

SUMMARY OF CONFERENCE

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I was a bit bemused about asking why ‘a summary’ is given. ‘A’ summary being the indefinite article; in other words it is a somewhat personal view. But, I think my perspective is important and I think that is why Mark asked me to do this. It is actually a European perspective and also that, three years ago, in London, we had a similar meeting on flow control, specifically addressing the issue of the relevance of MEMS. And some of the information that I am going to relay to you is actually very similar to what we produced then and I think it is still relevant. In the three years that have elapsed not that much progress has been made, and I shall say a bit more about that.

So the next four bullet points give a rough idea of what is going on in Europe. But it is all driven by these ACARE2020 targets, in other words basically it is a 50% reduction in CO₂ emissions, 80% in NO_x and 50% in noise. And obviously here we are really addressing 20% reduction in external sources of CO₂ emissions and then 20% from the engine. And really, as of this year, this huge program called the Clean Sky Programme has been put out. There are calls out at present for six Joint Technology Initiatives. The one I might get a small proportion of is something to do with Smart Fixed Wing aircraft; there is also another one on Aero Engines. And obviously the numbers look very big but obviously the number of participants is also big so you can work out the ratio for yourselves.

More directly Airbus, who fund some of our work, are actually really into laminar flow control, and that is really because they are actually building on what they perceive to be relatively mature technology. So really on airframe and fuselage aerodynamics.

SAMULET, this program is not new but it has hit the scientific press recently. This is also focused on environmental technologies.

So, that is where we are coming from. You can actually see that much of it comes from central funding, government sources.

On the first day I scratched out this little sketch, because it was clear to me that, even in terms of flow mechanics there are roughly two communities in the group. One lot are those who like our boundary conditions to be nice and pure. We actually set up the boundary conditions such that we just deal with one or two perturbations. So, I called that the external aerodynamics group. The fairly clean people, who like their boundary conditions nice and simple.

Then I suppose, what I was reminded of really was that in actual fact, in a gas turbine, you are pretty much stuck with what you have got. There are all sorts of loss mechanisms and processes and I will say a bit more about that in a minute. But

presumably there is a tension. We are all actually talking the same language, it is just a question of degree, degree of relevance. And in this case obviously the fuel loss mechanisms are all interacting so it is actually rather more complicated. This is what I have called a dynamic tension. I am sure there is scope for crossover and interplay and exchange.

I actually conceived this list from thinking about what happens in turbomachinery. Just scanning through the list of papers that we have been looking at. Really we have had a few papers on roughness, cavities and unsteadiness, and secondary flows. But then, when we actually get on to transition, free stream turbulence and all the others, you can see that we are actually a subset of a community. There is an awful lot going on here that is not really addressed in this meeting. The reason why I have put up this list, this actually goes back to a previous slide. For an external aerodynamicist, we might look at one of these in isolation. And yet in a turbomachine you have actually got pretty much all of these going on. They are all introducing loss mechanisms; their interaction is actually highly non-linear. If you have a model, say for transition, and then you also have another model, let's say for roughness, when you put the two together the combined effect is highly non-linear. So that you cannot make simple assumptions. Om made the point 'Why aren't we doing roughness experiments in a diffuser?' Well, it is hard and actually doing roughness experiments in very simple geometries is hard enough.

And I think Bill, you came out with 'Where is the MEMS revolution'? That struck a chord for me because I've actually spent quite a lot of time trying to talk to MEMS people. One's instinct is that you actually go to the perceived experts in the field.

But flow control is a multidisciplinary activity and the greatest challenge is probably communication. This is particularly a problem with MEMS because the MEMS culture is primarily silicon-based.

There are rapid advances in new materials and some are relevant to cold-side turbomachinery at least, e.g. polymers with C nanotubes (doped or not) and composites. The distributed sensing of skin friction is the greatest challenge, but it is essential for linear control. Robustness and reliability are the key here. Aero engines may have a thousand sensors in development but post development this is reduced to a few for health monitoring.

These next points are about the benefits of open and closed loop control; followed closely by comments on sensors. And again that shows you really how slow the process is. Part of that is quite simply because talking to control engineers is actually very difficult. You actually have to understand their terminology, even their symbols are somewhat confusing. So it is a very long process.

There are various issues here. One of which is smart ways of distributing sensors and actuators. The idea that model-based control is actually better than black box, things like genetic algorithms. This is actually the title of a paper, it is not me coining a phrase. It is

actually a no free lunch theorem by Ho and Pepyne, in 2002, which actually gets from this statement to a very large matrix in about three pages.

“If we cannot make any prior assumptions about the optimization problem we are trying to solve, no strategy can be expected to perform better than any other”.

Yu-Chi Ho and D.L. Pepyne, Simple Explanation of the No Free Lunch Theorem of Optimization, Cybernetics and Systems Analysis, Springer, 38, 2, March 2002.

So model reduction I think is actually key, or certainly the development of physically-based models, and their reduction is actually incredibly important. And at the risk of offending one or two people who have talked about POD in the past couple of days, I am told that POD and Kalman filters are really quite naïve. There is actually a lot out there, that could, more or less, be bolted on to simple fluid mechanical problems, which is already existing in the control community.

And lastly, we have to be pragmatic. Any sensors and actuators are going to be mounted in some sort of solid monolithic structure like a wing, or something like that. In other words, we really have to be realistic and think about estimators which are based on measurements of skin friction and surface pressure, and that is all. And that brings up questions about changes in behavior and dynamics between what is happening at the wall and what is happening further out in the flow. Beverley McKeon referred to that in her paper. Some of these points have already been made. I take on fully the need for more RANS development but, as Andrew says, in the academic community that is all a bit like history really. I think we’ve done it. Ten years ago I actually participated in a Newton Institute workshop at which this question arose. And then it turned out that much of the information that CFD guys in industry actually wanted was already in the published literature. So I am pretty clear about that. So there is a real drive on with LES but that introduces further difficulties. Computing resources. We’ve also seen one or two innovative numerical methods in the past couple of days. It struck me, and also Andrew, who gave me some feedback on this slide, that really, again, going back to the literature, Kline’s ideas about zonal modeling, they have been around for thirty years. In other words, it actually arose for how you model situations in which you have got two sets of shear layers interacting, and how you actually model that. And then what actually happens when that interaction ceases. What actually happens outside that interaction domain. And lastly there are techniques, by integrating the vorticity field, from which you can actually get losses. And these days with good experimental data and data base interrogation you can actually integrate that vorticity field to get estimates of drag. You can do that for the CFD data as well.

Howard was another contributor to some of these slides. This is actually a straight lift from what he has said. So the present essentials of turbomachinery are pretty clear and it is all to do with reliability, long lifetime, low specific fuel consumption and low maintenance cost. Just reading it now, it reads like an optimum for a partner in life. If you have a low maintenance partner who is very reliable and a long lifetime, with a low specific fuel consumption you are doing pretty well.

My point is I would say that's a very conservative list, but understandably so. And that conservatism is actually also mirrored in the airframe industry. Aircraft these days are actually very similar to the Comet of fifty years ago. But what are we going to do? Are we always going to be doing incremental work? Is science really like that? Is technology really like that? Where is our paradigm shift? If, as Mark says, we are getting in our car and going down the road and it is packed with MEMS, then we get on the aircraft and all those MEMS are actually the packaging of the cabin, and there is nothing on the engine, or the external airframe, aren't we missing something? So in other words 'what would an aircraft in our smart world of post 2020 be looking like?' This quote actually comes, not from me, it actually comes from a guy who works for QinetiQ in the U.K. In other words what is the post ACARE2020, realistically those are the time scales that we are looking at. In other words, if we all get busy and we meet these ACARE2020 targets will that be enough?

And I go back to the thought that in development we can put thousands of sensors on an aero engine, and then they are all taken away again, just to get down to health monitoring. Well, that says to me that the system is really quite mature. Doesn't that actually beg the question of a paradigm shift?

So, these are some key challenges. I think external aerodynamics has a lot to offer. The understanding is pretty good. The control is actually very much in its infancy. Doing this for internal flows in turbomachinery is actually a heck of a lot more difficult because the loss mechanisms are interacting. We don't necessarily know where the loss is coming from. So it is a much more difficult problem. So, I do really believe that the need for interchange between internal and external aerodynamics is a case that can be easily made.

The last point is actually a *caveat* because, again in our discussions, we talked a bit about heat transfer, roughness and wall functions. And coming from the Bradshaw school of experimental fluid mechanics, one of the things he always told me was that heat transfer was actually a bit of a black art and that Osborne Reynolds was actually a lucky man. Many of us know about the shortcomings of Reynolds analogy. One could also say that Moody was actually a lucky man; I have spent some time looking at Moody charts and in certain regions of Reynolds number it actually bears very little relation to what is actually going on. And similarly the log law; if you go back to wall functions for LES. Do you have a log law in a turbomachine?

So, some conclusions. Again these are a set of conclusions; it is not exclusive. I think the main issue is actually that our field is increasingly being driven by environmental issues. But that our subject is becoming increasingly multidisciplinary. That therefore means that we have to be able to communicate. Again not between sensors and actuators but actually between people and that, in some sense, is the hardest part. There are some things that we can do, and other things that we can't do. I suppose it is a wake up call when we actually realize that we have got some fantastic drag reduction scheme on an airliner and then it fails, then you end up in Reykjavik and not JFK, so you have a problem. That's not a good idea. I suppose, because I'm an experimentalist, I think there

is always scope for plenty more experiments. I think of the five or six papers that we had on experiments in compressors or turbine stages that only one or two have actually referred to data base interrogation. I think there is scope for actually taking on some of the really good work that Joe has done. There is lots of information to be had and I do believe now that we have all the tools to do it.

Glauser: I suppose we could take a few comments here. We have until a quarter to ten. Are there any thoughts or comments from that group? Yes Paul.

Gostelow: Is there a danger that we are selling ourselves a little bit short, say on the low pressure turbine issue? No-one ever promised efficiency improvements. Well some people may have done but by and large the paradigm at that time was a little different from the emerging one, shall we say. There is a paradigm shift but we should recognize the environment that we were in fifteen years ago maybe. And there, reduction in weight and parts count and cost was vitally important. The price of a barrel of oil was different and so on. As time changes the priorities change; reliability becomes a key issue and so on. But there were different things we were shooting for fifteen years ago and by and large they were achieved. I think that we should get credit as a community, the companies should get tremendous credit, for achieving some of those goals. Despite the fact that there have been losses as well. The efficiency has not really held up.

Glauser: That's an interesting point. We might want to wrap up this with a positive spin. I will certainly need to get the industry folks, and maybe you could work with the industry folks, to get maybe a paragraph that would summarize that. But then I like what Jonathan said right at the top. Environmental issues are a key driver, certainly right now. But let's emphasize some of our successes, I don't disagree with that. But then point to the need for meeting these new issues. So if you could maybe coordinate with the engine folks, Paul, and maybe you guys come up with a couple of key things where we have truly made progress. And of course if we can correlate it back to a Minnowbrook conference that would be even better.

Sharma: It actually does correlate.

Glauser: That would be awesome. This is what we talked about here. Not a lot but something to set the stage – that this is a credible group of people. At the end of the day we want to take this and get this in front of relevant folks and see if we can move the thing forward. So some statements of a positive nature about what has happened out of the ideas that have come out of this workshop in the past, that led to this, would be great.

Gostelow: In fairness to Om I should say I said all of this in the group and he has incorporated a large element of that.

Sharma: In my opinion we have made a lot of progress due to LPT related research conducted over the last two decades. We have trained a number of young engineers with good understanding of flow physics in low Reynolds number boundary layers and turbines. A number of these engineers currently hold leadership positions in

industry, Government research labs and universities. We have developed robust design systems for LPTs and have demonstrated that high performance turbines can be designed for large commercial aircraft engines by companies other than OEMs. We have also demonstrated that we can design highly loaded turbines with relatively low loss in performance. We have, however, been unable to design very high performance turbines with high lift (reduced airfoil count) airfoils. Our future effort, therefore need to focus on achieving this goal.

I believe this goal can be achieved and we can design LPTs with almost 2% enhancement in the efficiency (from 93% to 95%) to yield almost 1.8% reduction in fuel consumption for aircraft engines. NASA is investing money in the ERA program. This is one of the areas where we can help NASA achieve its objectives.

Solomon: I think it is severe when they talk about going from 93% to 95%; that's a 40% reduction in all loss mechanisms for that machine.

Hodson: Each of these loss mechanisms is 2, 3 or 4 percent of the dynamic head. A tiny quantity but when integrated it becomes significant. But that's the point, you've got to do all the little bits to get the bigger bit.

Volino: I think, picking up on one of the things Jonathan said here. The turbomachine has all these complicating effects that are difficult to understand, maybe impossible. I think that might sell us a little bit short too. Coming back to what Paul said, and Bill said earlier, we have learned a lot about individual mechanisms. And we haven't finished the problem. We need to figure out how to start putting this together.

Glauser: So, instead of maybe being quite as negative and throwing up our hands we should say 'Even in spite of the difficulties we have made this progress and with new technologies and thinking etc. we can go to this next level'. Keeping in mind the environmental issues certainly for commercial but also for military engines.

Volino: An example of that is the roughness we have talked about and that Jonathan mentioned here. O.K. we have looked at it in zero pressure gradients; the next logical step, as Om was saying, how it will behave under non-zero pressure gradients.

Glauser: I think that's a great suggestion Paul. And so if you want to try to extract a lead out of the engine guys, you guys can coordinate over the next week or so. Let's have some highlights. Let's advertise some of our successes and that sort of builds credibility that we are not just spinning our wheels, we are making progress, we are moving forward. We now have a new set of constraints and we move on from there.

Any other thoughts? I think John had some closing remarks he wanted to make.

LaGraff: Nothing too profound. I just wanted to thank everyone for coming. And specially some of the new faces we've brought in this time. We really appreciate and are impressed with the way the newcomers got into the spirit of this workshop. I think what

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A Summary

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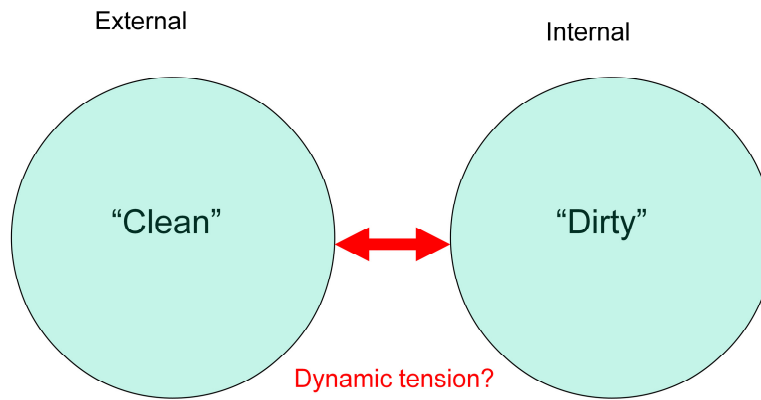
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Perspective (bias)

- IUTAM Symposium 2006 “Flow Control & MEMS”
- EU drivers such as ACARE2020: reductions per passenger km by 2020 relative to 2000:
 - 50% CO₂ (10% traffic management, 20% external, 20% engine)
 - 80% NO_x; 50% noise
- EU “Clean Sky” Programme €1.6B 2008-13, of which €393M for JTI “Smart Fixed Wing Aircraft”
- Airbus “Active Aircraft” programme, but current Airbus focus on natural/hybrid laminar flow control
- Rolls Royce led : SAMULET (Strategic Affordable Manufacturing in the UK with Leading Environmental Technology) programme TSB/EPSRC £40M total

•Clean Sky: 6 Integrated Technology demonstrators, Industry led. Call just out.

Boundary Conditions



Is the hummingbird relevant to the turbine?

- Extreme environment determines whole approach

Key Issues (loss mechanisms)

- Roughness
- Cavities
- Unsteadiness, (random & periodic)
- Secondary flows - streamwise vortices
- Pressure gradients
- Transition
- Free-stream turbulence
- Steps & sudden changes in boundary conditions
- Interacting shear layers
- Shock/boundary-layer interaction

•I think all have been mentioned except the last

Sensors & Actuators

“Where is the MEMS revolution?”

- Flow control is a multidisciplinary activity.
- Greatest challenge is probably communication
- MEMS culture is primarily Si based
- Rapid advances in new materials: some are relevant to cold-side turbomachinery at least, e.g., polymers with C nanotubes (doped or not), composites
- Distributed sensing of skin friction the greatest challenge – essential for linear control
- Robustness/reliability are key
- Post-development, aero engines have very few sensors for health monitoring but can have ~thousand in development.

•There isn't a single paper in this meeting on new sensor/actuator. Only reference to 'smart' surface is one to thermal barrier coatings.

Open- and closed-loop control

- Zero papers on sensors/actuators, but ~10 involving open/closed-loop control
- Good knowledge of flow behaviour essential to minimise demand for instrumentation (e.g. receptivity sites)
- Merits of model-based vs. “black-box” control: probably true to say that the former is always better (“No-free lunch” theorem)
- Need for better models and model reduction
- In control terminology, POD/Kalman filters are naive (I am told)
- Need for state estimators based only on wall information – again, the flow dynamics need to be understood better (e.g. changes in phase from wall to flow interior, McKeon).

CFD bottlenecks & opportunities

- Time to move on from (unsteady) RANS
- But LES invites similar problems (e.g. wall functions)
- Community needs to address resource issues & advances for HPC
- Innovative numerical methods (Davis *et al.*, Helenbrook)
- Zonal approaches for optimising computational resources in complex flows (Kline)
- Development of codes for drag/loss calculations using both cfd and experimental data

Essentials for turbomachinery design

- Reliability
- Lifetime
- SFC
- Maintenance
- Cost

So simpler the better

Note that loss is a fraction of a dynamic head while lift/drag are $O(1)$ dynamic head

Need for a paradigm shift

- With good reason, airframe & aero-engine manufacturers are very conservative
- Radically new designs post ACARE2020 are needed
- What is the paradigm shift that takes flow control beyond 2020?
- What would the aircraft 'smart' environment look like?
- 5 or 6 sensors on a modern aero-engine suggests that designs are mature

•Point is that ~5 sensors on a single engine indicates design maturity with incremental changes only.

Key challenges

- External aerodynamics has a good understanding of loss mechanisms, but control is still in its infancy.
- Interpretation & attribution of loss generating mechanisms in turbomachinery very difficult, if not impossible.
- So is knowledge transfer useful? Yes, but loss at a certain location in a turbine may come from the nonlinear interaction of several mechanisms which, in isolation (with simple boundary conditions) are well understood.
- Design tools for are incomplete (e.g. heat transfer and Reynolds analogy, roughness and the Moody chart, wall functions and the log law) – a key role for physical insight.

Some conclusions

- Environmental issues are a key driver
- Need for better mechanisms to enable discipline hopping/crossover (materials (MEMS), control, fluids)
- Better sensors & actuators and better communication for these to be developed
- Better understanding of the needs of the turbomachinery industry, especially in identifying where flow control can be beneficial (e.g. variable intake geometry)
- Challenge for flow control to be fail-safe, or to be developed for non-critical control goals (e.g. noise)
- More detailed information on stage through-flow behaviour (with/without control – Katz) – increased use of laser interrogation (PIV,PTV,MTV)