Perspectives

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Introduction by the Session Presidents

Parvis Moin made a contribution concerning Predictive Science. He took as example the value of Computational Fluid Dynamics for the Boeing company, showing that the number of wing tests has a plateau between 1995 and 2005 although the computer power has increased a lot. There is no relation between the predictive accuracy of the standard engineering tools and computing power. The plateau is due to the limitations of RANS, whose accuracy does not increase with resolution. There is a strong need to develop LES-type methods which benefit from increased resolution to offer better predictive value for CFD.

Eberhardt Bodenschatz started by quoting Feynman (1963) on the analysis of circulating and turbulent fluids. When are we mathematically satisfied? As questions for the future, he emphasized the development of a Lagrangian theory that takes into account geometry, the measurements of transients turbulent flows, and turbulence in granular matter. He insisted that we should worry about 10% effects, that we should pin things down to the percent level. He then showed a picture of convection which is just after onset (1.2 times critical), but that we don't understand, and used this to argue that we should go back to understanding the transition in order to tackle coherent structures.

Charles Meneveau made the case that we still need better bridges between the predictive engineering needs and n-th order structure functions. As an example, he pointed out the sub-grid scale stress tensor, that can be written in terms of smaller scale velocity gradients, and given the large scale quantities can be used to predict all the statistics correctly. This cannot be done only from structure functions, but the latter are however interesting because they constrain the statistics. Therefore, it would be very beneficial to predict conditional statistics, for example conditional distribution functions of velocity gradients at certain scales given the other scales. Another thing that has emerged from the discussions, especially at the beginning, was the link between coherent structures and statistics. This has a lot to do with how we plot things : when we look at a field our eyes are immediately drawn to patterns. Therefore pattern formation people should return to the field, and maybe they will be able to develop a theory of connection between scales, which seems to be beyond the capability of current chaos theory.

Summaries of all the Sessions

Session 1: Homogeneous turbulence and flow structure

by Toshi Gotoh

- Coherent structures are essential for understanding transport of heat, mass and generation of drag and aerodynamic noise.
- Interaction of coherent and incoherent components is non local and nonlinear is the critical aspect of turbulence.
- Reconnection constitutes a new alternative scenario for turbulence cascade.
- Lagrangian studies are necessary for understanding of turbulence transport and phenomena and statistics at small scales.

Questions :

1. What is a flow structure and coherent structure? In DNS we show a forest of vortices (HIT and BL). The point is that the distribution of strong vortices are important. Number density, size, mean distance. We have to look at the forest as well as as the leaves. 11 votes
2. What are the dynamical equations of coherent structures for prediction of their evolution? 16-18 votes
3. What is the physical scenario of cascade in turbulence? How does the statistics of turbulence change during cascade? 14-15 votes

Session 2: Shear and wake flow turbulence

by Gary Brown

The first order requirement is understanding. That has two components: one of them is qualitative, and the other is quantitative. Qualitative helps you be able to do things because you understand what's going on. Quantitative helps you develop models to make predictions. Why is the Biot-Savart relation so important? Is it kinematic? No, it's dynamic because it's part of the evolution equation for vorticity, which happens to simplify greatly the description for several important problems (example : two point vortices orbiting around each other).

Questions :

1. Why are there coherent structures? Is it simply stability? Is it rooted in the vorticity distribution that you start with? 21 votes
2. If we acknowledge that there are coherent structures, we know that there is a direct cascade, but we know much less about the reverse process. Is there universality in a reverse cascade to the large scales which dominate momentum transport in free shear flows? 9 votes
3. If the momentum transport in free shear flows is independent of Re, what is the connection with dissipation as Re goes to infinity? 4 votes

Session 3: Channel and pipe flow turbulence

by Zhen-su She

According to Lumley and Yaglom (2001), we have a crude, practical, working understanding of turbulence but nothing approaching a comprehensive theory. I have proposed a multi-layer similarity theory for pipe flows and other flows, based on Lie group analysis, which I consider to be approaching a comprehensive theory.

Questions :

1. Are we near a comprehensive theory for channel/pipe turbulence? How universal is the multi-layer description? 2 votes
2. What is the connection between observed coherent structures and global quantities? How accurate are the data? How well do we understand these features? 10-12 votes
3. What is the influence of exact coherent structures on transitional and fully developed turbulent pipe and channel flows? 20 votes

Session 4: Boundary layer turbulence

by Beverley McKeon

From the discussions in Session 4, the following important points emerged.

- How are structures in transitional and fully developed turbulent flows related?
- What are the elementary structures? What are the fundamental building blocks that we need to think about?
- What are the differences between the canonical flows? How do we extend this kind of discussion to non-canonical flows? How do the structures change increasing the Re? Do they survive?

- What is the origin of the large scales? Are the large scale motions accumulations of hairpin packets? Are the VLSM accumulations of LSM or is it the other way around? Do we need to go back thinking about pattern formation ideas? What are the pitfalls of Taylor's hypothesis when it is used to measure VLSMs in experiments?
- What is the additional complexity of wall turbulence compared to free-shear flows?
- There are evidence that linear processes are important for wall turbulence, as well as nonlinear stability also. If you remove the linear coupling term wall turbulence will decay. How can we extend linear theory to ideas like control?
- What progress can we expect with dynamical systems approaches? How can these be used to describe structures?
- What is the status of our understanding of the near wall cycle? What is driving it? How does scale modulation/amplitude modulation come about? How does the vorticity field structure change throughout the wall layer?
- How should we classify the VLSM motions? Are they inactive close to the wall? The small scales seem to react to sloshing motions.
- How far up in Reynolds number do we need to go when we think about control schemes?
- Are we in a position to write down equations for coherent structures? The previous POD efforts were destined to identify only the large scales, but we should try to include some of the smaller scales.

Questions :

1. How does collective organization of structures work in wall flows? What are the elemental building blocks? 15 votes
2. What is the relative importance of linear processes / instabilities in the nonlinear problem of turbulence? 17 votes
3. What do we know / don't know about the large scale outer structures? 11 votes

Session 5: Turbulent stirring and mixing

by Norbert Peters

The necessity of theoretical insight depends on the level of detail. How deeply do we need to go into anomalous scaling/structure functions in order to predict physics of relevance?

Questions :

1. Can the understanding of critical phenomena help understand anomalous scaling in turbulent mixing? renormalization? 3 votes
2. Can engineers benefit from fundamental research on mixing? 18-19 votes (1st round) 16 votes (2nd round)
3. Is it time to develop new models beyond the existing Kraichnan type? Should we include models for active scales, true nonlinearity? 19 votes (1st round) 18 votes (2nd round)

Session 6: Mathematics for turbulence

by EDRISS TITI

The mathematical community works on fluid mechanics in general, and not on turbulence in particular. For example, the recent most fashionable subject is non Newtonian fluids. Concerning turbulence proper, we don't know yet what we can prove.

The solutions of the Navier-Stokes equations in the vanishing viscosity limit converge to something, what does this limit satisfy? We have enough evidence that this is not the Euler equations. We believe that this is the mathematical analogous of the closure problem in turbulence theory. We have shown that the effect of boundary conditions is essential to mathematically treat this problem. As a simple example, consider the equation:

$$\frac{\mathrm{d}}{\mathrm{d}t}u?nuu_{xx}?(u_x)^4 = 0$$

This equation does not develop singularity in finite time with periodic boundary conditions, but it does with Dirichlet boundary conditions!

The mathematical study of the Navier-Stokes equations relies on the concept of weak solutions. Are they unique or not? This is an open problem for the Navier-Stokes equations, while for the Euler equations we already know that they are not unique. Leray in his seminal work invented the notion of turbulent solutions, because he thought the weak solutions that he had discovered could be non unique. But the physical relevance of this possibility is very dubious. For example, we have the following theorem : as long as the pressure is bounded from below, there is no singularity in the Navier-Stokes equations, and the solution has to remain unique.

Questions :

1. Should we work on the deterministic case (issues like finite time singularities, weak limits of solutions)? 9 votes

2. Should we look for invariant measures and averages, in order to introduce mathematically useful statistical tools for turbulence? 20 votes

3. Should we study the stochastically forced Navier-Stokes equations? 10 votes

Session 7: Geophysical turbulence

by JOEL SOMMERIA

There is a need for focusing the research in geophysical fluid dynamics on well defined benchmark configurations on which everyone could agree. In this meeting,

- the review presentation by NARASHIMA reconciled laboratory convection with moist convection in clouds. He showed that internal heat in clouds due to phase change changes the structure of turbulence and the entrainment rate. He also stressed the importance of unsteadiness.

- BODENSCHATZ showed how to use laboratory techniques to directly analyse turbulence in clouds and the effect of microphysics.

- SREENIVASAN analyzed recent data on solar convection.

- SPIEGEL proposed an analogy between hot stars and fluidized beds.

- DOERING provided rigorous upper bounds on convective fluxes.

- TATSUMI and CAMBON advocated the use of two-points closures for turbulence statistics.

- KEVLAHAN proposed to explain the $k^{-5/3}$ spectrum observed over 11 decades in the interstellar medium in terms of statistics of shocks.

Questions :

1. Is there a Kolmogorov-type cascade in stratified turbulence? 5 votes

2. Can we estimate the energy decay in the limit of small Rossby and Froude numbers? How do we solve the problem of missing mixing in the ocean? 10 votes

3. Is there a connection between coherent structures observed in the geophysical context, like the Madden-Jullian oscillation, and large scale motions in pipes? 19 votes

Session 8: Magneto-hydrodynamic turbulence

by Bérangère Dubrulle

The following themes emerged from the discussions in this meeting.

- Equilibria and their universality: do the spectra depend on initial conditions? What is the role of invariants in defining the equilibria? (Matthaeus)
- Dynamo: are mean dynamos or small scale dynamos more important? The importance of modeling correctly the mean Lorentz force, and of taking into account the various invariants, was stressed.
- How do the properties of MHD turbulence depend on the magnetic Prandtl number? Properties of spectra, PDFs, intermittency?
- Non-locality of MHD turbulence: Domaratzki gave a good insight that MHD turbulence is much more non local than hydro turbulence.
- Closure theories: DIA and RDT were discussed.
- Structures in MHD: can they be explained by selective decay/ maxent formalisms? Is there a dissipative anomaly in MHD turbulence?

Questions :

1. Can we construct a theory to show the possibility of self-consistent MHD dynamo, either laminar or turbulent? 12 votes
2. Can we deduce from first principles the mean properties of canonical turbulence? 17 votes
3. In the limit of zero magnetic diffusivity, does the magnetic dissipation tend to a finite limit? 10 votes

General discussion

co-chaired by Parvis Moin, Charles Meneveau, *and* Eberhardt Bodenschatz

Domotzakis: I see coherent structures in many places. I would like to focus on obtaining a quantitative description from this picture of coherent structures. Not just looking at their evolution in movies but getting actual equations with predictive capability for some quantities that are of interest to us (mean flow, RMS) from this picture. Is it possible at all?

OBERLACK: If you go to the history of turbulence modeling, turbulence modelers implemented more and more of the symmetries of the Navier-Stokes equations. Nowadays, the key models do have these symmetries. What we recognized two years ago is that all of the models need additional symmetries, that we call statistical symmetries. Otherwise you will not get, for example, the log-law. Several of these statistical symmetries are already in the present models.

SHE: Concerning quantification of coherent structures and statistical symmetries, the coherent structures near the wall are related to the scaling of the mixing length in the buffer layer (like $(y^+)^2$). The statistical symmetries may be related to the existence of coherent structures. Can we derive this?

MOIN: Do you mean that to link coherent structures with mean flows we need to use symmetries? But what I think is missing is the dynamics of the coherent structures! Perry and Chong, and others, have put the kinematics together to synthesize a coherent flow, but the dynamics is missing.

WALLACE: I want to stress the paper of Perry and Chong, who attempted (for the only time to my knowledge) to really explain the statistics in great detail. We know a great deal more about wall flows now that they did then, and we have numerics. Moreover I find it quite amazing that the statistics of wall flows, to great detail, even the fine scale statistics like dissipation rate, are so similar to what they are in a turbulent spot. In the seventies, there were experiments to look at the properties of turbulent spots, and we should come back to that. These spots are like baby turbulence, and they have smooth skins contrary to old turbulence which has bags under its eyes. The continuing debate about whether hairpins exist in fully developed flow is fruitless, because anyway the statistics are the same as for spots where we do see hairpins.

SREENIVASAN: It is very clear that something statistical had to be said in order to get the right quantities of interest in turbulence. It has been very clear from the beginning. Of course it is not the standard equilibrium statistical mechanics, nor even the standard chaotic dynamics. We are all trying to look for something like that. There is one interesting dichotomy here: as soon as you say speak about statistical descriptions, there are always people studying very closely coherent structures who will look at you with suspicion. But one lesson from the Kraichnan model is that there are certain statistical conservation laws. It simply says that there are certain shape fluctuations, and there are aspects related to them that are preserved as the geometry evolves. It is related to the preservation of certain geometrical properties. If we are clever enough to devise such a law, it will have such connection with coherent structures. One should not think that the statistical view and coherent structures are different from each other, it is just that we do not yet have the tools to relate them.

MOFFATT: On the question of dynamical equations for coherent structures, I think that a good starting point are the steady solutions of the Euler equations. Such solutions are going to sit there for a long time. I put forward such a model in a meeting at Cornell. Each blob is locally a solution to the Euler equation, which is intrinsically unstable.

HUSSEIN: I have always made a distinction between structure and coherent structure: structures are simply there, while coherent structures should, in addition, have a measurable signature on the mean flow. Therefore I think that the latter are inseparable from a statistical approach. We have always tried to look for coherent structures as an object and find an evolution equation as for an individual body. The challenge is to imaginatively decide what is the initial flow. The solution given by the computer of the Navier-Stokes equations is the evolution equation for the structures!

FARGE: As you know we have to be extremely careful about terminology. We have to distinguish what has to do with transition to turbulence (before the mixing transition), and what has to do with fully developed turbulence, after which all the flow is wild but you still see some structure out of highly fluctuating fields. You have zero mean in homogeneous isotropic turbulence but structures are still observed. If I remember well from some talk I heard this week, someone used the word "turbulent structure". I propose to use this work when we talk about the fully developed regime (i.e., the flow itself generates dissipative mechanisms and not molecular viscosity).

BROWN: If you look at the stream-wise vorticity ω_x, you can show that it is uncoupled from the mean velocity profile if the latter is independent of x. This explains why Couette flows can have counter rotating structures that completely fill the gap. Over long times the vorticity accumulates in that flow, although it is not injected at the boundary by the mean flow. Behind these things, there is real physics to be understood in why the large structures emerge the way they do.

KIM: What you all are going to say is so predictable. I know what senior people are going to say, so I would like to ask young scientists, who are going to carry on this research, to speak up.

TITI: I would like to pick up this issue of coherent structures from a different point of view. There is a lot of work at the moment on fast-slow systems. If you have separation of scales, we can proceed by averaging. But in some systems all the components are at the same time fast and slow, for example in molecular dynamics. In that case you have to find equations of motion for measures. I believe that when we talk about coherent structures we see them in Lagrangian coordinates but the equations we are looking for are Eulerian. So I suggest that we should maybe introduce new quantities to describe the coherent structures, we should move from the description that we have for the flows, do some kind of averaging in order to reveal some slow features of the dynamics.

JIMENEZ: I wanted to follow up on the comment by WALLACE, that transitional structures are maybe turbulence. If we have only babies we lose the species because they cannot reproduce. At some point there is something that happens, adolescence, which separates transitional structures from fully developed turbulence, and that difference may be crucial.

Bodenschatz: I grew up in pattern formation. The people told me: look at these beautiful cloud streets. Then I came to a meeting in Santa Barbara and we wanted to look at the influence of turbulence on coherent structures. We cannot calculate the wave number of cloud streets because they are very turbulent but we acknowledge their existence anyway. There is a complicated coupling between the chaotic spatio temporal pattern of structures and small scales.

McKeon: There is some value in trying to reconcile the results we get from various approaches because we are all looking at the same flow. One problem that we run into with that is still : what is a coherent structure? How to observe a structure? We know that the criteria that we have are not perfect.

Kevlahan: I would like to suggest a way of unifying several of these themes. Compared with a flow having Gaussian statistics, we see that turbulent flows tend to deplete nonlinearity significantly. Moreover if you remove coherent structures from the flow they tend to reemerge quite quickly. So maybe coherent structures deplete nonlinearity locally, but there is something left over. That is what we did with Marie and Kai, when we introduced the split between coherent and incoherent parts. I think that tracking individual particles/structures is going to be very hard, but maybe such a decomposition in a more global sense is possible.

Gotoh: By performing DNS we found structure in turbulent flow (vortex tubes). As the Reynolds number is increased, we are looking at more and more vortices and structures at fine scale. I see some analogy to statistical mechanics: suppose that you have some vortex tubes that interact or reconnect. This could be like interactions among molecules. It is very important to understand these interactions. But when the Reynolds number is high we have a huge amount of structures. Therefore we also need to think of the distribution of structures, not only of the individual structures. It is an ensemble of structures we are looking at.

Ray: I would like to respond to the comment of Sreenivasan about a statistical mechanics of turbulence. In critical theory, people were not afraid to go into dimensions which were no integers. There are special dimensions where the equilibrium solutions are not far away from K41 (for example dimension 4/3). Probably there might be some hope in terms of perturbation theory around these special dimensions. Another comment : the use of higher precision arithmetics may be more useful than going to higher Reynolds number.

Reynolds: I am glad about the question: why are there coherent structures? For most of my career, people have been trying to say that coherent structures are important but they were not able to say what role they play, and we have made a good job computing turbulence without particularly taking them into account. So I think we have maybe wasted too much time talking about them. I found three important things said at this conference:

1. we should first put the Reynolds number in, and *then* take the limit,
2. the comment by Keith Moffatt, that we should "tear down those old theories",
3. Bodenschatz this morning saying than a precision of 10% is not good enough.

The reason we accept an error of 10% is that it allows us to reconcile any new result with old theories! So this allows us to keep all the old theories. But we should really go for 1%.

SCHNEIDER: I would like to ask whether it is worthwhile using adaptive methods for turbulence or not? The computational power is going up, maybe it is not worth the trouble. Another comment, in answer to KEITH MOFFATT: it is very difficult to construct localized eigenfunctions of the curl operator which would be stationary Euler solutions. A third comment: what is the computational resolution which is really required when computing turbulent flows?

BOS: I was interested by a slide of JIMENEZ showing a flow field with streaks, and the streaks were still visible after the phases were scrambled. I think that this shows how much we should really try to separate between the dynamical and kinematic parts of coherent structures.

TATSUMI: Turbulence has randomness and determinism. So far, the randomness of turbulence is represented by statistical averages such as mean velocity and large structures. But the most proper way of dealing with such random phenomena is non equilibrium statistical mechanics. The distribution function of turbulent velocity around such and such mean value should be our main object. We have to use more such notions instead of simply averages. A second point: no one has talked about the future of turbulence research. I am most interested in quantum fluid turbulence, which could lead to deeper understanding of classical turbulence.

YOKOI: For me, as a physicist, structure formation is always related to breakage of symmetry. Therefore I agree with PARVIS' comments stating that the dynamics of small scale structures is very important to pursue. But it is also important to catch some physical quantity which can represent such structures. In the dynamo problem, cross helicity is very important, and it can be spatially distributed and different across scale even when its global average is zero. Such breakage of symmetries often comes from large scale motions.

TITI: Probability distribution functions are very important and are also studied in mathematics. There are even theorems which prove their existence for the Navier-Stokes equations, but the problem is that there are infinitely many of them, and we don't know which one is physical. A little known theorem of Foias states that the mean flows related to all invariant measures which maximize the energy dissipation rate are all the same.

MOIN: We haven't discussed as much as we should have the possibility to take advantage of the major development that has taken place in computer hardware. This is one thing that has advanced faster than any instrumentation in physics. The community of weather forecasters, engineers, etc. are all taking advantage of it, and if we don't do the same we are going to be left behind. Using the computers, we can handle the large scale features and then handle the small scales by statistical theories. Given the growth rate that we have, in 7 years we will be able to use 20000 cores as easily as we use 20 cores today.

TAYLOR: As I said at the beginning I came here to find out what the present situation was in turbulence research. And at the end I see that you are talking in the same terms about the same quantities. There has been evolution but no revolution. At the beginning of the subject someone invented this absurd idealization of homogeneous isotropic turbulence, why has it not been solved yet? Another point: many years ago, in the early days of laboratory plasmas, there were very few diagnostics, but we did have magnetic probes. At a certain point there were loads of records from these probes showing fluctuations. At this point I came across the Hausdorff dimension of these traces, but it got us nowhere. The reason it all failed is that people would say: when you measure this Hausdorff dimension, what on earth does it tell us about the plasma?? My suggestion at the time was that there must be some connection between the Hausdorff dimension of the signals and the number of unstable modes of the plasma. The point I want to make is that this work did not have any impact because it did not tell anything about the physics.

1 Closing remarks

SPIEGEL: Let KEITH do the Closing Remarks, I want to be part of the discussion. I've been always struck by the fact that over and over I keep seeing the splitting of the equations between mean and fluctuations. I call that the Ptolemy approach. Even as I understand large eddy simulations, that is also a similar decomposition. My way of looking at that was affected strongly by a movie that Leslie Kovaznoy showed of a fully developed turbulent flow and what I saw were patches of turbulence with patches of ambient fluid that were flowing right through them. So I see this as a two fluid model, by analogy with the Landau equations for superfluids. The turbulent fluid is really a fluid made up of excitations, vortex tangles, while the rest is laminar fluid which is essentially inviscid. Qualitatively the same effects are there. For me the whole story comes to that kind of models, and I don't see enough of that. I'm still struggling to get the relative densities of the two fluids.

NARASHIMA: Exactly that proposal was made in the 61 meeting by Liepmann, and he called it ?turbular? fluid. He advocated a two fluid theory. However nothing much has happened over that idea in the last 50 years.

SPIEGEL: Yes, you are right, when I published this I quoted Liepmann. I should have mentioned his contribution here as well. There is also a paper of Crowe on that.

SHE: I wrote this in 1991 in the volume for the 50th anniversary of K41.

MOFFATT: I really will make some closing remarks. We've heard a lot about coherent structures, and at least we are a very coherent community, and we make friendship at these meetings that really do endure. I'm sure many of you have similar experiences. We've had this great common endeavor which help these friendships to endure. In this context I would like to quote to you something that Batchelor said in 1997, in an article called ?research as a lifestyle? : *"Through having common objectives and principles by which new knowledge is assessed and disseminated, scientists concerned with a particular field like fluid mechanics form an international community of great unity and moral strength. I believe that the understanding, trust and goodwill between members of this scientific community transcends geographical and political boundaries and constitutes one of the most important forces for international harmony and friendship in the world today."* From G.K.Batchelor "Research as a life style", *Appl. Mech. Rev.* **50**, R11-R20 (1997)

Batchelor lived in that conviction, and many of you know that he was a man of wonderful moral force and integrity. Before running off I would like to thank once more MARIE and KAI for the organization and the care for detail and for the great stimulus that they've provided to the advance of this subject.

THE END