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Hyperbolic Aspects of Fluiddynamics

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As mentioned in C. Dafermos' concluding remarks, the mathematical analysis of hyperbolic systems in fluid dynamics is historically at a particularly broad and active stage. This is due to increased recent efforts of research groups in many countries and also to an opening towards new topics (stability of nonlinear waves, relaxation problems, boundary layers, geometrical optics, kinetic theory, liquid crystals, plasmas, atmospheric flows, avalanches, ...). Bringing together mathematicians of different backgrounds and interests, this meeting tried to capture the current state and induce new interactions, a goal which was smoothly reached thanks to the good work atmosphere of the center. The program comprised 26 talks held in the mornings and two afternoons, and two evening sessions that were devoted to short informal presentations in particular of open problems (W. E, R. Klein, and D. Serre). The meeting was organized by H. Freistühler (Aachen), B. Perthame (Paris), and A. Szepessy (Stockholm).

François Bouchut: BGK Models with Kinetic Entropies

We present a general framework that complements the works of R. Natalini and D. Serre for kinetic BGK models

$$\partial_t f + a(\xi)\cdot\nabla_x f = \frac{M_f - f}{\varepsilon}, M_f(t,x,\xi) = M(u(t,x),\xi), u(t,x) = \int f(t,x,\xi)\,d\xi, \qquad (1)$$

that are compatible with a family of entropies $\eta \in \mathcal{E}$ of the limit system obtained as $\varepsilon \to 0$,

$$\partial_t u + \sum_{j=1}^{N} \frac{\partial}{\partial x_j} F_j(u) = 0. \qquad (2)$$

The possible maxwellians $M(u,\xi)$ can be characterized by the moment equations

$$\int M(u,\xi)\,d\xi = u, \qquad \int a_j(\xi) M(u,\xi)\,d\xi = F_j(u), \qquad (3)$$

and by the compatibility conditions

$$\forall \eta \in \mathcal{E} \quad (M')^t \eta'' \quad \text{is symmetric}, \qquad (4)$$

while the stability of (1) reads as the nonnegativity of the bilinear forms of (4). We show by examples how this enables to construct new BGK models compatible with all entropies for given systems of the type (2).

Yann Brenier: Hydrostatic limit of the Euler equations

The formal limit of the 2D Euler equations for an incompressible fluid moving in an infinitely thin horizontal strip is addressed. The main feature of the resulting system is that the pressure field does not depend on the vertical coordinate (hydrostatic regime). From the PDE point of view, there is a loss of derivative and the well posedness of the equations if far from being obvious. However, there is a subclass of solutions, as the initial horizontal velocity has nowhere an inflexion point as a function of the vertical coordinate (which means that the initial flow satisfies a local Rayleigh condition), it is shown that the equations can be written as an infinite-dimensional symmetric system of conservations laws and are well-posed.

The contents of this talk has been published in Nonlinearity. Since then, Emmanuel Grenier proved the convergence of the 2D Euler equations to the hydrostatic equations, with similar assumptions on the initial conditions. I also got aware of the interesting papers of V. Teshukov, where the corresponding free boundary problem has been addressed.

Alberto Bressan: Cauchy problem for hyperbolic systems with small viscosity

The talk is concerned with the Cauchy problem for a nonlinear, strictly hyperbolic system with small viscosity:

$$u_t + A(u)u_x = \epsilon\, u_{xx}, \qquad u(0,x) = \bar{u}(x). \tag{$*$}$$

We assume that the integral curves of the eigenvectors r_i of the matrix A are straight lines. On the other hand, we do not require the system $(*)$ to be in conservation form, nor do we make any assumption on genuine linearity or linear degeneracy of the characteristic fields.

In this setting we prove that, for some small constant $\eta_0 > 0$ the following holds. For every initial data $\bar{u} \in \mathbf{L}^1$ with $TV\{\bar{u}\} < \eta_0$, the solution u^ϵ of $(*)$ is well defined for all $t > 0$. The total variation of $u^\epsilon(t,\cdot)$ satisfies a uniform bound, independent of t, ϵ. Moreover, as $\epsilon \to 0+$, the solutions $u^\epsilon(t,\cdot)$ converge to a unique limit $u(t,\cdot)$. The map $(t,\bar{u}) \mapsto S_t\bar{u} \doteq u(t,\cdot)$ is a Lipschitz continuous semigroup on a closed domain $\mathcal{D} \subset \mathbf{L}^1$ of functions with small total variation. This semigroup is generated by a particular Riemann Solver, which we explicitly determine.

Although these equations cannot be written in conservation form, we show that the Riemann structure uniquely determines a Lipschitz semigroup of "entropic" solutions, within a class of (possibly discontinuous) functions with small total variation. The semigroup trajectories can be obtained as the unique limits of solutions to a particular parabolic system, as the viscosity coefficient approaches zero.

The proofs rely on some new a priori estimates on the total variation of solutions for a parabolic system whose components drift with strictly different speeds.

Pierre Degond: On a gas dynamics model with measure-valued internal energy

This work is concerned with an extension of the classical compressible Euler model of fluid dynamics in which the fluid internal energy is a measure-valued quantity. This model can be derived from the hydrodynamic limit of a kinetic model involving a specific class of collision operators. In the present paper, we investigate diffusive corrections of this fluid dynamical model derived from a Chapman-Enskog expansion of the kinetic model, in the case where the collision time depends on the particle energy in the fluid frame. We show that the closure relations for the stress tensor and heat flux vector differ from their expression in the usual Navier-Stokes model. We argue why such a feature could be used as a tool towards an understanding of fluid turbulence from kinetic theory. (Joint work with M. Lemou.)

Weinan E: Boundary Layer theory and the zero-viscosity limit of Navier-Stokes equations

A central problem in the mathematical analysis of fluid dynamics is the asymptotic limit of the fluid flow as viscosity goes to zero. This is particularly important when boundaries are present since vorticity is typically generated at the boundary as a result of boundary layer separation. The boundary layer theory, developed by Prandtl about a hundred years ago, has become a standard tool in addressing these questions. Yet at the mathematical level, there is still a lack of fundamental understanding of these questions and the validity of the boundary layer theory. In this talk,we review recent progresses on the analysis of Prandtl's equation and the related issue of the zero-viscosity limit for the solutions of the Navier-Stokes equation. We also discuss some directions where progress is expected in the near future.

David Hoff: Nonformation of vacuum states for compressible Navier-Stokes equations

We prove that weak solutions of the Navier–Stokes equations for compressible fluid flow in one space dimension do not exhibit vacuum states, provided that no vacuum states are present initially. The solutions and external forces that we consider are quite general: the essential requirements are that the mass and energy densities of the fluid be locally integrable at each time, and that the L^2_{loc}-norm of the velocity gradient be locally integrable in time. Our analysis shows that, if a vacuum state were to occur, the viscous force would impose an impulse of infinite magnitude on the adjacent fluid, thus violating the hypothesis that the momentum remains locally finite. (Joint work with J. Smoller.)

Helge Holden: Operator splitting for Korteweg-de Vries-like equations

We discussed the initial-value problem for Korteweg-de Vries-like equations of the form

$$u_t + f(u)_x = u_{xxx}, \quad u|_{t=0} = u_0.$$

Operator splitting amounts to approximationg the solution u by U^n, that is

$$u(x, n\Delta t) \approx U^n, \quad \Delta t > 0$$

where

$$U^{n+1} = [R(\Delta t)S(\Delta t)]U^n.$$

Here $R(t)u_0$ denotes the solution of $u_t = u_{xxx}$, and $S(t)u_0$ the solution of $u_t + f(u)_x = 0$, both with initial data u_0. A Lax-Wendroff type of result is presented, that is, if the approximation converges as $\Delta t \to 0$, then the limit is a solution. Furthermore, various numerical simulations are presented. (Joint work with N. H. Risebro.)

John K. Hunter: Nonlinear Geometrical Optics

Nonlinear geometrical optics concerns the asymptotic behavior of high-frequency solutions, or singular solutions, of nonlinear hyperbolic partial differential equations. We review some recent progress and open problems for variational systems of hyperbolic equations, including the Einstein field equations, resonant wave interactions, nonlinear wave diffraction, and nonlinear surface waves.

H. Kristian Jenssen: Blowup in hyperbolic systems

We study various blowup phenomena for strictly hyperbolic systems. We consider systems both in quasilinear and conservative form. While the theory for single equations is well developed much less is known for systems of equations and the situation here is far from fully understood. Thus even simple examples of blowup mechanisms are of interest.

We present two types of blowup for systems. The first is a generalization of an example given by Jeffrey and illustrates how ordinary differential equations can be used to construct blowup patterns for systems of hyperbolic equations. We then give a class of 3×3-systems of conservation laws with solutions whose sup-norm and/or total variation become infinite in finite time. These last examples are based on the construction of a particular interaction pattern which yields infinitly many waves in finite time. We finally consider the effect of adding a viscosity term. We show that in this case one cannot have blowup in total variation without sup-norm blowup.

Rupert Klein: Low Mach - Low Froude number asymptotics for atmospheric flows

For atmospheric flows on length scales comparable to the pressure scale height, the Mach and Froude numbers are proportional. This suggests a distinguished low Mach / low Froude asymptotic limit. The leading order equations have a degree of complexity intermediate between the common hydrostatic primitive equations and more elaborate fully three-dimensional formulations. A systematic exploration of this insight may lead to accelerated and more accurate wheather forecast and climate prediction codes.

An extended multiple length scale, single time scale analysis that includes the so-called "synoptic length scales" of typical high and low pressure systems reveals the following: Through a unified multiple scales asymptotic expansion it is possible to re-derive a wide range of existing specialized meteorological models for particular flow phenomena. These include Lamb- and large scale acoustic waves, Rossby waves, internal gravity waves and the geostrophic flow model.

Gunilla Kreiss: Nonlinear Stability of Scalar, Viscous Shock Fronts in Multi-Dimensions

We prove decay in maximum norm of perturbations of planar shock front solutions of viscous conservation laws in two space dimensions. The initial perturbation must satisfy a zero-mass type requirement, and be sufficiantly smooth. There is no restriction of the shock strength. The proof is based on resolvent estimates of the linearized problem. (Joint work with H.-O. Kreiss.)

Dietmar Kröner: Adaptive grid control for conservation laws

One of the most efficient tool for improving the computing time for realistic problems from applications is adaptive grid control. Unfortunately no rigorous theory for systems of nonlinear conservation laws is available, which gives reliable error estimates. Finally we would like to compute a numerical solution, such that the error to the exact solution is within a given tolerance.

Partial results are known for linear symmetric hyperbolic systems of conservation laws and for scalar nonlinear conservation laws in 1-D. Just recently we could prove a new a posteriori error estimate for scalar nonlinear equation in n-D. It turns out that the L^1 norm of the error can be estimated by known quantities and suitable terms depending on the numerical solution in the corresponding cone of dependance. These theoretical results could be confirmed by numerical experiments.

Tai-Ping Liu: Entropy and admissibility of shocks waves

There are two admissibility criteria for shock waves. One is the the pointwise criterion, which starts with Oleinik's condition for scalar conservation law. It has been generalized by the author to system of conservation laws. It states that the shock speed reaches the minimum at the right state as one moves along the Hugoniot curve starting at the left state. The other is the entropy inequality involving the physical entropy. This is the integral version which is equivalent to the pointwise one only if the characteristic field is genuinely nonlinear in the sense of Lax. In general the integral version is strictly weaker than the pointwise one and therefore not sufficient to select physically relevant solutions. On the other hand, the entropy function is a basic physical concept. Thus it is desirable to formulate an admissibility criterion based on the entropy function. We will discuss a new entropy criterion of requiring that the entropy dissipation increases as the wave strength increases. This new criterion turns out to be equivalent to the pointwise criterion.

Jens Lorenz: Quantification of Nonlinear Stability

I consider ODEs and PDEs of the form $u_t = Pu + f(u)$ where P is linear and $f(u)$ vanishes quadratically at zero. If the spectrum of P lies in the left half plane one expects that u tends to zero as $t \to \infty$ provided that the initial data are sufficiently small. Which smallness requirement is realistic? To quantify the requirement, I use the resolvent technique, which is motivated by the recent interest in pseudospectra. Examples show that the details of the interaction of the linear and nonlinear part are important.

Charalampos Makridakis: A posteriori error estimates and adaptivity for approximations to conservation laws

We consider numerical (finite difference and finite volume) schemes approximating the entropy solution of the conservation law

$$\partial_t u + \mathrm{div} F(u) = 0, \quad x \in R^d, t > 0, \tag{1}$$

with initial data $u(x, 0) = u_0(x) \in L^1(R^d) \cap L^\infty(R^d)$. Our goal is to provide explicit a posteriori error estimates for schemes satisfying certain cell entropy inequalities. These estimates is a first step towards designing adaptive algorithms based on appropriate mesh refinement strategy for the efficient approximation of (1). The main tool for establishing such estimates is an appropriate (and simple) use of Kruzkov's estimates.

A basic property of a numerical scheme that can lead to the a posteriori error estimate is the discrete entropy. We first consider schemes satisfying "strong" entropy inequalities. Therefore we consider monotone finite volume schemes in unstructured meshes. These schemes satisfy an a posteriori error estimate in the local L^1 norm. This bound is of order $O(h^{1/2})$ if the approximate solution is bounded in BV. Next we consider schemes that satisfy "weak" entropy inequalities. Typical examples of such schemes are the second order schemes considered by Osher and Tadmor and the central NT schemes. It turns out that for such schemes one can derive similar a posteriori error estimates. We then show that, in the case of one dimensional convex flux, one can recover convergence rates known before for such schemes. Such a posteriori estimates provide the following useful information: If the (computable) upper bound of the error is less than a given tolerance τ we know that the error measured in the corresponding norm is at most τ even if we cannot prove the convergence of the scheme.

Roberto Natalini: Convergence of relaxation approximation to the initial boundary value problem for conservation laws

We investigate a relaxation approximation to the initial-boundary value problem for a scalar one-dimensional conservation law. We propose to approximate this problem by the classical Jin-Xin relaxation model by taking the second Riemann invariant at the equilibrium on the boundary. Under the subcharacteristic condition we are able to prove the convergence to the unique entropy solution of the limit problem when the relaxation parameter tends to zero. (Joint wortk with A. Terracina.)

Olof Runborg: Multiphase Geometrical Optics

Geometrical optics, the classical approximation of high frequency wave propagation, is often formulated as a pair of non-linear PDEs, the eikonal and the transport equations. For this formulation there is no superposition principle and it cannot accomodate solutions with multiple phases, corresponding to crossing rays. We reformulate geometrical optics for the scalar wave equation as a kinetic transport equation set in phase space. If the maximum number of phases is finite and known a priori we can recover the exact multiphase solution from an associated system of moment equations, closed by an assumption on the form of the density function in the kinetic equation. Those equations form a hyperbolic system of conservation laws with source terms. Unlike the eikonal equation, the equations will incorporate a finite superposition principle in the sense that while the maximum number of phases is not exceeded a sum of solutions is also a solution. We present numerical results of how the equations perform on a variety of homogeneous and inhomogeneous problems.

Paolo Secchi: The Incompressible Limit for the Equations of Ideal Magneto-Hydrodynamics in the Halfspace

We study the incompressible limit of solutions to the equations of ideal compressible MHD as the Mach number M goes to zero, in the presence of the boundary. We assume the boundary to be a perfectly conducting wall. Then the boundary is characteristic and a loss of regularity in the normal direction to the boundary may occur. Hence the natural functional setting for the solution is given by anisotropic weighted Sobolev spaces $H^m_{**}(\Omega)$ which take account of the singular behavior at the boundary.

While in the periodic case (already considered in the literature) the analysis is essentially a repetition of that for the Euler equations, in our case we need more subtle arguments, because of the above mentioned singular behavior at the boundary. The most difficult part is to estimate the solutions in $H^m_{**}(\Omega)$, uniformly with respect to M. Our analysis shows the convergence in the presence of or without the initial layer. We use compactness arguments and, in the first case, also the asymptotic behavior of solutions to the linearized acoustic equations in the unbounded domain. We also study the strong convergence of the gradient of the total pressure.

Peter Szmolyan: Geometric singular perturbation analysis of self-similar zero-viscosity limits in systems of conservation laws

Hyperbolic conservation laws with an artifical viscosity term

$$u_t + f(u)_x = \varepsilon t u_{xx}$$

admit selfsimilar solutions $u(x,t) = u(x/t)$. Existence of solutions of the corresponding boundary value problem on the real line and convergence to solutions of the corresponding Riemann problem in the limit $\varepsilon \to 0$ have been investigated by several authors. All results obtained so far rely on apriori estimates and compactness arguments, hence uniqueness of limiting solutions is not proved. We present a novel approach to the problem based on the invariant manifold approach of geometric singular perturbation theory. The method is constructive since solutions of the Riemann problem serve as singular solutions in the context of geometric singular perturbation theory. At shocks internal layers occur which have the structure of travelling waves. The analysis of the dynamics near rarefaction curves relies on the recently developed blow-up method. It turns out that structurally stable Riemann solutions have precisely the necessary transversality properties to conclude the existence of a selfsimilar viscous profile.

Eitan Tadmor: Approximate solutions to the incompressible Euler equations with no concentrations

We present a sharp local condition for the lack of concentration (and hence – the L^2 convergence of) a sequence of approximate solution to the incompressible Euler equations. We apply this so called H^{-1} stability characterization to greatly simplify known existence results for 2D flows in the full plane (— with special emphasize on rearrangement invariant regularity spaces), and obtain new existence results of solutions without energy concentrations in any number of spatial dimensions.

Our approach relies on using a generalized Div-Curl Lemma to replace the role that elliptic regularity theory has played previously in this problem.

Our results identify the 'critical' regularity which prevent concentration, regularity which is quantified in terms of Lebesgue, Lorentz, Orlicz and Morrey spaces. In particular, the strong convergence criterion cast in terms of circulation logarithmic decay rates due to DiPerna & Majda is simplified (— removing the weak control of the vorticity at infinity) and extended (— to any number of space dimensions). Finally, motivated by our H^{-1} stability condition we introduceof a new scale of regularity spaces which enables a precise characterization of concentration-free solutions based on their L^2-energy bound.

Athanasios E. Tzavaras: On the kinetic formulation of 2×2 systems of conservation laws

The kinetic formulation of systems of conservation laws is a way of describing a notion of entropy weak solutions that has its origin in ideas from the kinetic theory of gases. At a technical level it requires the calculation of the fundamental solution for the equations describing the entropy structure of the system, and a characterization of the generators of convex entropies. We will describe how this is done for srtictly hyperbolic 2×2 systems, and exhibit a kinetic formulation for the equations describing one-dimensional isothermal motions of elastic materials. (Joint work with B. Perthame.)

Wolf Weiss: Determination of Boundary Conditions in High Moment Methods by a New Minimax Principle for the Entropy production

It is well known that the laws of Navier-Stokes and Fourier are not able to properly describe processes in gases with large Knudsen numbers. One successful attempt to describe these rarefied gases is Grad's moment method. In these theories the set of the variables mass density, velocity, and Temperature is extended to quantities like pressure deviator, heat flux, and higher moments. Therefore, the vector of the variables is given by $N > 5$ quantities. Moment methods lead to first order hyperbolic systems. In order to solve a boundary value Problem we need typical N boundary values. However, in an experiment only few boundary values can be controlled! (For instance, it is not possible to control the temperature and the heat flux on a wall). In order to determine the remaining quantities, a new minimax principle for the Entropy production [Struchtrup & Weiss, Phys Rev Lett **80**, 23, 5048 (1998)] is proposed: *In a stationary process the boundary values which are not controlled in the experiment assume values such that the global maximum of the local entropy production becomes minimal.* An application to the 26-moment theory is given.

Tong Yang: Well-Posedness Theory of Hyperbolic Conservation Laws

We consider the Cauchy problem for system of hyperbolic conservation laws. We assume that the system is strictly hyperbolic, and each of its characteristic fields is either linearly degenerate or genuinely nonlinear in the sense of Lax.

The purpose of the research is to construct a nonlinear functional

$$H(t) = H(u_1(.,t), u_2(.,t)),$$

which is equivalent to the L_1 norm of the difference between two weak solutions u_1 and u_2 constructed by Glimm's scheme or front tracking method. Moreover, $H(t)$ is nonincreasing in time and depends explicitly on the wave patterns of these two solutions. The main new components in the functional $H(t)$ are the nonlinear functional $Q(t)$ capturing the nonliear coupling of different characteristic fileds, and the generalised entropy functional $E(t)$ registering the nonlinear evolution of each genuinely nolinear field. The entropy functional generalizes the traditional concept of entropy of second law of thermodynamics.

The construction of the functional will allow us to identify the nonlinear effects of the wave behaviour on the L_1 topology of the solution space. As a consequence of our results, we obtain the L_1 well-posedness of the initial value problem for system of hyperbolic conservation laws. By identifying a non-increasing functional in terms of the wave patterns of the solutions in studying the L_1 topology, we have obtained a robust way of measuring the distance between the solutions and therefore we do not require the particular approximation schemes. In fact, our analysis would apply to any approximate scheme based on the characteristic method. (Joint work with Tai-Ping Liu.)

Wen-An Yong: Basic Structures of Hyperbolic Relaxation Systems

This talk is concerned with basic structural properties of first-order hyperbolic systems with source terms divided by a small parameter ϵ. By using von Neumann's stability analysis for difference schemes, we identify a *relaxation criterion* necessary for the solution sequences indexed with ϵ to have reasonable limits as ϵ goes to zero. This criterion is shown to imply hyperbolicity of the reduced systems governing the limits. Such a result shows the non-existence of linearly stable (in the sense of Lax-Richtmyer) hyperbolic relaxation approximation for non-hyperbolic conservation laws. Moreover, initial-boundary value problems of relaxation systems were discussed and a similar non-existence remark was reported for such problems which are not well-posed in the sense of Kreiss.

Yuxi Zheng: A Nonlinear Variational Wave Equation

A nonlinear wave equation arises in a simplified liquid crystal model through the variational principle. The wave speed of the wave equation is a given function of the wave amplitude. It has been known from joint work with Hunter and Glassey for the equation that smooth initial data may develop singularities in finite time, a sequence of weak solutions may develop concentrations, while oscillations may persist. We formulate a viscous approximation of the equation and establish the global existence of smooth solutions for the viscously perturbed equation. For monotone wave speed functions in the equation, we find an invariant region in the phase space in which we discover: (a) smooth data evolve smoothly forever; (b) both the viscous regularization and the smooth solutions obtained through data mollification and step (a) for not-as-smooth initial data yield weak solutions to the Cauchy problem of the nonlinear variational wave equation. The main tool is the Young measure theory and related techniques. (Joint work with Ping Zhang.)

Kevin Zumbrun: Multidimensional Stability of Viscous Shock Fronts

We discuss recent results on multidimensional stability of viscous shock fronts, in particular: (i) a simple, generalized spectral condition determining multi-dimensional linearized stability; (ii) relations to inviscid stability theory; (iii) nonlinear L^p stability; and (iv) pointwise description of decay in the scalar case. These results, obtained in papers by the author and coauthors D. Hoff and D. Serre, feature a common set of techniques centered around the Evans function. Successes of the method include the first multidimensional stability/instability results for strong shocks, for equations with nonidentity viscosity, and for systems.

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