a job at Ametek/Straza, El Cajon, CA. He is now manager of the Advanced Systems Department, Stanwick Corporation, San Diego, CA. Starting out as Lockwood's assistant, Edward P. Cornet performed the experiments on focusing of an N wave by a spherical mirror (71-9) for his master's research and then returned to the Physics Department, where he completed a PhD degree in 1976. He now works for Austin Research Associates, Austin, TX. Mary Beth Bennett conquered the parametric array in air (73-1) as her master's project and, after a short period in Virginia, returned to Applied Research Laboratories as a staff member. F. Michael Pestorius, at the time an LCDR in the Navy, performed the pioneering experiments and calculations on finite-amplitude noise (73-9). After receiving his PhD degree in 1973, he returned to sea duty as the executive officer of a nuclear submarine. He was later promoted to Commander and in 1977 was given command of USS MARIANO G. VALLEJO. An able assistant to both Bennett and Pestorius, Solon Williams completed a bachelor's degree in chemical engineering in 1973 and now works for Monsanto Chemical Company at its Chocolate Bayou Plant, Alvin, TX. Mark O. Anderson extended the work on diffraction of an N wave by a circular aperture (74-7) and received his MS degree in 1974. He took a job with Haliburton Services, Duncan, OK. After breaking in as Anderson's assistant, Mark E. Schaffer performed the experiments in which low frequency sound was used to suppress high frequency sound (75-5). Shortly after receiving his master's degree in 1975, he began work as an acoustical consultant in the firm Paul S. Veneklasen and Associates, Santa Monica, CA. Developing the schlieren apparatus to visualize N-wave fields was the master's project of David R. Kleeman (76-6), and he completed his degree in 1976. After a period at IIT Research Institute, Annapolis, MD, he now works for Lockheed in Sunnyvale, CA.

III. CONTRACT (V), F44620-76-C-0040

1 November 1975 to 31 October 1978

A. Vital Statistics

Contractor: The University of Texas at Austin (Applied Research Laboratories)

AFOSR funds: $117,499 (average $39,166 per year)

Other funds (approximate)

Office of Naval Research:	$111,000
National Aeronautics and Space Administration:	73,000
National Oceanic and Atmospheric Administration:	17,000
Total (average $67,000 per year):	$201,000

AFOSR monitors: Lt. Col. Robert C. Smith, Lt. Col. Lowell W. Ormand

Students

Undergraduates: Benjamin J. Bourgeois, A. J. Gregorcyk, Jerry D. Jessup, Jeffrey R. Kuhn

Graduate Students: Wesley N. Cobb, Robert D. Essert, David R. Kleeman, Mark E. Schaffer, Mark A. Theobald, Don A. Webster, William L. Willshire

Degrees (at The University of Texas at Austin unless otherwise indicated)*

Benjamin J. Bourgeois	BS, Physics, December 1976
A. J. Gregorcyk	BS, Physics, December 1977
Jerry D. Jessup	BS, Physics, June 1977, at Hendrix College, Conway, AR
Jeffrey R. Kuhn	BS, Physics, June 1977, at Kalamazoo College, Kalamazoo, MI
Wesley N. Cobb	MS, Mechanical Engineering, December 1977
Mark A. Theobald	MS, Mechanical Engineering, May 1977

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* MS degrees of Schaffer and Kleeman are listed under Contract (IV).

Don A. Webster	MS, Electrical Engineering, December 1976 PhD, Electrical Engineering, expected 1980
William L. Willshire	MS, Mechanical Engineering, May 1977

Reports of research

Fourteen oral presentations:	76-1	77-2	78-2
	76-2	77-4	78-3
	76-4	77-5	78-5
		77-6	78-6
		77-7	
		77-10	
		77-11	

Three journal publications: 77-9, 78-1, 79-1

One paper submitted (and accepted) for publication: JS-2,

One paper in a proceedings: 76-5

Four theses: 76-7, 77-1, 77-3, 77-8

Five technical reports: 76-7, 77-1, 77-3, 77-8, 78-4

papers to be submitted for journal publication

The research activity, and expenditures to support it, was larger on an annual basis than during Contract (IV). The effort reached a maximum in 1976 and 1977. During these two years the outdoor propagation projects (see below), which absorbed most of our resources, also peaked.

B. Projects

The headings under which the various projects are classified are as follows: N waves and transients, interaction of sound with sound, propagation of periodic waves, finite-amplitude noise, and miscellaneous. Although this classification is in certain cases artificial, it is useful for reporting purposes.

1. N waves and transients

In this area there were two projects involving the use of a schlieren system, one project on N wave risetime, and one theoretical project on weak-shock decay.

a. Development of a schlieren apparatus

Kleeman finished developing the schlieren apparatus he had begun during Contract (IV). The apparatus allowed us to visualize the entire spatial wave field in N wave experiments; previously we had been limited to microphone measurements at single points. To demonstrate the usefulness of the apparatus, Kleeman used it to measure several classical acoustic phenomena: reflection of a spherical wave from a flat wall, diffraction by the edge of a flat plate, pulse propagation in a duct, and focusing by a spherical mirror (76-6). One of Kleeman's duct measurements is shown in Fig. 7.

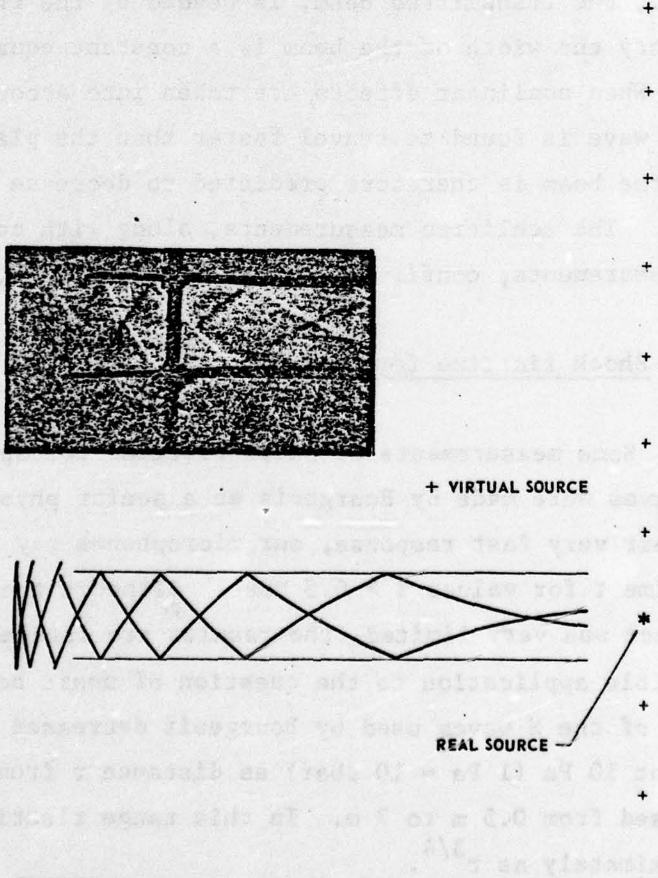

FIGURE 7. Pulse radiating into free space from a duct. (From 76-6)

b. Diffraction of a plane N wave by a slit

Cobb made several improvements on the schlieren system and used it to study the effect of nonlinearity on diffraction of a plane N wave by a slit. The acoustical apparatus was similar to that shown in Fig. 5 except that the opening in the plate was a long narrow rectangle instead of a circle. The incident N wave was made plane by placing a parabolic reflector behind the spark with the spark at the focus.

One of Cobb's schlieren measurements is shown in Fig. 8. The diagrams at the left represent the traditional explanation based on linear diffraction theory. The wavefronts shown are for the shock at the head of the N wave. As the plane wave comes through the slit, the two edges scatter cylindrical waves, which are headed by the circular arcs marked D and E. The plane wave segment that passes through the slit, i.e., the transmitted beam, is headed by the front marked U. In linear theory the width of the beam is a constant equal to the width of the slit. When nonlinear effects are taken into account, however, the scattered wave is found to travel faster than the plane wave segment. The width of the beam is therefore predicted to decrease with distance from the slit. The schlieren measurements, along with complementary microphone measurements, confirmed this prediction (77-8, 77-10, JS-3).

c. Shock risetime for N waves

Some measurements of shock risetime for spherically spreading N waves were made by Bourgeois as a senior physics project. Because of their very fast response, our microphones may be used to measure risetime τ for values $\tau > 0.5$ µsec. Although the time available for this project was very limited, the results are interesting because of their possible application to the question of sonic boom risetime.[13] The amplitude of the N waves used by Bourgeois decreased from about 300 Pa to about 10 Pa (1 Pa = 10 µbar) as distance r from the spark source increased from 0.5 m to 7 m. In this range risetime was found to vary approximately as $r^{3/4}$.

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[13] See, for example, J. P. Hodgson, "Vibrational relaxation effects in weak shock waves in air and the structure of sonic bangs," J. Fluid Mech. 58, 187-196 (1973).

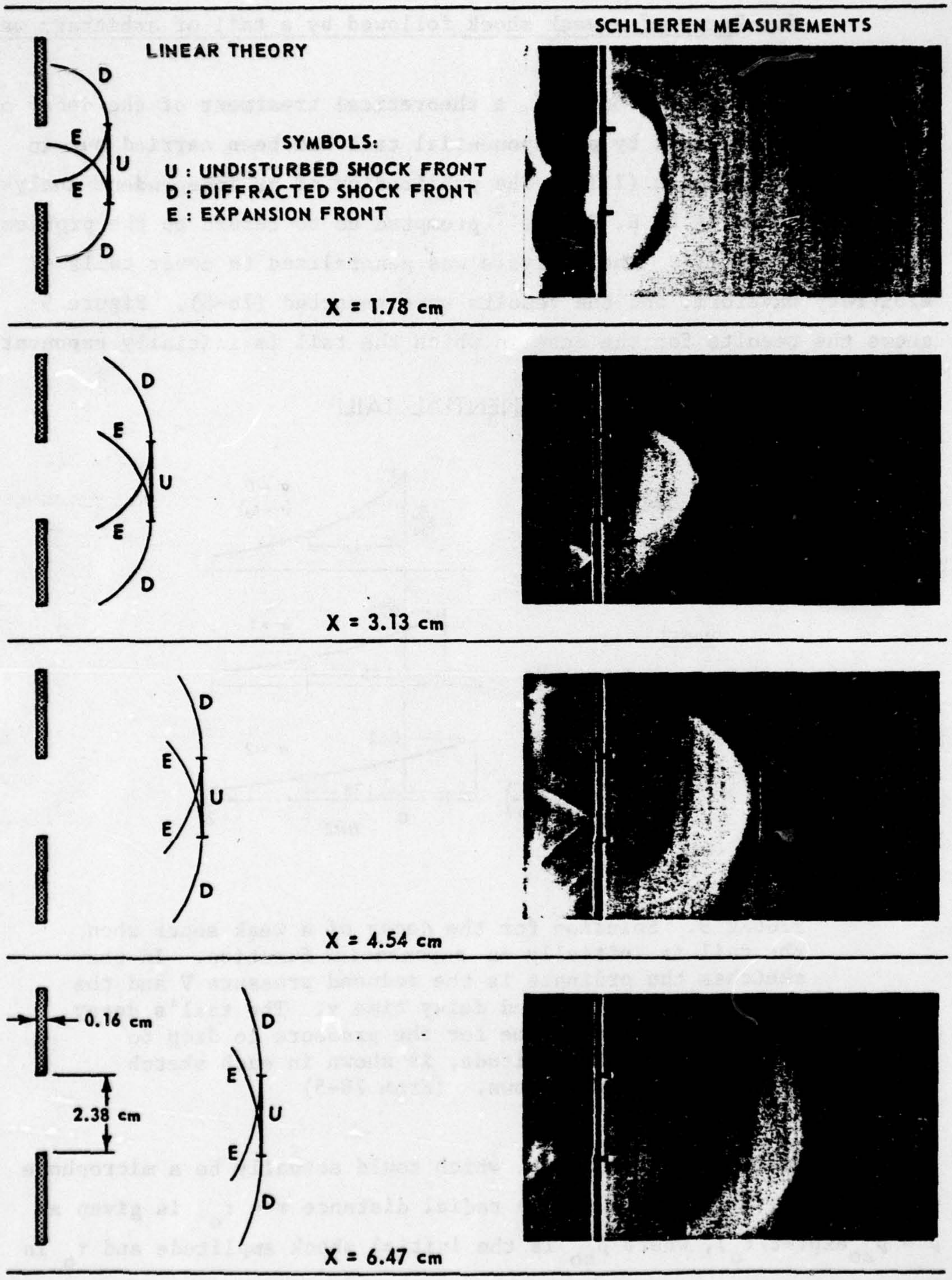

FIGURE 8. Schlieren measurements of the diffraction of a plane N wave by a slit; X represents the distance of the shock from the slit. (From 77-8)

d. <u>Decay of a weak shock followed by a tail of arbitrary waveform</u>

As noted on p.17, a theoretical treatment of the decay of a weak shock followed by an exponential tail had been carried out in 1969, during Contract (III). The publication of an independent analysis of this problem by P. H. Rogers[14] prompted us to return to the problem during Contract (V). The analysis was generalized to cover tails of arbitrary waveform, and the results were reported (78-5). Figure 9 shows the results for the case in which the tail is initially exponential.

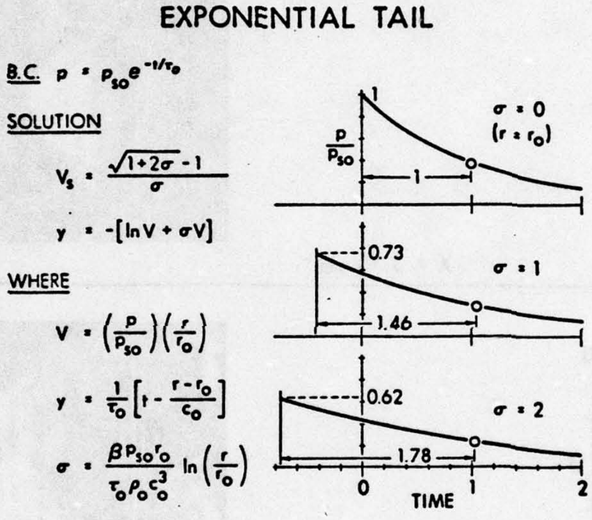

FIGURE 9. Solution for the decay of a weak shock when the tail is initially an exponential function. In the sketches the ordinate is the reduced pressure V and the abscissa is the reduced delay time y. The tail's decay time, that is, the time for the pressure to drop to 1/e of the shock amplitude, is shown in each sketch by the horizontal arrows. (From 78-5)

The pressure boundary condition, which could actually be a microphone or hydrophone measurement at the radial distance $r = r_o$, is given as $p = p_{so}\exp(-t/\tau_o)$, where p_{so} is the initial shock amplitude and τ_o is

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[14] P. H. Rogers, "Weak-shock solution for underwater explosive shock waves," J. Acoust. Soc. Am. <u>62</u>, 1412-1419 (1977).

the initial decay time. The solution is shown in terms of the reduced pressure V (compensated for spherical spreading) and the reduced delay time y, definitions for which appear in the figure. The sketches indicate the way in which (1) the shock decays and (2) the tail stretches out.

2. Interaction of sound with sound

Two projects were carried out in this area. The first was the suppression of one tone by another tone; the second was the interaction of a tone with noise.

a. Suppression of sound by sound

During Contract (IV) Schaffer had performed experiments in which a weak wave was suppressed by adding an intense wave, called the pump, of lower frequency (75-2, 75-5, JS-1). During Contract (V) Willshire investigated the suppression phenomenon for the case in which the pump frequency is higher than the weak wave frequency. It is convenient to refer to Schaffer's arrangement of frequencies as Case I, Willshire's as Case II.

The basis of the suppression phenomenon is modulation, not absorption. In a typical experiment the pump (source particle velocity amplitude u_{op} and frequency f_p) and the weak wave (source amplitude u_{ow} and frequency f_w) are emitted by a common source. In our case the source was a horn driver at one end of a plane wave tube. The composite signal becomes distorted as the signal propagates, and a complicated spectrum is produced. Two families of spectral components may be identified. The first is composed of the pump signal and its harmonics. The second is composed of the weak signal and various sidebands, that is, sum and difference frequency components, which result from the mixing of the weak signal with the pump and its harmonic components.

We are primarily interested in the second family of spectral components. For distances less than the shock formation distance, the particle velocity amplitude of the sideband at frequency $|nf_p \pm f_w|$ is predicted to be

$$u_{\pm 1,n} = u_{ow} \left| J_n \left[\frac{nf_p \pm f_w}{f_p} \sigma_p \right] \right| , \tag{5}$$

where $\sigma_p = x/\bar{x}_p$, and $\bar{x}_p$ is the shock formation distance for the pump. The (+) sign indicates an upper sideband, the (-) sign a lower sideband. The amplitude of the weak signal itself is given by

$$u_w = u_{ow} \left| J_o \left[(f_w/f_p) \, \sigma_p \right] \right| . \tag{6}$$

Equations 5 and 6 are derived from lossless theory.* Attenuation may be accounted for approximately by modifying u_{ow} and σ_p as follows (75-5):

$$u_{ow} \longrightarrow u_{ow} e^{-\alpha_w x} \tag{7a}$$

$$\sigma_p \longrightarrow \frac{1-\exp(-\alpha_p x)}{\alpha_p \bar{x}_p} , \tag{7b}$$

where α_w and α_p are the ordinary attenuation coefficients at frequencies

---

* Equations 5 and 6 are approximate. In their more accurate versions, which may be obtained from Fenlon's solution,[15] a multiplicative factor $2J_1(y_n)/y_n$ is included, where

$$y_n = \frac{f_w}{f_p} + n \frac{u_{ow}}{u_{op}} \sigma_p .$$

However, $2J_1(y_n)/y_n \doteq 1$ for arguments $y_n \ll 1$, that is, in general for orders $n \ll u_{op}/u_{ow}$. For the lower orders, therefore, Eqs. 5 and 6 are quite accurate.

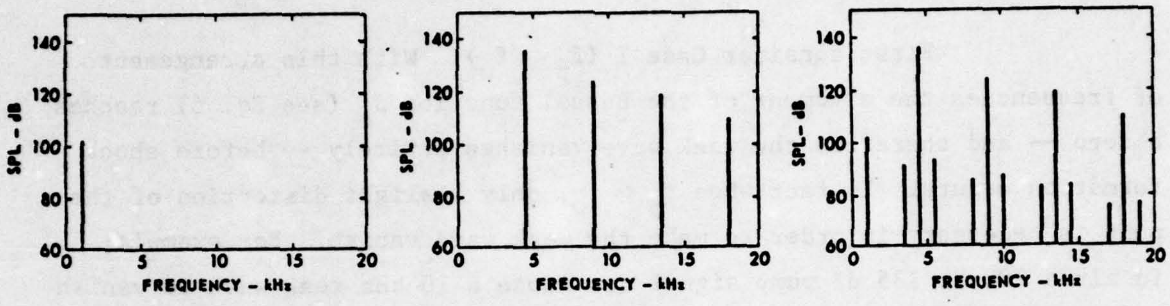
15. F. H. Fenlon, "An extension of the Bessel-Fubini series for a multiple-frequency cw acoustic source of finite amplitude," J. Acoust. Soc. Am. 51, 284-289 (1972).

f_w and f_p, respectively. It should be noted that when suppression is the goal, it is usually desirable to use a pump whose frequency is far removed from the frequency of the weak wave. The analyses for Cases I and II are now done separately.

First consider Case I ($f_p < f_w$). With this arrangement of frequencies the argument of the Bessel function J_o (see Eq. 6) reaches a zero -- and therefore the weak wave vanishes entirely -- before shock formation occurs. In fact when $f_p << f_w$, only a slight distortion of the pump is necessary in order to make the weak wave vanish. For example, in air a 200 Hz 135 dB pump signal can cause a 10 kHz weak wave to vanish at about 10 m even though the shock formation distance for the pump is about 200 m. Schaffer's experiments confirmed that substantial suppression may indeed be achieved. Despite its effectiveness, however, Case I suppression has a serious drawback: the spectrum in the neighborhood of the weak wave frequency is heavily polluted by the sidebands (frequencies $f_w \pm f_p$, $f_w \pm 2fp$, etc.). Since suppression is caused by energy transfer, not energy absorption, energy lost by the weak wave reappears in the sidebands, which in Case I are close in frequency to the weak wave.

Willshire undertook a study of Case II (77-3). In Case II sideband pollution is not a serious drawback because the sidebands occur as satellites of the pump and its harmonics, not of the weak signal. That is, when $f_p > f_w$, the sidebands occur at frequencies $f_p \pm f_w$, $2f_p \pm f_w$, $3f_p \pm f_w$, and so on. Unfortunately, however, a high frequency pump does not produce much suppression. The mathematical explanation is that the zero of the Bessel function J_o (see Eq. 6) cannot be reached because the argument is small even when $\sigma_p \rightarrow 1$. The physical explanation is that the low frequency wave always modulates the high frequency wave, regardless of their respective amplitudes, and so it is the high frequency wave, in this case the pump, that furnishes most of the energy to produce the sidebands. Using weak-shock theory, Willshire also investigated Case II suppression in the postshock region ($\sigma_p > 1$), where Eqs. 5 and 6 do not hold, but no significant increase in suppression was found. Experiments done for values of σ_p as high as 30 confirmed this finding.

An example of Willshire's experimental results (plane waves in a 5 cm diam tube) is shown in Fig. 10. The first spectrum (a) is that of the weak signal by itself, the middle spectrum (b) is of the pump by itself, and the last spectrum (c) is of the combined (interacting) signals. Although a generous development of sideband signals is evident, it is equally evident that there is little or no suppression of the weak signal. The observed sideband levels and the lack of suppression confirm theoretical calculations based on Eqs. 5-7. For example, using Eqs. 6 and 7b, one predicts less than 0.1 dB of suppression.



(a) WEAK SIGNAL ALONE, u'_w

(b) PUMP ALONE, u'_p

(c) COMBINATION OF WEAK SIGNAL AND PUMP, u

FIGURE 10. Case II tone-tone interaction experiment. Weak wave: source SPL = 104 dB, f_w = 1 kHz. Pump: source SPL = 140 dB, f_p = 4.5 kHz. Spectra measured 4.2 m from source (σ_p = 0.82). (From 77-3)

Another set of measurements taken deep in the postshock region ($\sigma_p = 11.4$) is shown in Fig. 11 (Eqs. 5-7 are not valid in this case). Here the values of x and u_{ow} are large enough that some distortion of the weak wave itself takes place. Secondary as well as primary sidebands therefore appear. Each spectral component is identified by a number pair. The first number pertains to the weak signal, the second to the pump. For example, -2,3 denotes the second lower sideband component associated with the third harmonic of the pump, i.e., it is the

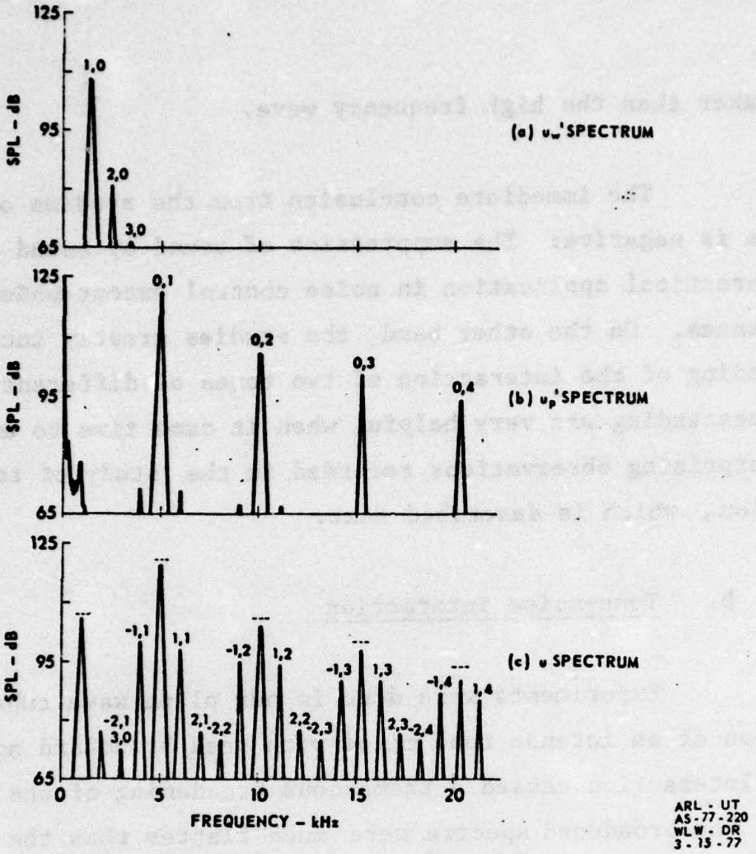


FIGURE 11. Case II tone-tone interaction spectra at an observation point deep in the postshock region. Weak wave: source SPL = 118 dB, f_w = 1 kHz. Pump: source SPL ≈ 146 dB, f_p = 5 kHz. Distance: 26.2 m from source (σ_p = 11.4) (From 77-3)

difference frequency signal formed by the interaction of the weak signal second harmonic with the pump third harmonic. The dashed lines above the main peaks in spectrum (c) indicate the positions of these peaks when the respective signals are by themselves, i.e., as in spectra (a) and (b). The gap between the peak and its dashed line is the amount of suppression. The amount of suppression of the weak signal is very slight; the harmonics of the pump suffer rather more. Thus the energy to form the sidebands seems to come more from the pump and its harmonics than from the weak signal. This is the reverse of what happens in Case I. It was observations of this sort that led to the comment made previously that the low frequency wave always seems to do most of the modulating, even if it is weaker than the high frequency wave.

The immediate conclusion from the studies of Schaffer and Willshire is negative: The suppression of sound by sound is not likely to find practical application in noise control except under very special circumstances. On the other hand, the studies greatly increased our understanding of the interaction of two tones of different frequency. This understanding was very helpful when it came time to explain the rather surprising observations recorded in the study of tone-noise interaction, which is described next.

b. Tone-noise interaction

Experiments were done in our plane wave tube on the propagation of an intense tone mixed with weak broadband noise (77-5, 78-1). Interaction caused a tremendous broadening of the noise spectra. Moreover, the broadened spectra were much flatter than the broadened spectra we had observed earlier in the noise-only propagation experiments done by Pestorius (73-9, 74-2).

The results of a typical experiment are shown in Fig. 12 (78-1). The top row shows spectra of the intense tone (source frequency 864 Hz, SPL 151 dB) when the noise is turned off. The distances are $x = 0$ (source), $x = 7.38$ m (approximately $\bar{x}$), and $x = 22.1$ m (approximately $3\bar{x}$). For the spectra in the second row the tone is turned off and only the noise is on.* Finally, the third row shows the spectra when both tone and noise are turned on. The noise portion of the combination spectrum may be inferred by mentally filtering out the harmonic components of the tone. The fact that the noise spectrum broadens as the combined signal propagates is not surprising because we have seen broadening before in our noise-only experiments. What is surprising is

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* A slight change in spectral shape with distance may be seen. This change is partly due to variation of the tube-wall absorption with frequency and partly due to very weak finite-amplitude distortion.

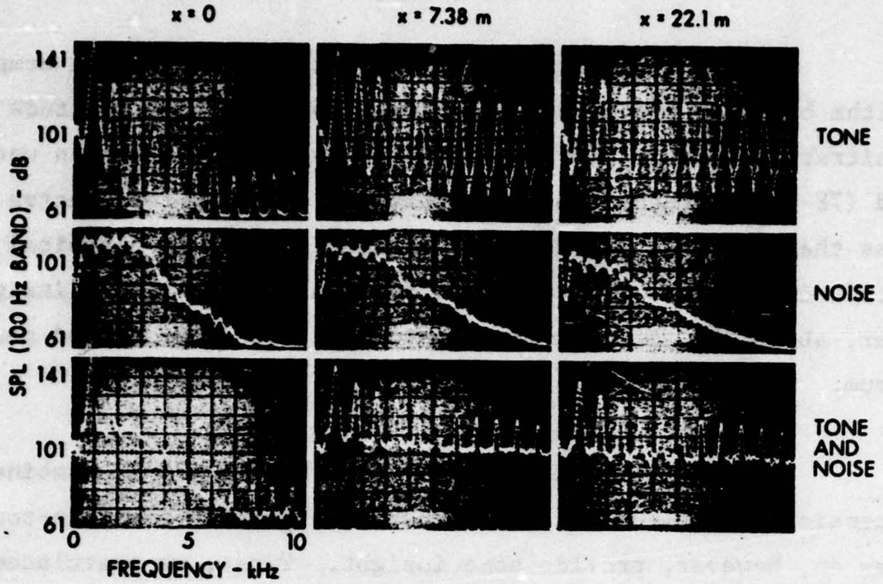

FIGURE 12. Interaction of noise with an intense tone, tone located at the lower end of the noise band.
Noise: OASPL = 128 dB, frequency band 400-3400 Hz.
Tone: SPL = 151 dB, f = 864 Hz, $\overline{x}$ = 7.45 m. (From 78-1)

the extent and character of the broadening. The noise spectrum is tremendously enhanced, becoming almost flat as the wave propagates to the shock formation point and beyond. In fact, when the spectrum analyzer bandwidth was extended to 50 kHz (its maximum), the flatness property was observed to extend at least that far. There is a slight decline of the noise spectrum with frequency about 2 to 3 dB/octave, but certainly not the 6 dB/octave rolloff characteristic of intense noise-only experiments.

Theoretical results were obtained by using a computer algorithm based on the Earnshaw solution for a finite-amplitude wave of arbitrary waveform; corrections for tube wall attenuation were included (78-1). Agreement between computed and measured spectra demonstrates that the observed spectral changes are due to classical finite-amplitude distortion. The computed results provide little insight, however, about why the interaction produced such a broad and nearly flat spectrum.

Results from companion experiments (78-1) combined with an extension of the analytical methods developed in the tone-tone interaction studies do, however, provide some insight. First, we postulated that the noise between tone harmonics is due to sidebands just as the satellites of the pump harmonics in tone-tone interaction (Figs. 10 and 11) are sidebands. To test this thesis, we used Eqs. 5 and 7 to compute the SPL of the noise component at 8114 Hz at $x = 7.38$ m (see bottom center spectrum in Fig. 12). The following interactions between tone harmonics and components in the initial noise band produce signals at 8114 Hz:

Tone Harmonic (n in Eq. 5)	Frequency of Noise Component (f_w in Eq. 5)
5	3794 Hz
6	2930
7	2066
8	1202
10	526
11	1390
12	2254
13	3118

The contribution due to each interaction was computed. Only the second through fifth interactions were significant. When their contributions were combined as uncorrelated signals, that is, on an intensity basis, the resulting composite signal had a (100 Hz) band level of 102.5 dB. This level compares very favorably with the measured level, 103 dB, which may be read from Fig. 12 at 8114 Hz. This sample calculation demonstrates quantitatively the validity of the sideband explanation. Moreover, for more distant parts of the spectrum, the sideband amplitude (see Eq. 5) is proportional to $J_n(n\sigma_p)$, or, as $\sigma_p \to 1$, to $J_n(n)$. Because $J_n(n)$ varies as $n^{-1/3}$ for large values of n, one infers that the high frequency rolloff of the noise should be only 2 dB/octave. A rolloff of 2 to 3 dB/octave was indeed observed in the experiment in which the spectral analysis was carried out to 50 kHz (78-1). Although our explanation of the gentleness of the high frequency rolloff is limited to the vicinity of the shock formation point, the similarity of the spectra at 7.38 m and 22.1 m in Fig. 12 shows that the spectral characteristics of the noise do not change much when the wave propagates into the postshock region. In summary, it appears fruitful to use the sideband thesis when attempting to predict tone-noise interaction spectra.

An obvious application of this research is to jet noise spectra that consists of broadband noise mixed with discrete frequency tones. Nonlinear interaction between the tones and the broadband noise may help explain the shape of the spectrum.

3. Propagation of periodic waves

Three projects are included in this section: acoustic saturation of plane waves in a tube, outdoor propagation of intense tones, and asymptotic decay of spherical waves.

a. Finite-amplitude saturation of plane waves in a tube

Using airborne waves in our plane wave tube, Webster performed an experiment that was similar in concept to the saturation experiment carried out during Contract (III). It will be recalled that the earlier experiment was done with spherical waves in water; see pp. 16-17. In both cases a source emitted a sinusoidal acoustic wave. The sound pressure level of the received signal at a given distance was then measured as a function of source level. Typical results for the plane wave experiment are shown in Fig. 13 (76-2, 76-7, 77-9). At low source levels

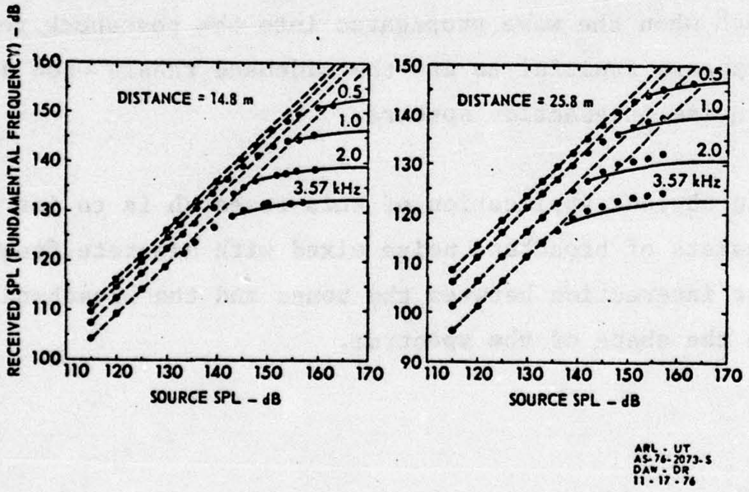

FIGURE 13. Amplitude response curves (received level vs source level) for fundamental component of a wave that is a pure sinusoid at the source. Fundamental frequency is indicated for each curve. Dashed curves: linear theory. Solid curves: nonlinear theory. Dots: experimental data. (From 77-9)

the received level follows source level dB for dB, in accordance with linear theory, which is represented in the figure by dashed lines. As the source level is increased, however, the received level begins to depart from the linear-theory prediction. Eventually, the received level reaches a plateau. The operating condition is now one in which the received signal does not increase no matter how much acoustic power is radiated by the source. This condition is called saturation.* It is due to severe nonlinear propagation distortion, which turns the sine wave into a sawtooth. Much of the energy in a sawtooth is carried by the high frequency components, which are more easily absorbed by the medium. When the saturation plateau is reached, all further source level increases are completely used up by increased absorption.

Certain differences between the underwater saturation experiment (pp. 16-17) and the one done in air are worth mentioning. The fundamental frequency in the underwater experiment was so high, 450 kHz, that no measurement of the sawtooth waveform was attempted (the receiver bandwidth required would have been too great). Sawtooth waveforms were observed in the tube experiment (measurements were possible because of the much lower fundamental frequencies used, 500 to 3570 Hz) but were found to be asymmetrical. As noted earlier [Contract (II), p. 7] the asymmetry is due to dispersion caused by tube wall effects. Dispersion was not a factor in the underwater experiment. Dispersion's companion, ordinary small-signal absorption, played only a minor role in the underwater experiment. In the tube experiment, however, ordinary absorption was so important that the weak-shock theoretical prediction for the saturation amplitude required considerable modification.

Both experiments proved that saturation does indeed take place: there is an absolute limit on the transmission of acoustical energy. They also proved that our theoretical understanding of saturation is quantitatively correct.

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* This kind of saturation is sometimes referred to as finite-amplitude saturation to distinguish it from other saturation phenomena in acoustics.

b. Outdoor propagation of intense tones

This project, to measure the propagation of intense periodic waves outdoors, was by design closely allied to the project on outdoor propagation of intense noise (see below). In fact, the tones experiment was regarded as Phase I and the noise experiment Phase II of a three-year program. Both projects were larger by a factor of about three, in terms of man hours and general effort, than any previous project. The purpose of the tone propagation study was to determine the extent to which the outdoor environment, especially random inhomogeneity of the medium, affects nonlinear propagation distortion. Most previous experiments on finite-amplitude propagation in air had been carried out indoors under highly controlled laboratory conditions, either in tubes (e.g., 62-2, 67-3, 73-9, and 77-9) or in anechoic enclosures.[12] The measurements were carried out by Theobald (77-1) and Webster (76-7) and were reported at meetings (77-4, 77-7). A summary appears in Ref. 78-4.

The heart of the experimental facility was an 85 m tall radio tower. Located on the ground, the source sent waves upward parallel to the tower; in this way ground reflection was avoided. After passing through a relatively short nearfield, the waves spread spherically over the remainder of the propagation path. The tower elevator carried the microphone. The source mounting had a tilt adjustment so that beam patterns as well as propagation curves could be measured. Three different sources were used: a circular array of 7 horns (driven by JBL 375 horn drivers), a triangular array of 10 horns, and a siren. The siren proved to be a very powerful source. Source frequencies and source levels (SL_{1m}) were in the range 6 to 8 kHz and 149 to 149 dB, respectively. Experiments were done at windspeeds (ground level) ranging from 0 to 24 km/h.

Although mainly experimental, the investigation had several theoretical aspects. In the design stages we developed a source-frequency level ($\text{SFL} = \text{SL}_{1m} + 20 \log_{10} f_{kHz}$) chart to evaluate the ability of a given source to produce spherical waves of finite amplitude. The chart, shown in Fig. 14, has plotted on it the operating points for several experiments. A source is classified as weak, moderate, or strong depending upon whether its operating point lies below the lower curve, between the two curves, or above the upper curve, respectively. The SFL chart proved to be a useful and faithful design tool. (To use the chart for sources in fresh water, use the right-hand scale.)

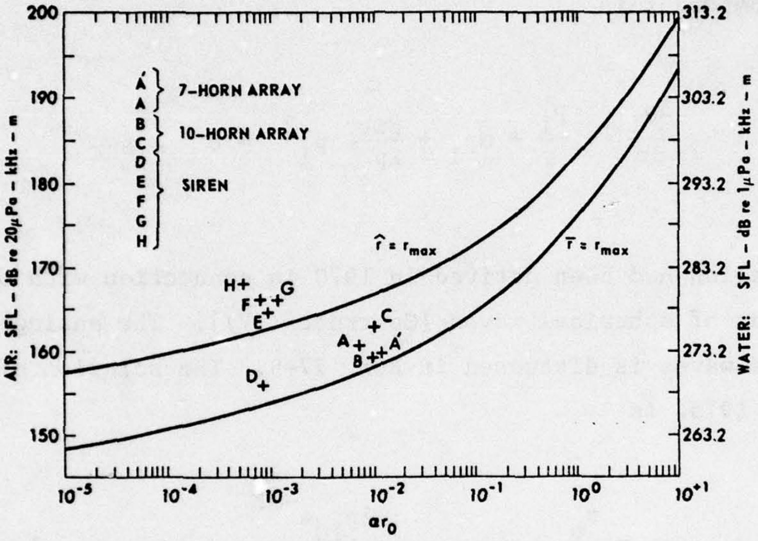

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FIGURE 14. Source-frequency level chart, used to assess the importance of nonlinearity on spherical wave propagation. Scale at left is for air, scale at right for fresh water. (From 78-4)

Three different methods were used to obtain theoretical curves to which the experimental data could be compared. First, for weak waves Webster obtained a perturbation solution of Eq. 3, Burgers' equation for spherical waves (76-7). All terms through fourth order were found and also some of the fifth-order terms. Although Burgers' equation applies only to a medium whose attenuation coefficient α is proportional to f^2, the atmosphere has this property over limited frequency ranges. Second, for strong waves in the region $\sigma > 3$, a model equation for the decay of the pressure amplitude p_1 of the fundamental component is

$$\frac{dp_1}{dr} + \frac{p_1}{r} + \alpha p_1 + \frac{\beta \epsilon k}{2p_{10}} p_1^{\;2} = 0 \quad . \qquad (8)$$

This equation had been derived in 1970 in connection with our work on saturation of spherical waves [Contract (IV)]. The analogous equation for plane waves is discussed in Ref. 77-9. The solution of Eq. 8, found in 1975, is

$$p_1 = \frac{r_o}{r} \frac{2p_{10}e^{-\alpha r}}{e^{-\alpha r_o} + \beta \epsilon k r_o [E_1(\alpha r_o) - E_1(\alpha r)]} \quad , \qquad (9)$$

where E_1 is the exponential integral (76-7). This solution was useful in predicting the decay of the fundamental component in the siren experiments. Finally, Pestorius's computer algorithm (73-9), generalized to apply to spherical waves in the atmosphere, was used to generate theoretical predictions for several of the experiments (77-1). In all three theoretical approaches the medium was assumed to be homogeneous, that is, no attempt was made to account for fluctuations.

Samples of the data are presented in Figs. 15 - 17. Figure 15 shows propagation curves for a weak-wave experiment. The theoretical predictions based on the perturbation solution of Burgers' equation (dashed curves) fit the data very well. Waveforms and spectra for a moderate-wave experiment (during which the atmosphere was very calm) appear in Fig. 16. The theoretical predictions were obtained by using the computer algorithm (the input to the computer program was the first waveform, that is, the one at 6.1 m). Shocks formed, about as predicted, and began to be smoothed away as the distance became large. One thing not predicted was the peakedness of the shocks. The peakedness, which reached a maximum at 12 m, is attributed to diffraction effects, which are not included in any of our theoretical models. Figure 17 shows propagation curves for a strong-wave (siren) experiment. Equation 9 was used to obtain the theoretical prediction in this case. The extra attenuation (of the fundamental) due to nonlinearity is measured by the deviation of the data from the linear theory curve. It is seen that the fundamental suffered an extra attenuation of about 4 dB as it traveled from 2.2 m to 37 m. Not indicated on the graph, however, is the fact that another 6 dB was lost between

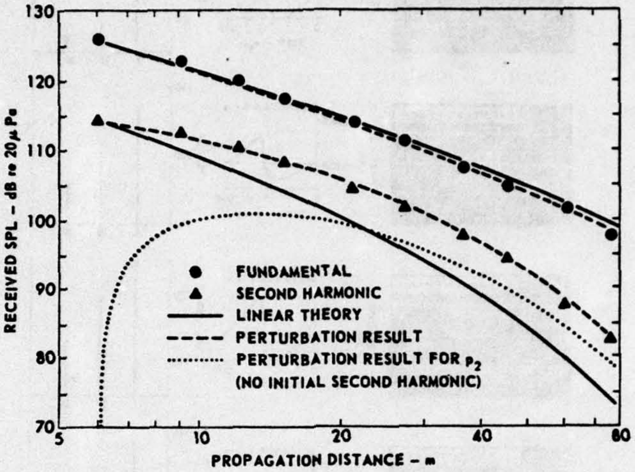

FIGURE 15. Propagation data for weak-wave experiment (7-horn array). SL_{1m} = 141.5 dB, f = 8.25 kHz, α = 0.0076 Np/m, R_o = 3.2 m (point A' in Fig. 14). (From 76-7, 78-4)

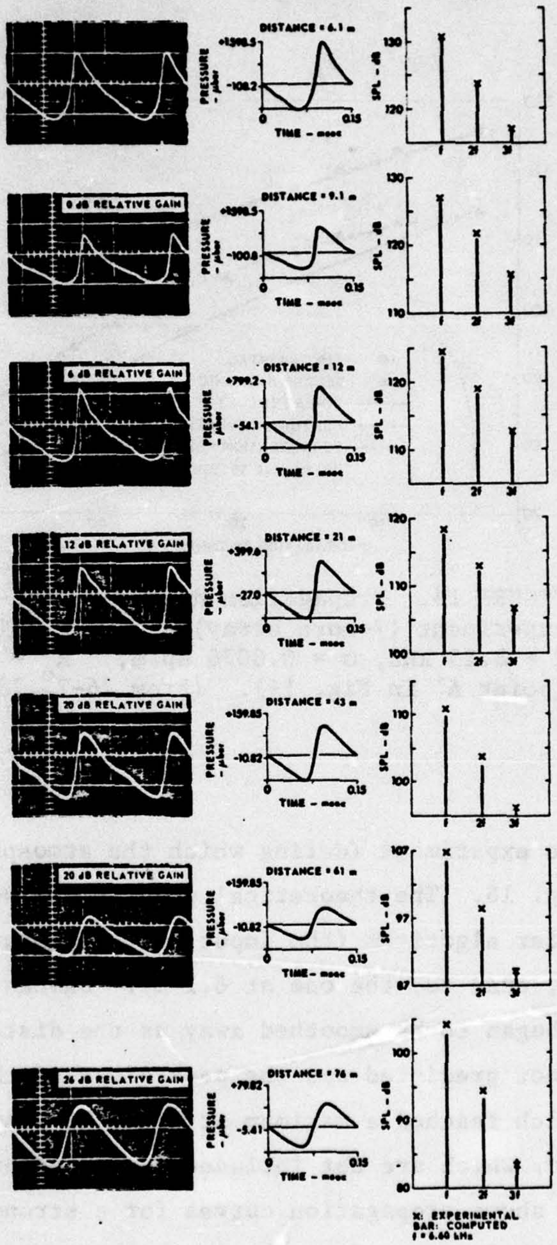

FIGURE 16. Waveforms and spectra for a moderate-wave experiment (10-horn array). SL_{1m} = 146.5 dB, f = 6.6 kHz, α = 0.0053 Np/m, R_o = 3.6 m (point C in Fig. 14). (From 77-1, 78-4)

the source and the 2.2 m point. The total loss was therefore about 10 dB. Extra losses of this magnitude were observed in several of the siren experiments.

Random inhomogeneity of the medium was observed to have a strong effect on instantaneous measurements but little if any effect on long term average measurements. For example, there were significant fluctuations, both in amplitude and wave shape, of the instantaneous waveforms. (The waveform variations seen in Fig. 16 are unusually mild; the atmosphere was completely calm when those data were taken.) The fluctuations increased with distance from the source. With sufficient time averaging, however, the spectral data showed excellent agreement with predictions based on theory for homogeneous media; see, for example, Figs. 15 and 17.

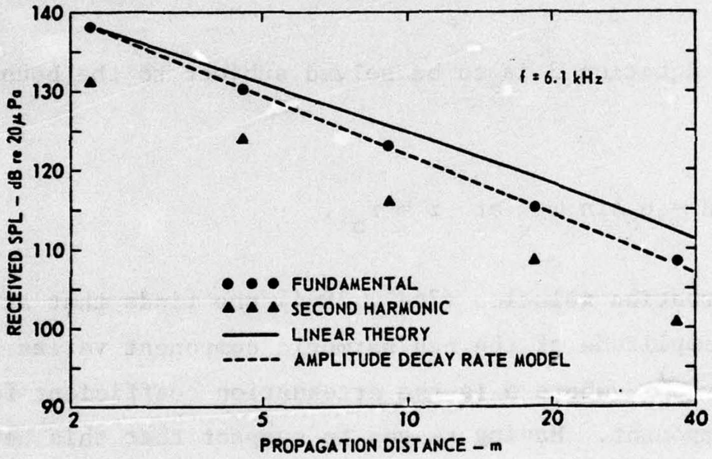

FIGURE 17. Propagation data for a strong-wave experiment (siren). SL_{1m} = 145 dB, f = 6.1 kHz, α = 0.0059 Np/m, r_o = 0.09 m (point H in Fig. 14). (From 76-7, 78-4)

In summary, the classical nonlinear propagation phenomena well known from indoor experiments -- harmonic distortion, shock formation, and extra attenuation (to the brink of saturation) -- were observed in the outdoor environment. Moreover, when sufficient averaging time was allowed for the measurements, theory and data were found to be in good agreement even though the theory was for a homogeneous medium. Asymmetric waveforms qualitatively attributed to diffraction effects were observed.

c. Asymptotic decay of spherical waves

Although it is of considerable practical importance, the problem of the decay of periodic, finite-amplitude, spherical waves at great distance from their point of origin is still not fully solved. For a medium in which the attenuation coefficient varies as f^2, the appropriate equation to be solved is Burgers' equation, Eq. 3, and although much is known about the solution of this equation,[15] its asymptotic solution has yet to be found. For relaxing media, such as the atmosphere and the ocean, methods similar to those described by Safar[16] or Pernet and Payne[17] may be used, but again no asymptotic solutions are known. We were able to find some of the properties of the asymptotic solution of Burgers' equation during the final year of the contract (78-6).

Equation 3 is to be solved subject to the boundary condition

$$u = u_o \sin \omega t \quad \text{at} \quad r = r_o \; . \qquad (10)$$

From the perturbation solution (76-7, 78-4) one finds that at great distances the amplitude of the nth harmonic component varies as $(r\ /r)^n \, e^{-n\alpha(r-r_o)}$, where α is the attenuation coefficient for the fundamental component. Having reason to suspect that this behavior might hold for strong waves as well as weak waves, we assumed a solution of Eq. 3 in the form

$$u = u_o \sum B_n (r_o/r)^n \, e^{-n\alpha(r-r_o)} \sin n\omega t' \; . \qquad (11)$$

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

[16] M. H. Safar, "The propagation of spherical acoustic waves of finite amplitude in fresh and sea water," J. Sound Vib. 13, 1-7 (1970).

[17] D. F. Pernet and R. C. Payne, "Non-linear propagation of signals in air," J. Sound Vib. 17, 383-396 (1971).

A recursion relation among the coefficients B_n was found. At great distance the relation reduces to

$$B_n = B_1\left(B_1\Gamma/4\right)^{n-1} ,$$

where $\Gamma = \beta\epsilon k/\alpha$. The asymptotic expression for the amplitude u_n of the nth harmonic is therefore

$$u_n = \frac{4\alpha c_o}{\beta k}\left(\frac{B_1\Gamma}{4}\right)^n\left(\frac{r_o}{r}\right)^n e^{-n\alpha(r-r_o)} \qquad (12)$$

The quantity B_1 is still undetermined. Some limiting values were found, however. For weak waves it is necessary to take $B_1 = 1$ because only then does Eq. 12 match the perturbation result. For the other extreme, very strong waves, u_n must be independent of ϵ and so we take $B_1 = 4K/\Gamma$, where K is a constant. The result is

$$u_n = \frac{4\alpha c_o}{\beta k} K^n \left(\frac{r_o}{r}\right)^n e^{-n\alpha(r-r_o)} \qquad \text{(strong wave limit).} \quad (13)$$

This is perhaps the most interesting result of the analysis. Unfortunately, the value of K is still unknown (in the plane wave limit, $r_o \to \infty$, one must take $K = 1$).

When its physical implications are considered, Eq. 12 is a remarkable result. Regardless of the source amplitude, the nth harmonic decays asymptotically as $(r_o/r)^n e^{-n\alpha(r-r_o)}$. This result is not at all what one would expect if one relied on linear theory. The linear theory decay $(r_o/r)\, e^{-n^2\alpha(r-r_o)}$ is more rapid. The conclusion is that when a finite-amplitude wave propagates, it never reaches a farfield where linear-theory laws take over. This conclusion also holds when the source emits finite-amplitude noise rather than a periodic signal (see next section).

4. Finite-amplitude noise

The major project in this area was an outdoor propagation experiment, which was the successor to the outdoor tone propagation study (Item 3b above). Two smaller topics, the effect of nonlinear distortion on random signals and amplitude density of a finite-amplitude wave, grew out of the outdoor investigation.

a. Outdoor propagation of intense noise

A series of experiments was carried out on the propagation of finite-amplitude noise outdoors (78-4). This was Phase II in our outdoor propagation program (see Item 3b above). The purpose of the study was to determine the extent to which nonlinear effects influence the propagation of noise from a controlled source in the outdoor environment. A secondary purpose was to develop, if possible, a theoretical model for the noise propagation. A ground-mounted electroacoustic source (a horn array like those used in Phase I) transmitted broadband, octave band, or 1/3 octave band noise in the frequency range 2 to 10 kHz. The source level (overall sound pressure level) of the noise was in the range 121 to 145 dB re 20 μPa at 1 m. As in Phase I, the propagation path was vertical and parallel to an 85 m tower, whose elevator carried the traveling microphone. The maximum propagation distance was about 80 m. The experiments were done at night during the months June through September 1977. The meteorological conditions (ground level) were as follows: temperature range 23 to 31°C, relative humidity range 55 to 90%, and wind speed 0 to 24 km/h. The measurements were made by Webster and Alexander.

Spectra from one of the experiments are shown in Fig. 18. In this experiment there were two sets of measurements, one about 20 dB higher in level than the other. The spectral shape of the input noise was the same for both sets. The distance r is measured from the face of the horn array. At the first measurement point, which was inside one of the horns ($r = -0.23$ m), the overall sound pressure level (OASPL)

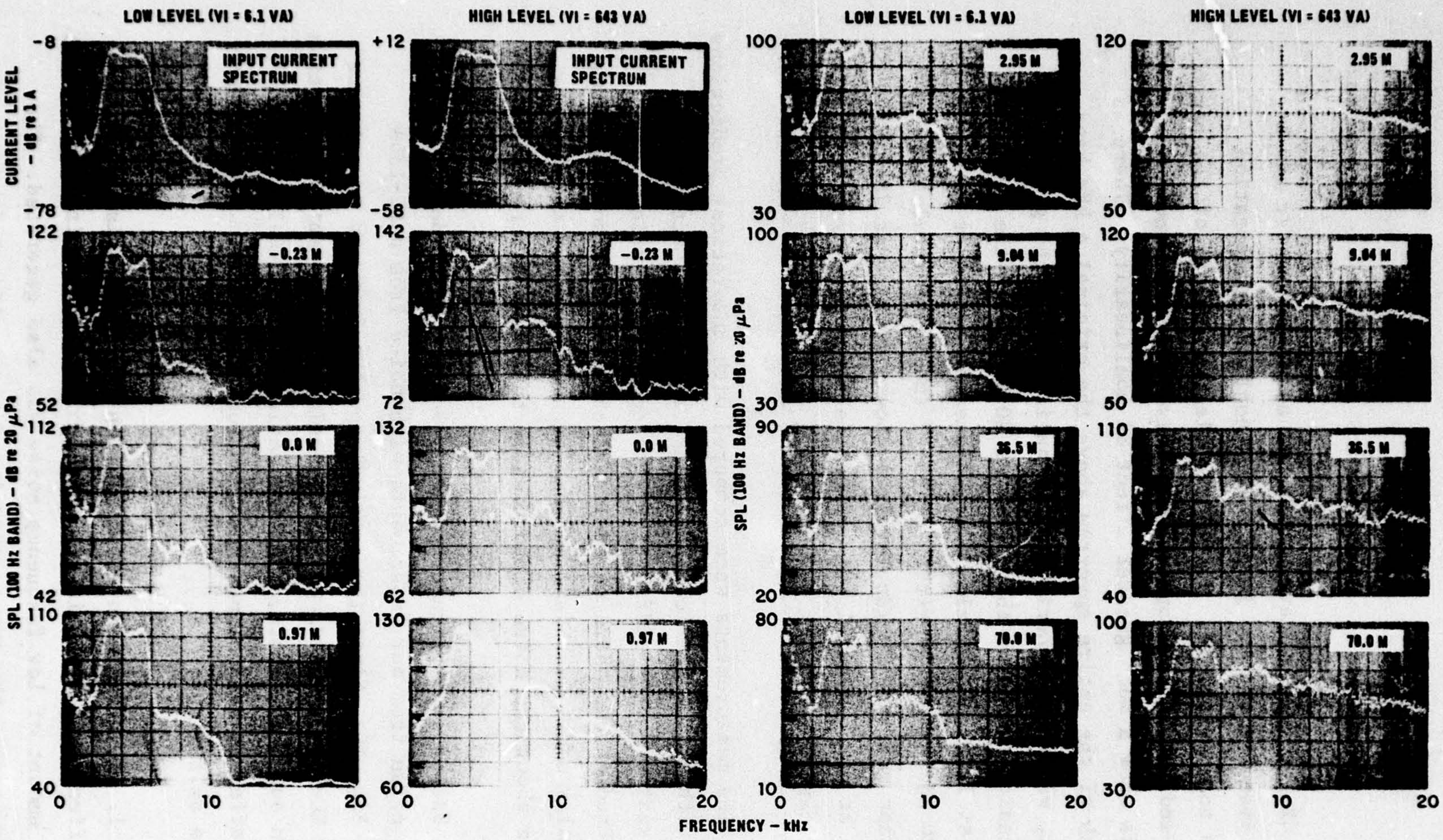

FIGURE 18. Comparison of measured low and high level noise spectra (experiment AEM4). The maximum ambient noise level for frequencies greater than 1 kHz is approximately 25 dB (100 Hz band) re 20 μPa (From 77-11, 78-4, JS-2)

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R_o(10 kHz) = 7.6 m
Low level: OASPL = 123 dB at 1 m
High level: OASPL = 142 dB at 1 m

was about 126 dB for the low level noise and about 145 dB for the high level noise. Even for the low level noise, nonlinear propagation distortion was not negligible. There is a clearcut growth of the second harmonic band and even a development of a third harmonic band. The high level data show a much greater effect of nonlinearity. There is a robust growth of the entire spectrum above the original 4 kHz band. Even at 20 kHz, where atmospheric absorption is strong, the growth is impressive. Inside the horns the signal at 20 kHz is in the instrumentation noise, at least 60 dB below the fundamental band. At 70 m, however, the 20 kHz signal is within 30 dB of the fundamental band. To put it another way, the 20 kHz level is about the same at 70 m as it seems to be at 0 m. A small but noticeable low frequency growth may also be discerned.

The measurements were compared with theoretical predictions based on linear theory. Spherical spreading, atmospheric attenuation, and, as appropriate, source diffraction were accounted for in these predictions. Predictions based on nonlinear theory were also attempted, but the particular model was based on what turned out to be an unjustified assumption about the noise distortion in the transmitter nearfield.

Use of an amplitude-frequency scaling law made it possible to compare the noise from our experiments with noise from a KC-135A aircraft. See Fig. 19. Since the (scaled) spectra from our experiments fall below the KC-135A spectra, and since nonlinear propagation distortion was observed in our experiments, the implication is that KC-135A noise is definitely affected by nonlinear propagation distortion. The primary conclusions are as follows:

1. A strong generation of high frequency noise caused by nonlinear effects was found in all the high intensity noise experiments. A very limited amount of low frequency noise was also generated. The intense, middle part of the spectrum deviated little if any from expectations based on linear theory. These observations indicate that although

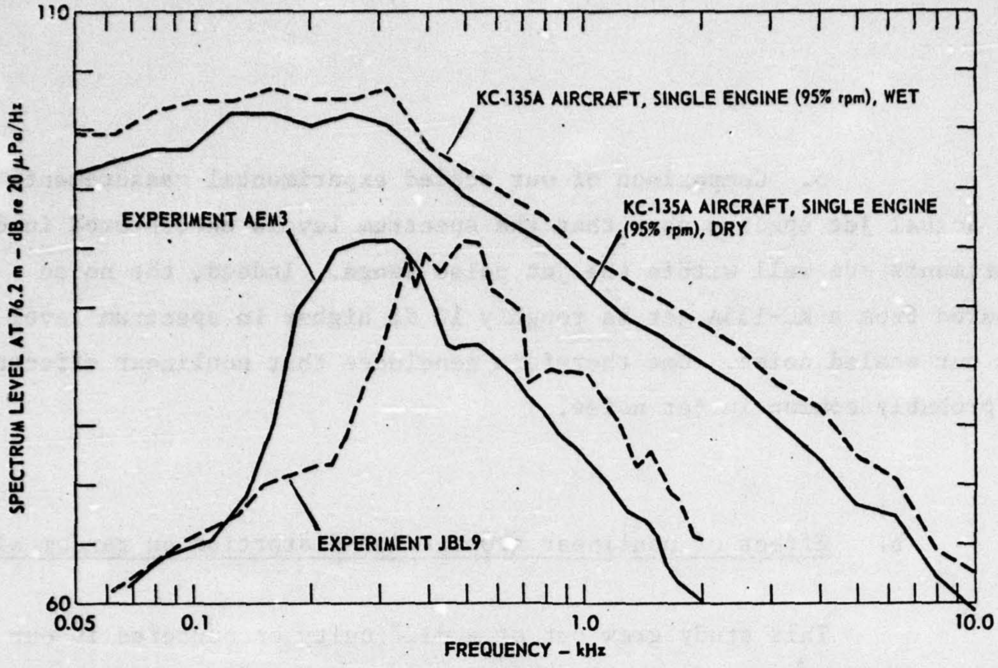

FIGURE 19. Comparison of actual jet noise spectra with scaled spectra (scaled down by a factor of 10 in frequency, scaled up 20 dB in level) from experiments AEM3 and JBL9 (From 77-11, 78-4, JS-2)

shocks formed in the noise waveform, distortion did not reach the stage at which shock merging was important.

2. The spectral distortion occurred in both the transmitter nearfield and farfield. Moreover, the distortion in the nearfield was over and above the spectral changes associated with diffraction.

3. At no measurement point was small-signal behavior established for the high frequency noise. Theoretical calculations for tone signals (see Item 3c above) support the proposition that the nonlinearly generated high frequency noise never achieves a farfield where small-signal behavior is established.

4. Comparison of the measured spectra with predictions from a model based on nonlinear theory showed poor agreement for the high frequency noise. The failure of our predictions was not due to an error in the nonlinear theory per se, but rather due to an inadequate description of the source noise waveform. In the future, use of a directly recorded input waveform should be tried.

5. Comparison of our scaled experimental measurements with actual jet spectra show that the spectrum levels encountered in our experiments are well within the jet noise range. Indeed, the noise measured from a KC-135A jet is roughly 10 dB higher in spectrum level than our scaled noise. One therefore concludes that nonlinear effects are probably common in jet noise.

b. Effect of nonlinear propagation distortion on random signals

This study grew out of a difficulty encountered in our outdoor propagation project: we were unable to properly predict the high frequency end of the spectrum of the transmitted noise. The basic element in the prediction scheme was Pestorius's computer algorithm (73-9, 74-2) for calculating the distortion of a random noise signal. However, the required input for this algorithm is the time waveform of the noise at the measurement point nearest the source. Having recorded only the spectrum, not the time waveform, at the nearest measurement point, we had to construct a suitable time waveform. We assumed this could be done by assigning random phase to the measured spectral components. An FFT^{-1} operation then yielded the time waveform to be used as the input signal. This method of constructing a suitable input waveform had worked well in a previous study (78-1). Unfortunately, however, it did not work well in the outdoor noise investigation. At high frequencies the computed spectra were considerably lower than the measured spectra. After due consideration we blamed the discrepancy on our seemingly reasonable assumption that the spectral components of the input noise signal have random phase (uniform probability density from $-\pi$ to π). Propagation from the source, through the nearfield, to the nearest measurement point apparently affects the randomness of the phase.

In order to study the phase question in detail, Webster made some noise propagation measurements in our plane wave tube and compared them with predictions obtained with our computer program (78-2). Briefly, Webster found that the method based on the random phase assumption seemed to work satisfactorily (i.e., computed spectra agreed with measured spectra) whenever the input microphone, that is, the microphone used to specify the input noise, was close enough to the source that the input noise was free of prior finite-amplitude distortion. This result seemed to be independent of the intensity of the noise. On the other hand, when the input noise was contaminated by prior finite-amplitude distortion, for example, when the separation between the source and the input microphone was not small, success or failure of the method depended on intensity. Surprisingly, the method continued to work well for strong or moderately strong noise. Failure occurred only when the noise was weak. This finding is, however, consistent with our experience in the outdoor propagation study. In that study both "failure elements" were present: the noise was relatively weak and the noise had already distorted quite a bit by the time it reached the input microphone.

c. Amplitude density of a finite-amplitude wave

Because noise may be described in terms of its statistical properties, one way to investigate finite-amplitude noise is to find out how nonlinearity affects the statistical properties. For example, if a noise is gaussian to begin with, is it still gaussian after nonlinear propagation distortion?

One of the simplest statistical properties of a noise signal is its amplitude density. We have shown that as long as shocks do not form, propagation distortion does not change the amplitude density of the signal (79-1). (However, the amplitude density does change as soon as shocks begin to form.) We have also found that the amplitude density of the derivative of a random signal does not remain constant as the wave distorts. This means that the gaussian property is not preserved under propagation distortion.

5. Miscellaneous

a. Construction of an anechoic chamber

At the beginning of the outdoor propagation program we needed an indoor anechoic space in which to evaluate horns and horn drivers for use as sources of high intensity sound. A simple yet relatively spacious anechoic chamber was developed by converting a 3 m (height) by 5.5 m (width) by 7.6 m (length) vacant room in an old building near Applied Research Laboratories. The interior surfaces (walls, ceiling, and floor) were covered with 4 in. of Navy shipboard sound insulation fiberglass board. The fiberglass, as well as all lumber necessary for the supporting framework, was surplus material obtained under the G.S.A. Excess Property Program. Most of the construction was done by Willshire and Theobald, but Schaffer, Kleeman, and Webster also assisted. The main material that had to be purchased was the supply of stick clips used to fasten the fiberglass board to the walls and ceiling. Inverse square law tests carried out along a room diagonal showed that the room was anechoic down to a surprisingly low frequency, 250 Hz (tests were carried out at octave intervals, up to 16 kHz).

The only difficulty with the chamber was the longevity of the ceiling. After a period of time the glue holding some of the stick clips to the ceiling gave way, and many of the ceiling panels sagged or fell. However, our evaluations (and several other experiments) had been completed before the ceiling troubles began, and we were comforted by A. H. Sommer's comment[18] "The best equipment is one that falls apart after the last experiment; any effort to make it more durable is a waste of time and effort."

Details of the construction and testing of the anechoic chamber are contained in Theobold's technical report (77-1).

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[18] A. H. Sommer, Letter to the Editor, Physics Today 29, 9 (1976).

b. History of physical acoustics in North America up to World War II

In recognition of the Bicentennial Year, a special session on the history of acoustics in the United States was held at the Washington, D. C., Meeting of the Acoustical Society of America, 4-9 April 1976. Blackstock gave a paper on physical acoustics in North America up to World War II. The topics covered were Joseph Henry's work on fog signals and airborne propagation at sea (1865-77); the first-ever measurements of sound absorption in air, by A. W. Duff (1898-1900); and some of G. W. Pierce's measurements (1) of sound velocity and dispersion, and (2) propagation over surfaces (76-1).

CHRONOLOGICAL BIBLIOGRAPHY

Code

AR = administrative report
B = chapter in a book
J = journal publication
JS = submitted for journal publication
O = oral presentation
P = paper in a proceedings or preprints of a symposium or congress
T = thesis or dissertation
TR = technical report

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