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A Fourth Year Experimental Course in the Measurement of Unsteady and Turbulent Flows

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ABSTRACT: *An experimental course has been developed to introduce undergraduate students to modern experimental techniques and instrumentation used in fluid mechanics, and particularly in turbulence. The aim of the course is to teach students to design, plan, execute and report an experiment of scientific quality. They should also gain the ability to choose which tool is right for the specific problem at hand. Additional desired outcomes are to enable them to evaluate the experiments of others, as well as to learn to use published data in a critical way. The course has been given twice, 2003 and 2004, and is divided into three parts: lectures and extensive project work at Chalmers in Sweden plus an additional short hands-on segment with state-of-the-art equipment at DTU (The Technical University of Denmark). The first provides a solid fundamental theoretical base, the second (carried out in parallel) applies this knowledge through extensive project work on a single experiment. In the third part at DTU, the students use state-of-the-art experimental techniques (e.g., PIV, LIF, LDA) and execute a series of pre-arranged experiments. The course has been very well received by the students, and (based on the very positive reaction of employers and thesis advisors) appears to provide a good base for their future.*

1 BACKGROUND

There are strong reasons for providing an experimental course in turbulence and unsteady flows at the undergraduate level, even though it is quite uncommon in undergraduate education around the world. Even when turbulence is not the primary interest, it is almost always present when there is flow and sets up the basic difficulties. Unfortunately, turbulence is one of the most difficult problems remaining in classical physics. In this subject, many 'laws' are actually empirical relations with an often vague and repeatedly questioned theoretical foundation. Increasingly, numerical simulations are performed using some turbulence model. With the advent of high powered computers and commercial user-friendly codes, these have become standard industry design tools. Today even bachelors and masters level engineers in industry are expected to be able to use, modify and understand such codes. Unfortunately graduate engineers are often very poorly prepared for this responsibility, since they have been exposed to only the most elementary (and often wrong) ideas about turbulence.

The course described in this paper is part of an International Master's program in Computational and Experimental Turbulence at Chalmers University of Technology in Göteborg, Sweden. The Master's program is described in an accompanying paper by Johansson *et al.*, 2004. The course described below has been given two times within the master's program, 2003 and 2004. The material of the course was mostly taken from Ph.D. courses like the one offered at DTU since 1998 and before that at the SUNY/Buffalo since 1978, both taught in conjunction with the hardware manufacturer Dantec Dynamics. The fundamental problem is that most industry flows are turbulent, and there is really not much known for sure about turbulence. Unlike many other fields in engineering, for most transport processes involving turbulence, it is not possible to simply buy a code and run a computation with a reasonable expectation the result will be correct. The problem is not only the multiplicity of turbulence models (e.g., Fluent provides more than 20 to choose from) and the absence of general criteria to choose among them. More troubling is the very fact that no model works well all the time, and this means models are continuously being developed and implemented. Thus even the practicing engineer must have some basis for choosing and evaluating among the often conflicting choices. Also, because the turbulence problem has not truly been solved, new theories are continuously being put forward. These are sometimes immediately embraced, but more often strongly resisted. The reasons for either response are easily understood: In the absence of a solid understanding new ideas should flourish and do. But in the absence of indisputable evidence to support them, new ideas can be quite threatening, since they often imply old ideas are wrong and codes might have to be altered. Either is quite painful to those who have the most invested in them. What should be high level intellectual discussions about a subject of great importance often resembles more a religious debate, to the total confusion of those who only wish to run a code to solve an immediate problem. Thus, unfortunately, even the lowest level engineer who must run a commercial code needs some basis for making such judgements, and most often it is his/her own experimental data base.

In the absence of physical understanding, the only way to evaluate theories or models is to test them against experimental data. For example, almost all numerical simulations require a model that has at some point been compared to experimental results to evaluate the model in question and to determine flow-specific parameters or constants. Unfortunately, it is not an uncommon situation that the difference between two competing models or theories can not be resolved, usually due to the limited resolution of the measurement device or the inadequacy of the experimental design. Therefore, since all data and experiments are not equal (i.e., not well performed), it is vital that even students who will go to industry to work on numerical simulations are able to evaluate how the experiments are set up and whether the experimental techniques were used correctly, since these will be used to evaluate the computed results.

In addition to providing a solid foundation for engineers who will go directly to industry, another reason for providing the course within the undergraduate programme is that future Ph.D. students get a jump-start towards their Ph.D. This enables them to be able to finish the Ph.D. education faster, consistent with the goals of the Bologna model that is currently being implemented around Europe.

Beyond the early point at which the knowledge base of this course is introduced, the method of instruction is also rather unusual. The novel approach implemented in this course was that, in addition to ordinary lectures, the students were given the task of designing and physically assembling an experimental facility. This is quite different from the usual approach where students perform a series of pre-arranged laboratory exercises designed to illustrate certain techniques. The pre-arranged experiment approach, although more efficient (at least from the man-hours involved), has the disadvantage that students often very quickly forget what they learn and learn almost nothing about how to put a real experiment together. Furthermore, they do not get a feeling for what kind of results and accuracy can be expected, i.e., how to evaluate experimental results. In our course, the students were divided into groups of four to five students at an early stage of the course. The project groups designed and set up a specific experiment with the aid of a supervisor who was either a Ph.D. student or senior researcher. The supervisors were chosen such that they themselves had a special interest in the particular problem. Almost all of the students had already completed two quarters of study in the Turbulence Masters program, so they already had a basic theoretical understanding of both fluid mechanics and turbulence. One measure of success was that the project work resulted in three conference papers presented at the Swedish Days of Mechanics 2003: Arroyo *et al*. (2003), Frohnapfel *et al.* (2003), and Werner *et al.* (2003), a rather remarkable outcome for only eight weeks of effort.

The important goals of the Chalmers course were four-fold: to gain an understanding of the theory of measurement, to learn to apply the theory in the laboratory, to gain expertise in using modern measurement techniques, and to gain confidence in measuring in a new environment. The manner in which these were accomplished through lectures, project and off-campus experience is described briefly in the following paragraphs.

2 LECTURES

The lecture format at Chalmers is such that an hour is divided into a 45 minute lecture and a 15 minute break. In this course, four to six lecture hours a week were scheduled, divided into two-hour blocks. The lectures consisted of two parts. The first section dealt with fundamentals of random processes and Fourier analysis. Since the students following the Masters program in Turbulence had studied the basics already, this section was quite advanced. (Students who did not follow the Masters program were given additional material.) The second part was focused on techniques to measure quantities like velocity, pressure, temperature, shear stress and also force and volume and mass flow. The lecture arrangement during the seven weeks of the course is shown in Table 1. The lectures were given mostly by the examiner, but knowledgeable experts were invited to give lectures regarding certain experimental techniques.

Table 1: Course Outline

COURSE WEEK	LECTURE TOPIC		
1	Introduction	Planning and executing	Experiment design
2		Random processes	Signal processing
3	Student presentations	Signal processing 2	Model experiments
4		Pressure and temperature	HWA 1
5	HWA 2	LDA 1	LDA2
6		PIV and Flow viz.	Model experiments
7		Other techniques	Closing

3 PROJECT WORK

The students were divided into groups consisting of about six students per group in 2003 and four in 2004. This division was made in the first week and the selection of groups was made in the following manner: The experimental topics were chosen beforehand by the course examiner and the supervisors so that the experiments covered as broad a range as possible using the equipment at hand at Chalmers. The experiments were also selected with the thought that it should be possible to answer an interesting scientific question, and perhaps even to extend the project to thesis work. The latter assured the project supervisors were interested enough to monitor the experiments closely; it also gave students an idea of what kind of projects could be considered when the time came to choose a thesis project.

Special care was taken when composing the groups to achieve a good mix of students. In the second lecture, the students were shown around the laboratory and the supervisors explained the main principles of each experimental facility and what they could be used for. The students were given time to ask questions over a coffee break, and then they were asked to select the three projects they were most interested in. The student choices were studied and the groups formed so that there were an equal amount of students in each. No more than two students from each country were allowed in each group, in part to maximize the use of English as the common language. In 2003 the students got their first or second choice, and in 2004 all students got their first choice.

The groups received their first task immediately. They were asked to contact the supervisor of each experiment and together discuss what kind of experiment to do – especially which question to answer. They were given two weeks to formulate the problem and to suggest what kind of technique to use (even though the techniques had not been studied in detail in the lectures yet). Then they were required to present their plan to the other groups during a lecture hour. This task was done to insure they would quickly get started, quite important since the course only lasts seven weeks. The project names and the techniques used 2003 are listed in table 2. The topics were similar in 2004, but with five projects instead of six.

Table 2. Projects 2003

PROJECT TITLE	NUMBER OF STUDENTS	PRIMARY EXPERIMENTAL TECHNIQUE USED
Axisymmetric porous disk wake	6	Array of hot-wires
Buoyant plume	6	Hot-wires and cold wires
Axisymmetric jet	6	Hot-wires
Swirling flow	6	Laser-Doppler anemometry
Flow around a generic side mirror	6	Pressure measurements, hot-wires, visualization.
Flow through a contraction	5	Two-component hot-wires

The remaining weeks the students worked on designing and actually manufacturing or assembling the experiments. In 2003 most groups actually built models or entire experimental set-ups. In 2004 the students disassembled, moved and re-assembled complete experimental rigs. This was a very important part of the course, since it triggered many important questions that otherwise would have been unnoticed. One example is that if you want to put a probe in a flow, how stable must the probe holder be? Or how accurately must one align his/her probe traverse relative to the flow direction? Or how does one check that it is aligned? This was the most time consuming part of the course and once the set-up was finished, the measurements were quickly performed. This, of course, is an accurate reflection of a real experiment; and it highlights the importance of performing a careful set-up – otherwise there is a significant risk that the experimental results are extremely hard to interpret or even useless!

4 PRESENTATION OF PROJECT WORK

In 2003, the final results were presented in a report written by the group as well as oral presentations by pairs of students from each group. The presentations were arranged by splitting up groups with students AAAAAA, BBBBBB, CCCCCC etc so that new constellations AABBCC, AABBCC, AABBCC, etc were formed. Then the presentations of the projects were performed so that the A:s presented their work to the B:s and C:s, B:s presented their work to A:s and C:s etc. The presentations were done in three different rooms simultaneously with one chairman in each room so that the students only had to listen to one presentation from each group. The chairman was a senior researcher who had previously participated in the course as project supervisor. Each presentation was about 20 minutes with 10 additional minutes for questions. The presentation was judged by the chairman as well as by all the students in the room based on a pre-printed checklist.

The instructions to the students regarding the presentations were formulated such that the students should answer the following questions:

- What was the question you wanted to answer initially?
- How were you initially going to attack the problem to get an answer?
- What did you actually do?
- What were your results?
- Could you draw any conclusions regarding the initial question?
- What would you have done differently from the beginning if you knew what you know now?

These points were on the checklist handed out to the chairman as well as to all students along with the following questions:

- How well did the presenters answer questions regarding what they actually did?
- How well did the presenters answer questions regarding the underlying theory?
- Overall quality of presentations.

These were answered by choosing between a four grade scale consisting of the following grades:

Poor – Average – Good – Excellent.

The reason for having all students judge each other was that it was believed to be easier to keep everyone stay alert by having a task of their own instead of thinking only about their own presentations. The students were very positive towards each other and only in a few cases were the grades Average and only in one case Poor.

This scenario was changed somewhat in the 2004 course so that the students instead of a written report produced a conference-like poster of their experiment. The poster was then presented orally in a very short (3 minutes) presentation. Thereafter the students were stationed for 10 minutes each by their experiment answering questions from the project supervisors as well as other students in line with the guidelines presented above using the same system described above for rotating the responsibility.

5 THE 'GRAND FINALE'

Two important goals of the course remained to be fulfilled: first to let the students have hands-on experience with the very latest in flow measuring equipment; and second, to let them demonstrate that they could transport their knowledge and skills to a different environment. The staff of the Turbulence Research Laboratory at Chalmers has long cooperated with the special short course offered at regular intervals at the Energy Department of DTU, who in turn cooperate closely with Dantec Dynamics, a leading manufacturer of flow measuring equipment. Therefore it seemed that both objectives could be most easily met by extending our cooperation to include a 'finishing course' at DTU. As evidenced in part by the second author of this paper, the staff of DTU happily agreed and participated actively in the planning and instruction of the three day effort. Therefore at the end of the fourth quarter and before students began their thesis work, the Chalmers staff and students migrated *en masse* to DTU approximately 300 km away in Denmark. This truly international effort concluded with a hosted lunch and exhibition/demonstration at nearby Dantec Dynamics.

The students and staff assembled on the first evening for a brief introduction and an ice-breaker, and the formal instruction began on the following morning. This consisted of one morning of lectures, followed by three exercises using three different laser-based optical techniques for flow measurement: Laser Doppler Velocimetry, Particle Image Velocimetry and Planar Light Induced Fluorescense. In each exercise the students were presented with a working flow facility, and were then asked to setup the measurement equipment. Each exercise took four hours and was done in groups of 5-6 students with an instructor present during the full exercise. The exercises were thus a hands-on demonstration of the measurement systems, and were performed entirely by the students themselves under guidance. Each exercise consisted of several steps: planning of a measurement strategy, setup and alignment of optical systems, calibration, measurements to optimize instrument settings and measurement parameters, a measurement series on a selected flow phenomenon, processing and reduction of data and finally a short report on the results.

The exhibition at Dantec Dynamics was the perfect ending, and included a brief overview of many applications and evolving technologies. The entire effort was spectacularly successful, leaving students enthused to begin their thesis work, and staff satisfied and refreshed to see the results of their efforts.

6 SUMMARY AND CONCLUSIONS

An experimental course has been developed to introduce undergraduate students to modern experimental techniques and instrumentation used in fluid mechanics, and particularly in turbulence. The aim of the course is to teach students to design, plan, execute and report an experiment of scientific quality. They should also gain the ability to choose which tool is right for the specific problem at hand. An additional desired outcome is to enable them to evaluate the experiments of others, as well as to learn to use published data in a critical way.

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