ABSTRACTS FROM THE WORKSHOP ON
OSCILLATION THEORY, COMPUTATION, AND METHODS OF COMPENSATED COMPACTNESS

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INSTITUTE FOR MATHEMATICS AND ITS APPLICATIONS
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Oscillation Theory, Computation, and Methods of Compensated Compactness

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CONTINUUM PHYSICS AND PARTIAL DIFFERENTIAL EQUATIONS

WORKSHOP ON

OSCILLATION THEORY, COMPUTATION, AND METHODS OF COMPENSATED COMPACTNESS

April 1 - April 6, 1985

Conference committee: Constantine Dafermos, Jerry Ericksen, David Kinderlehrer, Marshall Slemrod

Historically, one of the most important problems in continuum mechanics has been the understanding of hyperbolic conservation laws. This is because such systems arise from the underlying balance laws of mass, momentum, and energy. Their nonlinearity and hyperbolicity arise from the simplest constitutive assumptions, even in an ideal gas. The goal of this workshop is to examine the implications of compensated compactness and dispersion in the analysis and numerical analysis of such equations. The influence of viscosity and fluctuation mechanisms in nature will be discussed as well. Recently there has been remarkable progress in all of these fields.

Participants will include representatives of these areas. Since one of the ultimate users of these ideas will be the applied engineer or scientist engaged in numerics, those in the forefront of applying theory and writing codes were sought.

In addition to the talks, whose abstracts are reproduced here, the conference ended with a stimulating round table discussion chaired by Constantine Dafermos and Luc Tartar.
NUMERICAL SIMULATION OF FLUID FLOWS WITH STRONG SHOCKS

Phillip Colella
Lawrence Berkeley Laboratory

The numerical calculation of discontinuous solutions to the Euler equations for inviscid compressible flow is often carried out using finite difference methods to capture discontinuities. In this technique, one uses difference approximations which have a form which is a discrete analogue of divergence form for the differential equations, and represent the discontinuity as a steep gradient on the mesh. Capturing methods have developed to a point that shocks are represented by sharp monotone transitions on the the grid without sacrificing accuracy in smooth regions.

We discuss how the accurate representation of shocks by capturing depends on the discrete travelling wave structure in the case of strong shocks, i.e. those for which there is substantial production of entropy at the shock. We give examples of cases where capturing fails to give adequate results for strong shocks because of irregular mesh spacing, vanishing characteristic velocities, or the introduction of a fast time scale due to chemical reactions. In all these cases, capturing methods perform adequately for smooth solutions, or even for weak shocks. As a partial remedy to this problem we propose an algorithm for tracking selected discontinuities. We treat a discontinuity as an interior free boundary for a capturing calculation, at which Rankine-Hugoniot relations are applied as boundary conditions. Thus we can treat problems for which there is a single strong shock interacting with a weak wave background, including weak shocks and other discontinuities which intersect the tracked boundary. We apply this technique to the problem of self-similar shock reflection in two space dimensions, and present preliminary results of a counterexample to von Neumann's criterion for transition from regular to Mach reflection.

1
We discuss the notion of measure-valued solutions to hyperbolic systems of conservation laws. One of the goals is to represent weak limits of associated singularly perturbed equations. Two classical examples are provided by the zero diffusion limit and the zero dispersion limit for the inviscid Burgers equation.

For a scalar conservation law, we prove that if a measure-valued solution begins as a Dirac mass then it remains a Dirac mass for all time provided that it satisfies an averaged version of the Lax entropy inequality. As a corollary one obtains a new proof of convergence of the viscosity method for a scalar conservation by observing that the Young measure for a diffusive sequence constitutes a measure-valued solution of the underlying hyperbolic equation which satisfies an averaged version of the Lax entropy inequality.
ON NONOSCILLATORY HIGH ORDER ACCURATE SCHEMES

Ami Harten

School of Mathematical Sciences,
Tel-Aviv University
and
Department of Mathematics
UCLA

In this paper we present nonoscillatory shock capturing schemes that are high order accurate in the sense of local truncation error wherever the solution is smooth. These schemes are obtained via a high-order reconstruction of the solution from its cell averages, time evolution through an approximate solution of the resulting initial value problem, and averaging solution of the resulting initial problem, and averaging of this approximate solution over each cell. The nonoscillatory nature of the numerical solution is achieved by employing a new interpolation technique in the reconstruction step. This interpolation has the property that it generates a high order accurate approximation to the interpolated function wherever it is smooth, without having a Gibbs phenomenon at points of discontinuity.
DISPERSEE DIFFERENTIAL AND DIFFERENTIAL EQUATIONS

Peter D. Lax
Courant Institute

In 1944 V. Neumann proposed a difference scheme for computing compressible fluid flows with shocks. The scheme lacked any viscosity, real or artificial, and consequently produced solutions that had mesh-scale oscillations behind the shock. V. Neumann identified tentatively these oscillations with the thermal motion of molecules heated by shock wave, and conjectured that the weak limits of such oscillatory approximate solutions would be weak solutions of the equations of compressible flow. I surmise, but cannot prove that the weak limits involved are analogous to the weak dispersion limit of solutions of the KdV equation, and therefore do not satisfy in the weak sense the equations of fluid dynamics.
NONLINEAR GEOMETRIC OPTICS

by Andrew Majda
Princeton University

The method of weakly nonlinear geometric optics is one of the main perturbation techniques used in analyzing nonlinear wave motion in hyperbolic systems. Recently, this method has been developed systematically as a tool for nonlinear wave propagation in multi dimensions with applications to the diffraction of weak shocks, the formation of Mack stems in reacting shock fronts, and the development of simplified asymptotic models in combustion theory. First we describe these methods in detail for nonlinear hyperbolic systems in a single space variable then we describe a number of generalizations and applications in several space variables.

The tacit assumptions used in deriving these approximations are that the underlying solutions of the hyperbolic system remain smooth. These assumptions are rarely satisfied in practice due to shock formation; nevertheless, the approximations work quite well in practical problems. We also report on joint rigorous work with R.DiPerna for weak solutions for systems in a single space variable which prove that the formal approximations are also valid for weak solutions with shocks and even better than predicted by the formal theory!! This is a partial explanation and justification of the methods for weak solutions.
THE PROPAGATION OF INTEGRABLE OSCILLATIONS

David W. McLaughlin
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In this lecture I describe some results on the nonlinear propagation of finite amplitude, rapidly oscillating, integrable waves. These results were obtained with the mathematical methods of modulation theory. My goal in the lecture is to explain the additional features which integrability supplies, both with regard to the implementation of the mathematical techniques and with regard to the understanding of the macroscopic properties of the wave.

First, a large robust family, called N-phase waves, of exact solutions of the integrable equation is introduced. Two types of stability for members of this family is investigated - (i) with respect to periodic perturbations of the initial data and (ii) modulational stability. A representation of the modulation equations for the propagation of macroscopic properties of the wave in terms of differentials on a Riemann surface is obtained. Advantages of this representation of the modulation equations are discussed. Explicit solutions of the modulation equations for two initial value problems is described in some detail. Finally, I discuss those results should survive the removal of integrability.

REFERENCES


In this paper we will review some of the recent experiences we have had at Sandia National laboratories in computing solutions for several different classes of nonlinear fluids in relatively simple geometries. The purpose of this presentation will be to display, by example, some of the interesting numerical analysis issues that arise as a result of nonlinear material behavior. As the first example, we consider a nonlinear elastic fluid with chemical reactions and discuss solutions for detonation and detonation failure in a two-dimensional channel. In this case, the numerical algorithm utilizes a finite difference method with artificial viscosity and is shown to lead to two distinctly different stable solutions depending on the time step criterion used. Physically, this problem is characterized by two disparate time scales; one based on the acoustic transit time across a fluid element and the other associated with the thermal decomposition of the fluid. The correct solution is obtained using a numerical stability criterion based on the smaller time scale.

The second example to be considered involves the thermally-induced convection in a viscous fluid as a result of an exothermic polymerization reaction. In the context of a rectangular container, a solidification front develops near the top of the container and propagates down through the fluid changing the aspect ratio of the region ahead of the front. Using a Galerkin-based finite element method, a numerical solution of the partial differential equations is obtained which
tracks the front and correctly predicts the fluid temperatures near the walls. However, there is evidence of oscillating behavior with regard to the number of convection cells in the fluid ahead of the front and in the direction of flow. The final example concerns the one-dimensional radial flow of a nonlinear viscoelastic (Maxwell) fluid and numerical solutions were again obtained using a Galerkin-finite element method. In this case, convergence to a stable solution was obtained for all values of the Weisenberg number provided a continuous linear approximation was used for the stress. However, for a continuous quadratic approximation, there is a combination of mesh size and Weisenberg number for which solution convergence fails.

These three examples are not atypical. They serve to demonstrate that in numerically solving nonlinear partial differential equations, it is quite easy to obtain multiple solutions, oscillatory phenomena, instabilities, and lack of convergence (possible non-existence). It is clear that these computational difficulties can arise either due to the numerical method involved or from the complexities of the physical model being addressed. In pressing to solve problems of technological interest, it is extremely important to sort out these matters. This requires considerably more detailed mathematical analysis of the governing partial differential equations at the outset so that the numerical analyst can utilize the proper numerical algorithm, identify the appropriate physical solution, or at least recognize that the problem posed does not lead to physically meaningful results.
A systematic procedure for constructing semi-discrete families of $2m-1$ order accurate, $2m$ order dissipative, variation diminishing, $2m+1$ point band width, conservation form approximations to scalar conservation laws is presented. Here $m$ is any integer between 2 and 8. Simple first order forward time discretization, used together with any of these approximations to the space derivatives, also results in a fully discrete, variation diminishing algorithm. These schemes all use simple flux limiters, without which each of these fully discrete algorithms is even linearly unstable. Extensions to systems, using a nonlinear field-by-field decomposition are presented, these non-linear approximations are variation diminishing, and hence convergent. A new and general criterion for approximations to be variation diminishing is also given. Finally, numerical experiments using some of these algorithms are presented.
HOMOGENIZATION OF SLIGHTLY COMpressible INviscid Flows

T. Chacon

O. Pironneau

INRIA

We propose to study the following problem:

\[ u_t + u \nabla u + \nabla p = 0 \]
\[ \rho_t + \nabla \cdot u = 0 \]
\[ u(x,0) = u^0 \left( x, \frac{x}{\varepsilon} \right), \quad p(x,0) = p^0 \left( x, \frac{x}{\varepsilon} \right) \]

which describes slightly compressible adiabatic inviscid flows with rapidly varying initial data (\( \varepsilon \) small). Following the multiscale asymptotic expansion used in [1][2] we derive an equation for the mean flow

\[ u_t + u \nabla u + \nabla p + \nabla \cdot \varphi \left( \text{tr} (\nabla a \nabla a^T) \right) \nabla a \nabla a^T = 0 \]
\[ \rho_t + \nabla \cdot u = 0 \]
\[ a_t + u \nabla a = 0 \quad a(x,0) = x \]
\[ q_t + u \nabla q + \varphi \left( \text{tr} (\nabla a \nabla a^T) \right) \nabla a \nabla a^T : \nabla u = 0 \]

This system is compared with the incompressible case studied on the 3-D flow between parallel plates.
Figure 1

Tableulation of $\beta$ by solving

$$w \nabla w + \nabla \pi = 0 \quad \text{in } ]0,1[^3$$

$$\nabla \cdot w = 0$$

with periodic boundary conditions, as a function of the trace of the matrix $C$.

REFERENCES


TWO APPLICATIONS OF THE THEORY OF COMPENSTATED COMPACTNESS

Maria E. Schonbek
Princeton University

We will discuss two applications of the theory of compensated compactness. The first is concerned with the zero dissipation-dispersion limit for the Korteweg-deVries-Burger equation

\[ u_t + uu_x + \delta u_{xxx} = \epsilon u_{xx} . \]

The second applications is the existence of singular conservation laws of the form

\[ u_t + f(u)_x + \phi'(u) = 0 . \]

Finally I will speak about a decay result for solutions of the Navier Stokes equations.
INTERRELATIONSHIPS AMONG MECHANICS, NUMERICAL ANALYSIS, COMPENSATED COMPACTNESS AND OSCILLATION THEORY

Marshall Slemrod
Rensselaer Polytechnic Institute

This lecture discusses:

1. The role of viscosity and capillarity in continuum mechanics as introduced in the work of Rayleigh, Korteweg, Van der Waals.

2. How these ideas motivate finite difference methods for numerical solution of systems of conservation laws, eg. The Lax-Friedichs method.

3. How attempts have been taken to compute "viscous" limits eg. the Hopf-Cole transform and formal ideas of oscillation theory.

4. How a rigorous theory of "viscous" limits arises out of Tartar and DiPerna's results on compensated compactness and the related Young measure.
THE ZERO DISPERSION LIMIT OF THE KORTEweg DE Vries EQUATION
WITH PERIODIC INITIAL DATA

Stephanos Venakides
Stanford University

We study the initial value problem of the Korteweg de Vries equation

\[ u_t - 6uu_x + \varepsilon^2 u_{xxx} = 0 \]

\[ u(x,0,\varepsilon) = -\varphi(x) \]

in the limit \( \varepsilon \to 0 \), when \( \varphi(x) \) is a \( \mathbb{Z} \)-periodic function. The blow-up of the first derivative of the solution of the unperturbed problem \( u_t - 6uu_x = 0 \) in finite time leads to the emergence of a shock region in the solution of the perturbed problem in which a fast spatial and temporal scale appears. Our analysis utilizes the complete integrability of the Korteweg de Vries equation to rigorously obtain the weak limit:

\[ \overline{u}(x,t) = \lim_{\varepsilon \to 0} \frac{d}{dx} \lim_{\varepsilon \to 0} \int_{x'}^{x} u(x',t,\varepsilon) dx' \]

Furthermore we describe the problem in terms of a microstructure which allows us to conclude that in the shock region \( u(x,t,\varepsilon) \) is a modulated periodic or multiply periodic solution of (1) having wave numbers and frequencies of order \( \frac{1}{\varepsilon} \). Our conclusion on the oscillations rests on a plausible assumption of "molecular chaos" in the microstructure. This assumption can be verified at \( t=0 \).
STABILITY OF FINITE DIFFERENCE APPROXIMATIONS FOR HYPERBOLIC INITIAL BOUNDARY VALUE PROBLEMS

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We consider the stability of finite-difference approximations to hyperbolic initial-boundary value problems (IBVPs) in one spatial dimension. A complication is the fact that generally more boundary conditions are required for the discrete problem than are specified for the partial differential equation. Consequently, additional "numerical" boundary conditions are required and improper treatment of these additional conditions can lead to instability and/or inaccuracy. For a linear IBVP with homogeneous analytical boundary conditions, a finite difference approximation with requisite numerical boundary conditions, can be written in vector-matrix form as $u^{n+1} - Cu^n$. Lax-Richtmyer stability stability requires a uniform bound on $||C^n||$ (i.e., $C$ to the $n$th power) in some matrix norm for $t=n\Delta t < T$. One would like to have a simple algebraic test for Lax-Richtmyer stability. We state a conjecture that provides an algebraic test based on the normal mode analysis of Gustafsson, Kreiss, and Sundstrom. The conjecture is corroborated by extensive examples where the matrix norm of $C$ is computed numerically at a fixed time as the spatial mesh is refined. The maximum modulus of the normal mode eigenvalues or Cauchy eigenvalues is related directly to the growth rate of unstable schemes. An analogous conjecture is also considered for the semi-discrete approximation, i.e., the method of lines for hyperbolic IBVPs.

Paper to be presented at a Workshop on Oscillation Theory, Computation, and Methods of Compensated Compactness to be held at the University of Minnesota, Minneapolis, Minn., April 1-5, 1985
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