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REFRACTION AND FOCUSING OF UNDERWATER SHOCK WAVES: Bibliography of Technical Reports, Memoranda and Papers Published in Scientific Journals

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13. ABSTRACT
In media for which the speed of sound is position dependent, propagating sound will be refracted and, in some cases, focused. In the focusing regions, usually referred to as caustics or convergence zones, significant amplification of the pressure levels above those predicted by spherical spreading has been observed for continuous waves as well as explosive pulses. In addition, the waveforms of explosive pulses undergo drastic distortion.

In order to obtain a theoretical understanding of the behavior of shockwaves at caustics, an asymptotic theory of the refraction and focusing of sound originating from a point source in a stratified medium has been developed. The titles and abstracts of the technical reports, informal memoranda, and journal publications generated in the course of this development are listed. Topics covered in these reports include: (1) the formulation of the Caustic Boundary Layer (CBL) theory of sound focusing, (2) the phase shifts of harmonic waves at caustics, (3) a comparison of the CBL theory's predictions with experiment, (4) the development of higher order correction terms in the CBL theory and their application as criteria for the validity of the theory, (5) the theory of lateral (precursor) waves associated with discontinuities in the sound speed profile, (6) the domain of validity of the CBL theory and ray theory and (7) the extension of ray acoustics into caustic-related shadow zones.

In addition, abstracts are given of two earlier reports concerned with the interaction of shockwaves with various types of boundaries.

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PREFACE

This bibliography is primarily a Final Report for Contract N00014-70-C-0080, whose period of performance was 1 August 1969 through 31 August 1971. However, it was thought that it would be useful to include the reports produced under the two preceding contracts: N0014-66-C0110 - 1 January 1966 - 31 August 1969 and Nonr-3439(00) - 1 October 1962 - 31 December 1965.

ABSTRACT

In media for which the speed of sound is position dependent, propagating sound will be refracted and, in some cases, focused. In the focusing regions, usually referred to as caustics or convergence zones, significant amplification of the pressure levels above those predicted by spherical spreading has been observed for continuous waves as well as explosive pulses. In addition, the waveforms of explosive pulses undergo drastic distortion.

In order to obtain a theoretical understanding of the behavior of shockwaves at caustics, an asymptotic theory of the refraction and focusing of sound originating from a point source in a stratified medium has been developed. The titles and abstracts of the technical reports, informal memoranda, and journal publications generated in the course of this development are listed. Topics covered in these reports include: (1) the formulation of the Caustic Boundary Layer (CBL) theory of sound focusing, (2) the phase shifts of harmonic waves at caustics, (3) a comparison of the CBL theory's predictions with experiment, (4) the development of higher order correction terms in the CBL theory and their application as criteria for the validity of the theory, (5) the theory of lateral (precursor) waves associated with discontinuities in the sound speed profile, (6) the domain of validity of the CBL theory and ray theory and (7) the extension of ray acoustics into caustic-related shadow zones.

In addition, abstracts are given of two earlier reports concerned with the interaction of shockwaves with various types of boundaries.

REPORTS COVERING RESEARCH FROM 1 OCTOBER 1962 THROUGH 31 AUGUST 1971

David A. Sachs, "Sound Propagation in Shadow Zones," (to be published in the Journal of the Acoustical Society of America).

By admitting complex-valued solution to the equations of ray acoustics (complex rays), ray theory is extended to yield non-trivial sound pressure levels in the shadow zone adjoining a caustic. For a steady-state source, the sound field in the shadow is found to decay exponentially with frequency and with distance from the caustic. In the transient case, the theory appears to be in general agreement with results from Barash's and Goertner's experiments involving explosive sources.

D.A. Sachs and A. Silbiger, "Focusing and Refraction of Harmonic Sound and Transient Pulses in Stratified Media," J. Acoust. Soc. Amer. 49, 824-840 (1971).

In media for which the speed of sound is position dependent, propagating sound will be refracted and, in some cases, focused. In the focusing regions, usually referred to as caustics or convergence zones, significant amplification of the pressure levels above those predicted by spherical spreading has been observed for continuous waves as well as for explosive pulses. In addition, the waveforms of explosive pulses undergo drastic distortion. In the present paper, an asymptotic theory of the refraction and focusing of sound originating from a point source in a stratified medium is presented. It is applicable to realistic velocity profiles and encompasses both transient pulses and harmonic waves. A comparison with Barash's and Goertner's recent experiment involving explosive pulses indicates that the theory gives reliable estimates of the peak pressure levels at caustics, but reproduces only qualitatively the shape of the focused pulse. The discrepancy is attributed mainly to the neglect of finite-amplitude effects in the theory's formulation. The inaccuracies inherent in the high frequency asumptotic methods employed in the theory are discussed in some detail.

D.A. Sachs, "Sound Propagation in Shadow Zones," CAA Tech. Report U.-365-222, February 1971. AD 724, 349

Sound propagation in stratified media such as the ocean is conveniently analyzed using geometric (ray) acoustics. In this theory, sound energy propagates along curved trajectories, the rays. However, in regions behind certain curves called caustics, formed from envelopes of intersecting rays, no rays penetrate and ray theory predicts no sound disturbance whatever. Yet experimental observations indicate not only detectable but significant signals in these shadow zones. We extend traditional ray theory into the shadow zone by admitting complex-valued solutions to the equations of ray acoustics. Our theory is applicable to realistic sound speed profiles and encompasses both transient as well as harmonic sound sources. In the steady-state case, the sound field in the shadow is found to decay exponentially with frequency and with distance from the caustic. Within its approximations, the theory appears to be in agreement with experimental results.

D.A. Sachs, "Precursors in a Stratified Medium," Tech. Memo to I.M. Blatstein, USNOL, 27 January 1971.

D.A. Sachs, "Series Expansion for the Sound Field at a Caustic," CAA Tech. Report U-363-222, September 1970. AD 713, 597

Higher order terms in a series expansion of the sound field in the vicinity of a caustic are given. The results are applicable to a caustic zone in an arbitrarily stratified medium at which sound energy from a time-harmonic point source is focused. The higher order terms can be used either to extend the domain of applicability of the lower order terms or to provide a measure of their accuracy.

D.A. Sachs, "Precursor Waves from a Continuous Transition Layer in the Sound Speed Profile," CAA Tech. Report U-361-222, August 1970. AD 713, 601

If a sound speed profile exhibits a relatively abrupt transition between two more or less uniform regions of differing sound speeds, it is often observed that among the signals produced by a distant sound source is one which arrives earlier than all others. This type of signal, which has been variously referred to as the precursor wave, the lateral wave or the head wave, is not explainable on the basis of ray acoustics. In the past, theoretical investigations have been made of the formation of precursors on both sharply abrupt and continuous transition layers. Following the methods of Lang, we consider the precursors arising from a point sound source located in a homogeneous half-space connected to another isovelocity domain of higher sound speed through a transition zone in which the square of the index of refraction is a linear function of height. High frequency asymptotic expressions for the precursor pressures are developed for both the transition zone and the half-space in which the sound source is located. By means of Fourier transformation, the treatment is extended to include transient sound sources.

D.A. Sachs, "Focusing of Shockwaves at Caustics," J. Acoust. Soc. Amer. 48, 129(A) (1970).

As a result of the depth dependence of the speed of sound in the ocean, the sound energy of a shockwave produced by an underwater detonation focuses in some regions, producing pressures much greater than would be observed if the ocean were uniform. In addition, the initial waveform is drastically distorted. A theory to describe the amplification of shockwaves in these focusing regions, usually called caustics, was recently proposed by Silbiger [A. Silbiger, Cambridge Acoustical Associates, Inc., Tech. Report U-268-188 (June 1968)]. A comparison of theoretical predictions with the experimental results of Barash and Goertner [R.M. Barash and J.A. Goertner, U.S. Naval Ordnance Lab., Tech. Report 67-9 (19 April 1967)] shows fair agreement: order-of-magnitude predictions of peak overpressures are achieved along with a qualitative description of the waveform's distortion. Sources of error include the neglect of finite amplitude effects and the effects of the experimental equipment as well as inaccuracies inherent in the use of the asymptotic methods employed in the theory. [Research sponsored by the Field Projects Branch of the Office of Naval Research.]

D.A. Sachs, "Underwater Shockwave Focusing at Caustics: Comparison of Theory and Experiment," CAA Tech. Report U-322-188, August 1969. AD 693, 313

The theory of shockwave focusing (developed by Silbiger) is employed in an attempt to predict the extent of focusing of explosive pulses at caustics as observed experimentally by Barash.

Assuming a viscous medium and a physically reasonable model for the explosive pulse, an order of magnitude comparison with experiment is obtained. The omission of viscosity from the mathematical model leads to unacceptably large amplification at the caustic.

M.C. Junger, "Comments on 'Phase Changes and Pulse Deformation in Acoustics' [I. Tolstoy, J. Acoust. Soc. Amer. 44, 675-683 (1968)]," Letter to the Editor, J. Acoust. Soc. Amer. 45, 518 (1969).

The $-\pi/2$ phase jump predicted in Tolstoy's analysis for refracted waves passing through a caustic is also predicted, by an entirely different analytical technique, for the related situation of diffracted waves traversing a caustic, specifically the caustic at the center of the shadow zone of a spherical scatterer. The phase jump is shown to be related to the cylindrical symmetry of the diffracted field.

A. Silbiger, "Focusing of Sound and Explosive Pulses in the Ocean," CAA Tech. Report U-286-188, June 1968. AD 672,914

Pressure disturbances propagating in the ocean may converge as a result of gradients in the sound velocity. Significant amplifications above the levels predicted by spherical spreading have been observed for continuous waves as well as for explosive pulses. Published theories concerning convergence zones generally have only dealt with time-harmonic waves and idealized sound velocity profiles. A comprehensive theory is presented here, applicable to realistic profiles and encompassing transient as well as harmonic pulses. For waves originating at a point source it is shown that at most one caustic is encountered after the traversal of a turning point. The pulse spectrum amplification exhibits a marked frequency dependence, as a result of which the pulse shape undergoes considerable distortion, with enhancement of the high frequency components. After passing through the caustic region the pulse regains its original power spectrum; its shape will however remain distorted as the result of a phase shift. The analysis is restricted to the early time behavior (near the shockfront) and does not include large amplitude and viscous effects. Within these limitations the conclusions appear to be in agreement with experimental results.

A. Silbiger, "Phase Shift at Caustics and Turning Points," Letter to the Editor, J. Acoust. Soc. Amer. 44, 653-654 (1968).

The phase shift observed in recent underwater pulse propagation tests is shown to originate at the caustic rather than at the turning point.

A.Silbiger,"Focusing of Underwater Step-Waves near a Caustic," 74th ASA Meeting, J. Acoust. Soc. Amer. 42, 1154 (1967).

The pressure field near a caustic (convergence zone) is analyzed for transient pulses with vanishing rise time. On the caustic, linear acoustic theory predicts a singularity of the order of $(t-t_s)^{-1/6}$ at the shockfront, t_s being the arrival time of the front at the caustic. The corresponding total impulse remains finite. Factors limiting the peak pressure are discussed. Theoretical results are compared with data obtained by the Naval Ordnance Laboratory with explosive sources in a flooded quarry. (This work was supported by the U.S. Office of Naval Research.)

D. Feit and W. Thompson, Jr., "Analytical Study of Certain Aspects of Underwater Shockwave Propagation: Sloping Bottom, Icecap, Sedimentary Bottom," CAA Tech. Report U-246-174, October 1966. AD 644,197

Various problems concerning the effects of the boundaries of the ocean on the propagation of pressure waves in the ocean are considered. The propagation of a transient pressure wave in a wedge shaped region of fluid is treated. This is the model chosen to describe the situation in which an underwater explosion takes place in a coastal ocean region which is characterized by a strongly sloping bottom. In an attempt to study the effects of the polar ice cap on the propagation of a pressure wave, the reflection of a plane wave onto a rough boundary separating a fluid half space and a thick fluid layer of differing sound speed and density is considered. These results are currently being used to construct the response to a transient pressure pulse and to generate numerical results for conditions representative of underwater explosions. The final section presents numerical values of the reflection coefficient as a function of grazing angle for the case of a plane wave incident on a porous elastic bottom. The analytical expressions used were derived in an earlier report of this series.

Ewald Eichler and Jasti V. Pattayya, "Pressure Transmission from an Explosion in a Liquid Layer Overlying a Porous Solid, and Related Problems," CAA Tech. Report U-184-134, July 1964. AD 453, 271

A study is made of the pressure field of an underwater explosion as modified by bottom and surface reflection. Linear theory is applied to a fluid layer overlying a porous fluid-saturated solid half-space.

The porous medium supports three types of free waves. The combination of inertial and viscous coupling between its components makes it dispersive, and hence limits the application of Cagniard's method. Explicit long-range approximations are presented for the pressure and for its Fourier transform.

Available geophysical parameters are scarce. Data for a globigerina ooze are supplemented to give two complete sets of parameters for a porous solid ocean bottom. Reflection coefficients computed therefrom are generally lower than for a simpler liquid or solid bottom.