International Journal of Computational Acoustics, Vol. 9, No. 2 (2001)


INTERNATIONAL ASSOCIATION
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COMPUTERS IN SIMULATION

# UNIFORMLY ASYMPTOTIC SOLUTIONS FOR PSEUDODIFFERENTIAL EQUATIONS WITH SINGULAR INTEGRAL OPERATORS*

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Received 18 June 1999
Revised 28 May 2000

Uniformly asymptotic frequency-domain solutions for a class of hyperbolic equations with singular convolution operators are derived. Asymptotic solutions for this class of equations involve additional parameters — called attenuation parameters — which control the smoothing of the wavefield at the wavefront. At caustics the ray amplitudes have a singularity associated with vanishing of ray spreading and with divergence of an integral controlling the rate of exponential amplitude decay. Both problems are resolved by applying a generalized Kravtsov–Ludwig formula derived in this paper. A different asymptotic solution is constructed in the case of separation of dispersion and focusing effects.

*Presented at ICTCA'99, the 4th International Conference on Theoretical and Computational Acoustics, May 1999, Trieste, Italy.

International Journal of Computational Acoustics, Vol. 9, No. 4 (2001)


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COMPUTERS IN SIMULATION

# THE KIRCHHOFF–HELMHOLTZ INTEGRAL PAIR*

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Received 11 June 1999
Revised 6 July 2000

The Kirchhoff–Helmholtz integral models the reflected acoustic wavefield by an integration along the reflector over the incident field multiplied by the specular plane-wave reflection coefficient. Based on the structural relationships between the reflector and the reflection-traveltime surface, we design an asymptotic inverse Kirchhoff–Helmholtz integral. Analogously to the forward integral, the proposed inverse consists of an integration along the reflection-traveltime surface over the recorded reflected field. We show that the new inverse integral asymptotically recovers the input to the standard Kirchhoff–Helmholtz integral, that is, the reflector position and the reflection coefficients along it. A simple numerical example demonstrates the inverse relationship between the proposed and the standard Kirchhoff–Helmholtz integrals. In this way, a new technique for kinematic (positioning) and dynamic (amplitude) wavefield inversion becomes available. This is realized by means of an integral operation that is most naturally related to its counterpart Kirchhoff–Helmholtz integral.

*Presented at ICTCA'99, the 4th International Conference on Theoretical and Computational Acoustics, May 1999, Trieste, Italy.

International Journal of Computational Acoustics, Vol. 9, No. 2 (2001)


INTERNATIONAL ASSOCIATION
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COMPUTERS IN SIMULATION

# ANALYSIS AND PROCESSING OF RECEIVED SIGNALS IN BOREHOLES*

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Received 14 June 1999
Revised 9 March 2000

This study is a part of a project to develop a borehole sonar for acoustic imaging of the geological structure of the rock formation near to a deviated or horizontal borehole performed while drilling. The purpose of the sonar is to provide a direct measure of the distance and the direction to bed boundaries parallel to the borehole. This paper gives a theoretical analysis of the effect of the borehole and the drillstring on the received response on sensors positioned on the drillstring and proposes a method for processing the received signal to enable the determination of the direction of an incoming plane wave and time of arrival. In the first part of this paper, the response at any position in a fluid filled borehole is determined for an incoming plane P-wave. It is shown that the response is quite complicated and consists of several vibrating modes with resonance structure. Secondly, the paper presents how the received signals can be decomposed and the individual modes can be resolved by utilizing the orthogonal properties of the mode functions. The individual mode functions are resolved by performing a spatial Fourier transform of the sensor signals. A requirement is that the sensors are uniformly distributed around the circumference of the drillstring and that the number of sensors is at least two times the number of significant modes. It is demonstrated that the spatial and temporal characteristics of the resolved modes can then be exploited to determine the time of arrival and the angle of direction of the incoming reflected waves.

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*Presented at ICTCA'99, the 4th International Conference on Theoretical and Computational Acoustics, May 1999, Trieste, Italy.

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International Journal of Computational Acoustics, Vol. 9, No. 4 (2001)


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# INFORMATIONAL CAPACITY OF ACOUSTIC MEASUREMENTS*

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Received 16 June 1999
Revised 14 July 2000

Presented is the theoretical model for extracting the system response from measurements of the acoustic wave propagating through the linear system. Based on the results of this analysis, measurements are described as a convolution of the impulse response of the system with the mixed-phase-lag nonstationary forward wavelet (or source-generated wavefield). The source-generated wavefield includes all multiple terms generated within the system as well as the energy source signature and the detector characteristics.

It is shown that the decay ratio of the source-generated wavefield can be used to separate the energy spectrum of the source-generated wavefield and the energy spectrum of the impulse response from the measurement function. The level of separability of energy spectrum of the source-generated wavefield and the impulse response reflects the amount of information about the measured system, which can be obtained from experimental data. In particular, if the source-generated wavefield does not decay during the propagation through the system, or, if the effective distance of the decay is comparable with the size of the measured system, the impulse response cannot be extracted from the result of measurements. Based on the theoretical conclusions, the computational procedure is proposed for one-dimensional deconvolution algorithm. The application of this algorithm is illustrated using seismic data as an example. The forward wavelet is extracted from seismic data itself. The deconvolution of data with the extracted wavelet provides surface-consistent scaling along with peg-leg and short-period multiples attenuation.

*Presented at ICTCA'99, the 4th International Conference on Theoretical and Computational Acoustics, May 1999, Trieste, Italy.

International Journal of Computational Acoustics, Vol. 9, No. 3 (2001)


INTERNATIONAL ASSOCIATION
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COMPUTERS IN SIMULATION

# RESONANCES OF ACOUSTIC WAVES INTERACTING WITH AN ELASTIC SEABED*

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Received 8 July 1999
Revised 7 September 2000

An exact expression for the reflection coefficient is obtained with the Thomson–Haskell technique for the geoacoustical model of an ocean bottom consisting of an elastic homogeneous sediment layer overlying an elastic half-space. Characteristic equations for explicit determination of the position of each individual resonance contribution to the reflection coefficient are derived. Analytical expressions for the angular and frequency resonance positions are found. The resonance expression for the reflection coefficient is written in the form of a sum of resonance terms. Comparison between resonance theory and exact calculations for the elastic layer covering the elastic half-space is presented. The results of resonance formalism show excellent agreement with exact theory in all the cases.

*Presented at ICTCA'99, the 4th International Conference on Theoretical and Computational Acoustics, May 1999, Trieste, Italy.

International Journal of Computational Acoustics, Vol. 9, No. 4 (2001)


INTERNATIONAL ASSOCIATION
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COMPUTERS IN SIMULATION

# MODELED VELOCITY AND REFLECTIVITY PROPERTIES OF ANISOTROPIC HYDRATED SEDIMENTS*

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Received 17 July 1999
Revised 29 June 2000

The potential of mapping the extent gas hydrate from seismic data relies on the micromechanical model linking the actual material properties to the relevant observational data. We here consider four-phase sediment models consisting of hydrate, fluid, quartz (grains) and clay (platelets). The hydrate may occur in two ways when the pore volume is partially saturated, either in the pore voids without grain contact (unconnected), or as a grain coating, i.e. acting as a cementation of the grains (connected). In this model, the spatial orientations of the clay platelets are taken into account. By considering a model with a dominant horizontal grain distribution, we find that the elastic stiffnesses and velocities increase with an increasing proportion of hydrate. Both P and S velocities are largest for connected hydrates. Furthermore, the P wave anisotropy is largest for connected hydrates, while the S wave anisotropy is largest for the unconnected hydrates. If we consider the hydrate model as unconnected for low saturation (less than 50%) and connected for higher saturation, the reflectivity properties of the bottom simulating reflector (BSR) are similar to those found by other investigators considering no preferred grain orientation.

*Presented at ICTCA'99, the 4th International Conference on Theoretical and Computational Acoustics, May 1999, Trieste, Italy.

International Journal of Computational Acoustics, Vol. 9, No. 2 (2001)


INTERNATIONAL ASSOCIATION
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COMPUTERS IN SIMULATION

# REFLECTION/TRANSMISSION COEFFICIENTS AT A PLANE INTERFACE IN DISSIPATIVE AND NONDISSIPATIVE ISOTROPIC MEDIA: A COMPARISON*

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Received 12 July 1999
Revised 15 June 2000

The problem of reflection/transmission of plane waves in homogeneous isotropic dissipative media is investigated. In dissipative media, the elastic moduli, seismic velocities and slowness vectors are complex-valued and frequency-dependent. Results of extensive computations of R/T coefficients for plane waves incident at a plane interface are presented and discussed. In all cases, the "reference R/T coefficients" are considered, computed for a fixed frequency equal to the reference frequency $f_r$, for which the elastic moduli are specified. The influence of angle of incidence $i$ and attenuation angle $\gamma$ of the incident wave on the coefficients is studied in detail. In general, the differences between the moduli of the R/T coefficients for dissipative and nondissipative models are usually small for realistic $Q$'s and $\gamma$'s. These differences are more distinct in critical and post-critical regions for the reflection coefficients, particularly for small $Q$'s, large contrast of $Q$'s across the interface, and for large $|\gamma|$'s (say, $|\gamma| > 50°$). The differences between the phases of R/T coefficients for dissipative and nondissipative media may be larger. For some $\gamma$'s, the signs of the phases for dissipative and nondissipative media may be roughly opposite, even for very high $Q$'s.

*Presented at ICTCA'99, the 4th International Conference on Theoretical and Computational Acoustics, May 1999, Trieste, Italy.

International Journal of Computational Acoustics, Vol. 9, No. 4 (2001)


INTERNATIONAL ASSOCIATION
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COMPUTERS IN SIMULATION

# ANALYSIS OF THE REFLECTION AND TRANSMISSION COEFFICIENTS IN THREE-PHASE SANDSTONE RESERVOIRS*

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Received 2 July 1999
Revised 10 April 2000

As it is well-known, seismic and acoustic data play a very important role in the characterization of hydrocarbon reservoirs. The correct interpretation of the anomalies observed in seismic wave velocities, quality factors and reflection coefficients in such environments makes necessary to use accurate models taking into account the main petrophysical features of the rocks. This also brings into play the importance of adequately describing the *in situ* properties of the reservoir fluids.

This work investigates the influence of gas saturation and excess pore fluid pressure on wave energy splitting at plane interfaces within a Biot-type porous medium saturated by a liquid–gas mixture. Using laboratory measurements made on a wide variety of sandstones, we incorporate in the model the effective pressure dependence of rock matrix properties such as bulk and shear modulus, porosity and pore space compressibility. Also, using empirical laws, we estimate the properties of real hydrocarbon gases, oils and brines of different compositions under variable pressure and temperature conditions. We present analytical computations of the amplitude reflection and transmission coefficients to study the combined effect of the forementioned variables, aiming at a further AVA trend analysis.

*Presented at ICTCA'99, the 4th International Conference on Theoretical and Computational Acoustics, May 1999, Trieste, Italy.

International Journal of Computational Acoustics, Vol. 9, No. 4 (2001)


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FOR MATHEMATICS AND
COMPUTERS IN SIMULATION

# FRACTIONAL DIFFUSIVE WAVES*

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Received 25 June 1999
Revised 6 March 2000

By fractional diffusive waves we mean the solutions of the so-called time-fractional diffusion-wave equation. This equation is obtained from the classical D'Alembert wave equation by replacing the second-order time derivative with a fractional derivative of order $\beta \in (0,2)$ and is expected to govern evolution processes intermediate between diffusion and wave propagation when $\beta \in (1,2)$. Here it is shown to govern the propagation of stress waves in viscoelastic media which, by exhibiting a power law creep, are of relevance in acoustics and seismology since their quality factor turns out to be independent of frequency. The fundamental solutions for the Cauchy and signaling problems are expressed in terms of entire functions (of Wright type) in the similarity variable. Their behaviors turn out to be intermediate between those found in the limiting cases of a perfectly viscous fluid and a perfectly elastic solid. Furthermore, their scaling properties and the relations with some stable probability distributions are outlined.

*Presented at ICTCA'99, the 4th International Conference on Theoretical and Computational Acoustics, May 1999, Trieste, Italy.

International Journal of Computational Acoustics, Vol. 9, No. 4 (2001)


INTERNATIONAL ASSOCIATION FOR MATHEMATICS AND COMPUTERS IN SIMULATION

# ACOUSTIC EXCITATION OF SCHOLTE-STONELEY AND LAMB WAVES ON A REINFORCED CYLINDRICAL SHELL*

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Received 12 July 1999
Revised 24 April 2000

The scattering of sound from a submerged elastic cylindrical shell, evacuated and bare of reinforcements, is known to excite the pseudo-Lamb $S_0$ wave propagating circumferentially around the shell, and also the Scholte-Stoneley (A) wave, but the latter only in a limited frequency region. For thin shells (of less than 10% thickness), excitation of the $A_0$ wave has not been observed in a distinct resonant fashion, at least at moderate frequencies around and above coincidence. (Its excitation in a nonresonant fashion, i.e., immediately beyond the locus of its generation, has, however, recently been observed experimentally.[1]) We show here that even the presence of internal attachments to the shell will not cause the excitation of the $A_0$ wave, while greatly extending the excitation region of the A wave, however. A modification of resonance frequencies by the internal attachments ("frequency doubling") is discussed, and is explained by the phase matching principle of resonance excitation.

*Presented at ICTCA'99, the 4th International Conference on Theoretical and Computational Acoustics, May 1999, Trieste, Italy.
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International Journal of Computational Acoustics, Vol. 9, No. 2 (2001)


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COMPUTERS IN SIMULATION

# ON THE ADIABATICITY OF ACOUSTIC PROPAGATION THROUGH NONGRADUAL OCEAN STRUCTURES*

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Received 9 February 2000
Revised 24 August 2000

To assess the adiabaticity of sound propagation in the ocean is very important for acoustic field calculating (forward problem) and tomographic retrieving(inverse problem). Most of the criterion in the literature is too restrictive, specially for the nongradual ocean structures. A new criterion of adiabaticity is suggested in this paper. It works for nongradual ocean structures such as front and internal solitary waves in shallow-water.

*Presented at ICTCA'99, the 4th International Conference on Theoretical and Computational Acoustics, May 1999, Trieste, Italy.

International Journal of Computational Acoustics, Vol. 9, No. 2 (2001)


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COMPUTERS IN SIMULATION

# FERROMAGNETS AND KELVIN'S MEDIUM: BASIC EQUATIONS AND WAVE PROCESSES*

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Received 13 June 1999
Revised 20 April 2000

The nonlinear constitutive equations of Kelvin's medium (a nonlinear elastic polar medium consisting of rotating particles) are obtained. We establish the analogy between basic equations of saturated elastic ferromagnetic insulators and basic equations of Kelvin's medium. The most general way of taking the couplings of magnetic and elastic subsystems into account is suggested. Wave processes are investigated from this point of view. All results are interpreted both in terms of mechanical medium and ferromagnets.

*Presented at ICTCA'99, the 4th International Conference on Theoretical and Computational Acoustics, May 1999, Trieste, Italy.

International Journal of Computational Acoustics, Vol. 9, No. 4 (2001)


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COMPUTERS IN SIMULATION

# PROPAGATION OF ULTRASONIC WAVES IN NONLINEAR MULTILAYERED MEDIA*

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Received 4 October 1999
Revised 22 June 2000

In the framework of the Local Interaction Simulation Approach (LISA), iteration equations are derived for the simulation of the propagation of ultrasonic waves in nonlinear multilayered 1-D media. The numerical results are compared with analytical solutions obtained in a perturbation treatment. The method is then applied to study several problems of nonlinear propagation, including the distortion of pulses, the formation of shock waves and, in the case of cw's, anharmonic effects and coupling between extended and localized vibration modes.

*Presented at ICTCA'99, the 4th International Conference on Theoretical and Computational Acoustics, May 1999, Trieste, Italy.

International Journal of Computational Acoustics, Vol. 9, No. 2 (2001)


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# OPTIMAL MODEL FOR THE DIFFRACTION EFFECT IN THE ULTRASONIC FIELD OF PISTON TRANSDUCERS*

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Received 18 June 1999
Revised 3 March 2000

In this work, the analytical and experimental examination of the problem of diffraction effect is treated. In the laboratory, the diffraction phenomena have been mainly due to the beam spread of the ultrasonic plane wave propagating through a viscoelastic material. In fact, this effect has been found to be related, essentially to the attenuation and dispersion losses on a viscoelastic material. In this work, a frequency domain system identification approach is applied to determine an optimal function correcting the beam spread effect in both the normal and oblique incidences for a large frequency band (300 kHz–3 MHz). The Maximum Likelihood Estimator is applied to the magnitude and phase of the measured beam patterns of the used transducers in order to determine the model parameters. The calibration procedure is also discussed. Once the proposed model is established, the propagation through a viscoelastic plate is described and a comparison with measurements is done to validate the investigated model. The obtained longitudinal and shear attenuation and dispersion of the ultrasound in the viscoelastic plate are compared with those obtained by applying the complex harmonic plane waves combination model.

*Presented at ICTCA'99, the 4th International Conference on Theoretical and Computational Acoustics, May 1999, Trieste, Italy.

International Journal of Computational Acoustics, Vol. 9, No. 3 (2001)


INTERNATIONAL ASSOCIATION
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COMPUTERS IN SIMULATION

# OBLIQUE ACOUSTIC AXES IN TRIGONAL CRYSTALS*

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Received 5 August 1999
Revised 6 April 2000

A general analysis on the subject of acoustic axes for bulk acoustic waves in trigonal crystals is presented. It is shown that the effect of piezoelectricity increases the maximum allowable number of acoustic axes in the plane of elastic symmetry from three to five for trigonal crystals of class 3m, and from 3 to 7 for trigonal crystals of class 32. The theory of acoustic axes of general orientation developed by Khatkevich (1962) is revised. A new, simpler and more general derivation of the conditions for the occurrence of acoustic axes of general orientation in crystals is presented. It is found that the previous analytical results and conclusions stating the absence of such axes in trigonal crystals are incorrect. New correct equations for acoustic axes of general orientation in trigonal nonpiezoelectric crystals are derived and confirmed by independent numerical calculations. Acoustic axes of general orientation oblique to the elastic symmetry planes are found to exist in berlinite (class 32) and in nonpiezoelectric lithium niobate (class 3m), however piezoelectricity eliminates these axes in the latter crystal. Some illustrative examples of the relationship between leaky surface acoustic wave branches and acoustic axes in trigonal crystals are given.

*Presented at ICTCA'99, the 4th International Conference on Theoretical and Computational Acoustics, May 1999, Trieste, Italy.

International Journal of Computational Acoustics, Vol. 9, No. 4 (2001)


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COMPUTERS IN SIMULATION

# ACOUSTIC TIME SERIES VARIABILITY AND TIME REVERSAL MIRROR DEFOCUSING DUE TO CUMULATIVE EFFECTS OF WATER COLUMN VARIABILITY*

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Received 2 July 1999
Revised 8 November 2000

The variability of the arrival structure of narrow band waveforms is derived for adiabatic propagation in a fluctuating ocean channel. Expressions for the expected value of the signal intensity are obtained for sound speed fluctuations characterized in a second moment sense over range, depth and time. Similar expressions are obtained for the focus intensity of a time reversal mirror.

*Presented as "Acoustic time series variability due to cumulative effects of perturbative sound speed fluctuations" at ICTCA'99, the 4th International Conference on Theoretical and Computational Acoustics, May 1999, Trieste, Italy.

International Journal of Computational Acoustics, Vol. 9, No. 3 (2001)


INTERNATIONAL ASSOCIATION
FOR MATHEMATICS AND
COMPUTERS IN SIMULATION

# NUMERICAL AND EXPERIMENTAL TIME-REVERSAL OF ACOUSTIC WAVES IN RANDOM MEDIA*

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Received 29 June 1999
Revised 13 April 2000

In classical mechanics, a time-reversal experiment with a large number of particles is impossible. Because of the high sensitivity to initial conditions, one would need to resolve the positions and velocities of each particle with infinite accuracy. Thus, it would require an infinite amount of information, which is of course out of reach. In wave physics however, the amount of information required to describe a wave field is limited and depends on the shortest wavelength of the field. Thus we can propose an acoustic equivalent of the experiment we mentioned above. We start with a coherent transient pulse, let it propagate through a disordered highly scattering medium, then record the scattered field and time-reverse it: surprisingly, it travels back to its initial source, which is not predictable by usual theories for random media. Indeed, to study waves propagation in disordered media theoreticians, who find it difficult to deal with one realization of disorder, use concepts defined as an average over the realizations, which naturally leads to the diffusion approximation. But the corresponding equation is not time-reversal invariant and thus fails in describing our experiment. Then, to understand our experimental results and try to predict new ones, we have developed a finite elements simulation based on the real microscopic time-invariant equation of propagation. The experimental and numerical results are found to be in very good agreement.

*Presented at ICTCA'99, the 4th International Conference on Theoretical and Computational Acoustics, May 1999, Trieste, Italy.

International Journal of Computational Acoustics, Vol. 9, No. 3 (2001)


INTERNATIONAL ASSOCIATION FOR MATHEMATICS AND COMPUTERS IN SIMULATION

# FLUCTUATIONS OF ELASTIC WAVES DUE TO RANDOM SCATTERING FROM INCLUSIONS*

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Received 25 June 1999
Revised 28 March 2000

Exact solutions for elastic compressional and shear waves scattered from a homogeneous sphere are used to obtain formulas for fluctuations of velocity and attenuation of plane waves propagating through a layer of randomly distributed inclusions over a broad range of frequencies. The size and contrast of the inclusions are arbitrary, but interactions between scatterers are not considered and the concentration of scatterers is assumed to be small. The analytical solutions are also compared with numerical simulations and it is demonstrated that they satisfactorily explain the effects of scattering on both the mean and variance of the phase and the mean and variance of the attenuation. The need for spatial averaging of observational data and methods of interpreting such averaged data in terms of the material properties of the scattering medium are discussed.

*Presented at ICTCA'99, the 4th International Conference on Theoretical and Computational Acoustics, May 1999, Trieste, Italy.

International Journal of Computational Acoustics, Vol. 9, No. 3 (2001)


INTERNATIONAL ASSOCIATION
FOR MATHEMATICS AND
COMPUTERS IN SIMULATION

# NUMERICAL STUDY OF THE WAVE INSTABILITY PROBLEM WITH THE EFFECT OF THE TRANSVERSE VELOCITY COMPONENT*

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Received 2 July 1999
Revised 14 October 2000

We will numerically investigate the wave instability problem with the effect of the transverse velocity component. An accurate and easy to program finite difference scheme will be developed for this purpose. The eigenfunctions will be normalized and computed simultaneously with the eigenvectors. Numerical results will also be presented.

*Presented at ICTCA'99, the 4th International Conference on Theoretical and Computational Acoustics, May 1999, Trieste, Italy.