ABSTRACT

Easy access to video imaging, digital frame grabbing and image processing technology has opened up exciting opportunities in fluid mechanics education. This paper presents several examples of student work, and discusses new curricula based on these new developments. Complex, unsteady flows can now be quantified using multi-dimensional techniques. Image sequences can be stored and used in problem-solving. The author extrapolates these experiences to the hypothesis that image-based curricula can revolutionize fluid dynamics education, and permit the undergraduate to become familiar with fluids engineering technology, exploiting unsteady flows.

INTRODUCTION

In the hectic environment of a modern engineering school, it is difficult to conduct laboratory experiments suitable for hands-on participation by large classes. Advances in computational capabilities have created the demand for (and the relatively easy solution of providing) increased attention to computational fluid dynamics. At the same time, the time available to teach fluid dynamics is compressed by demands for “broader” curricula, advances in other fields, and the pressure to reduce the total hours required for the first degree. The laboratory course is an easy candidate for cuts, as Shop classes were in the past. There are two undesirable results:

1) The typical undergraduate gets very little exposure to the beauty, variety, and realities of fluid dynamics, instead seeing a collection of smart techniques for solving differential equations “governing” steady, laminar, attached, single-component flows of perfect gases over streamlined shapes. Sometimes this occurs at the expense of physical insight, and of students who might otherwise become intuitive leaders in fluid dynamics.

2) Prevalent opinion holds that the future is all in CFD, and that hardware experiments, if done at all, are purely for “code validation”, with attention restricted to those phenomena which are already known and modeled in the codes.

The popularity of the CFD revolution is partly because it allows everyone to participate actively in studying flows. High-tech experimental facilities lack the open access and user-friendliness of the computer. This need not mean that their products should remain inaccessible: the video camera and the image processing board in a personal computer have opened the way for all of us to see, analyze, and explore ideas for modification of flow phenomena without ever going near a laser, by working with image sequences. The image sequences themselves may be acquired behind closed doors. This can help re-think and re-design our entire approach to fluid dynamics. Such a change is sorely needed. Except for computational methods, the content of undergraduate textbooks appears to be stuck where it was when today’s senior professors were undergraduates. Complacent that “the fundamentals remain the same”, we have perhaps allowed the frontiers to pass us by, and the gap between graduate research and undergraduate education to widen beyond leaping distance.

The experience of seeing and comprehending the realities of fluid flow is crucial to interest, innovation and problem-solving in flow analysis and flow control. Ideally, experiments must explore what is not computable or even suspected, and lead advances in fluid dynamics. Without the ability to do this, there is a clear danger that our graduates of tomorrow will be reduced to being mere operators of huge and complex “black box” computer codes, totally at the mercy of the admirable few who write such codes.

OBJECTIVES

This paper describes a tentative experiment to try to help this situation. We hope to:

a) bring the dynamics of flows into the curriculum and the problem-solving process using digital image processing,
b) enable flow-control experiments, and
c) enable students to try independent experimental projects.

These efforts aim to give the engineering graduate the comprehension, experience, and confidence to use advanced concepts and techniques in fluids engineering.

Why should our curricula improve?

Fluid mechanics has moved into an era where multi-dimensional, unsteady multiphase flows must be controlled for useful purposes. High-lift devices, artificial hearts, cryogenic turbines, fluidic cutting tools, fluid bearings, and techniques for drag reduction, noise cancellation, mixing enhancement, and vibration control are becoming common parts of engineering practice. The teacher at the undergraduate level faces an uphill task, if the starting
point for most fluid dynamics curricula still stays stuck at the steady, laminar, incompressible, single-phase, irrotational level. Very few real-life flow problems are solved using the Laplace equation. We must seek new ways to get the student more efficiently to the leading edge of technology while still mastering the theoretical discipline needed to become a versatile problem-solver and innovator. Chalkboard-textbook techniques are simply not enough.

The objectives of a curriculum revision are non-controversial: we all want to achieve vast improvements in 1) the percentage of what we teach that our students actually comprehend 2) the success rate of all of our students 3) their ability to apply what they learn to solve new engineering problems 4) our ability to carry our courses to the very edge of technology and a little beyond. Of course, these must be achieved with no increase in our workloads, and with an increase in our ability to work individually with each student. Whatever solution we attempt must fit within all of our current constraints.

The state-of-the-art

In the laboratory, detailed dynamics of flows can be captured, at least on a model scale, using visualization techniques. Pulsed or strobed lasers and fast-shutter video (the latter available on most home camcorders) can "freeze" practically any time scale of motion, and tomographic and holographic techniques enable 3-D quantitative imaging. The dynamics of vortex pairing, shear layer instability, acoustics-turbulence energy exchange, and flow-induced vibrations can be captured, quantified, and tailored. Flows can be made to do things that defy many of the "limits" taught in the steady-flow classroom (e.g., maximum lift coefficient, diffuser divergence angle). Digital feedback control offers the potential to carry these abilities much further, if only one can be sure of exactly what to control. With "smart materials", flows can be made to do what we want, on an instantaneous basis. Even with all these, we have just begun to get our toes wet: whole oceans of possibilities are opening up in fluids engineering.

THE PRESENT CURRICULUM

The undergraduate fluid dynamics curriculum at Georgia Tech's School of Aerospace Engineering begins with AE3003, which introduces potential flow theory and analyses, going on to the steady incompressible aerodynamics of airfoils and unswept finite wings. AE3004 covers compressible flows, enabling quasi-1-d analysis of nozzle flows, moving shocks, supersonic tunnel starting problems, flows with friction and heat addition, and going on to oblique shocks, Prandtl-Meyer expansions, and nozzle exit flows. AE3005 teaches analyses of viscous flows, concentrating on boundary layer approximations of the Navier-Stokes equations. AE4001 teaches linearized analyses of high-speed aerodynamics. Beyond the core, interested students choose from a range of advanced elective courses on computational fluid dynamics, combustion, hypersonics, viscous flow, and rotor aerodynamics.

The only laboratory course in the core curriculum is the 2-quarter-credit-hour AE3010, which serves many purposes. Groups of 3 to 5 students operate a series of eight experiments:
1. Force and moment measurement on a finite wing in a 42" square-section low-speed wind tunnel, with flap deflection, end-plate effects, and angle-of-attack variations included. The balance requires calculation of interactions between components, and a careful analysis of error bounds.
2a) A survey of the boundary layer of the wind tunnel and the wake of a full-span wing using a flattened Pitot probe, combined with measurements of the pressure distributions on the wing using a Scanivalve pressure switch and a Baratron transducer.
2(b) Visualization of flow patterns over a variety of shapes in a smoke tunnel, with provisions for rotating the models.
3. Hot-film anemometer survey of the wake of an airfoil in a 6" x 6" wind tunnel, where the students must calibrate the probe, decide on traverse resolution, and keep track of signal amplitude and amplifier and filter settings on the data acquisition system. Only mean and root-mean-square values are computed, going across the wake.
4. A survey of the turbulence profile across a round jet inside the 6" tunnel using a single-component, forward-scattering laser Doppler velocimeter. Histograms are used to compute mean and rms values.
5. An unsteady combustion experiment, where a Rijke-type vertical pulse combuster is used to demonstrate resonance phenomena involving acoustics and heat release, and phase relationships between pressure and flame radiation. (note: experiments 1 - 5 use a PC-based A/D converter and digital data acquisition system with menu-driven user interfaces)
6. A shock tube experiment, where transient shock properties are captured on Polaroid film using an oscilloscope and pressure sensors.
7. An indraft nozzle exhausting to a vacuum tank, where nozzle pressure distributions are measured using a bank of manometers and a pitot tube, and used to study shock locations.
8. A blow-down supersonic tunnel, where a schlieren system is used to visualize shocks and expansions.

The labs are run by two carefully-selected first-year graduate students, with minimal supervision needed from the instructors. Each experiment is accompanied by a set of questions whose answers must generally be found from the experiment. The reports on the experiments, which each student must write independently, introduce publication formats. The grading takes note of the rate of improvement of lab reports. At the end of the course, each student is assigned a hypothetical problem where a measurement solution must be designed to meet specified criteria. The problem may involve measuring anything from reaction kinetics in home heaters or supersonic combustors to flows
through roof-top ventilators or over swiveling advertising signs. The six-minute presentation followed by questions tests the student's preparation and thought. The results are often amazing, both in innovative spirit and in thoroughness. Obviously, some students find the workload, as in the other lab courses in Structures and Controls, disproportionate for a 2-credit course, and this is the topic of complaints on the anonymous course evaluations. On the positive side, student performance on this course is far above the average, and there is no indication that performance on other courses suffers as a result of the workload. In fact the demand for efficient completion of high-quality work pays off in their performance in later courses. Nine quarters of this exhilarating experience have convinced the author that the traditional courses, where our students sit quietly and copy down equations from the chalkboard to survive written tests, do not even begin to tap their true potential.

No doubt this can be argued to be a state-of-the-art curriculum. The fact remains that we have little time to let the students see the beauty and variety of unsteady fluid phenomena, and to learn how to control flow phenomena.

THE CONCEPT OF AN IMAGE-BASED CURRICULUM

Now let us imagine the following situation for a moment, from the student's perspective:

In the first course in fluid dynamics, the instructor calls up real sequences of flow images, both in isolation and in dynamic sequence, to explain concepts, assumptions, and approaches. Back in the dormitory, flow images can be brought up on computer screens using diskettes, with the sequence of images showing what the flow will really do. One can measure instantaneous velocity vectors, vorticity contours, vortex trajectories, and pressure distributions from the images. The homework assignments demand solution by going over the images carefully, observing, analyzing, and correlating facts with the theory learned in the classroom. Eventually one learns to figure out and use simplifying assumptions. As one moves deeper into the curriculum, the assignments become more complex, and require more analysis, engineering judgement, improvisation, and bold hypotheses.

Seeing and struggling with such images through several courses, the "average" student completes the core curriculum with the same (or better) level of experience of seeing flow behavior as the experts of today. The common misconceptions of today's graduates could be reduced, and the overall level of comprehension greatly improved. On the other hand, the theoretical analyses which must now be hammered into somnolent students on the "learn this now; you'll be glad you did later" basis, can be introduced as useful tools from the beginning, and fluid mechanics may no longer be feared as a subject which is all differential equations and not much fun.

Our experiment is to see how to implement such a curriculum. The clear intent is to increase the theoretical rigor and complexity, but to make this feasible and palatable using advanced tools. Once such a system is in place, the sequence of topics in the curriculum can be rearranged in many ways; several items which are now "indispensable" can be deleted to make room for new knowledge. The restricted, approximate, analysis techniques can be taught as what they are, not as the gospel of fluid dynamics. Alternative approaches can be explored. At the same time, the student's experience of seeing images generated using modern experimental techniques can increase interest in experimental work, and in methods for actively controlling flow phenomena. It will emphasize that fluid phenomena can be diagnosed, isolated, extracted, analyzed and controlled.

Previous Work

The NSF Workshop on Fluid Mechanics in Fall '86 emphasized the usability of Fluids technology and identified shortcomings in current curricula. The opportunity to design more integrated learning methods is being recognized. Beasley, Culkowski, and Gufner describe integration of laboratory, lecture, and office space, where students use full-scale equipment to quickly test out what they learn in the classroom. This recognizes the advantages of "learning on the job", a concept similar to what is advocated here. Lamancusa reports on a laboratory aimed at giving mechanical engineering students an integrated look at electronics and computer interfacing.

Alam, Bakos, and O'Leary explore the opportunities offered by new video and computer technology in designing an "Image Database", an "instructional picture database" for a pavement design class. They used PC-type computers, with an optical disk drive and image capture and video systems. They explored the requirements of storage, transmittal, retrieval, and usage. Van Valkenburg advocates "tutored video instruction" as the preferred mode of teaching of the future, as a superior alternative to large-group lectures. Again, the opportunities presented by the high-speed workstation as a semi-intelligent information source are recognized. Greenfield discusses the impact of new CD-ROM technology on Integrated Learning Systems.

Relation to Present Work

The curriculum discussed here uses technological capabilities similar to what is advocated by these educators. Here, the computer serves two purposes:

a) it enables comprehension of dynamic processes,
b) it enables precise analysis of dynamic features, and the extraction of desired information.

The learning enhancement comes from first-hand experience of working with actual fluid flows on the one hand, and by extensive use of modern diagnostic techniques on the other. The improved capability comes from an accelerated learning path, which makes students comfortable with fluid dynamics earlier, so that they can go on to experiment with flow phenomena.
control techniques with a solid theoretical and practical background. Improved comprehension comes from the opportunity for "iterative learning"; improved performance comes from the opportunity for continuous improvement.

A Model Laboratory for the Future Undergraduate Curriculum

The place of the planned Flow Imaging and Control Laboratory in the curriculum is shown in Fig. 1. The laboratory will first produce dynamic image sequences on selected flows. These will be used to create computer-based data sets accessible to the student. The core courses (AE3003-4-5, 4001) will use dynamic image sequences to illustrate such concepts as vortices, streamlines, rotational vs. irrotational flows, circulation, boundary layer transition, shear layer formation, mixing, and dissipation, and shock formation. Image sequences will be used in problem sets, along with user-friendly digital image analysis routines, to actually compute flow quantities. Velocity fields will be calculated from image pairs, as will circulation, vorticity contours, shear, and dilatation. Lift coefficients will be calculated directly from these, and compared with theoretical and measured values. The detailed starting process of a supersonic wind tunnel will be studied, revealing the mysteries of the "starting problem", "shock reflections", and the relation of shock angle to Mach number. The starting of a jet and a pipe flow will be examined, and the detailed structure of a supersonic jet will be seen. The added physical insight will reduce the incidence of common theoretical misconceptions, and, hopefully, light up the student's curiosity and imagination.

The laboratory will be organized around the strengths of the present undergraduate fluid dynamics laboratory. The new ingredient will be the flow visualization, the addition of experiments on unsteady flow processes, the image acquisition, and the image analysis capabilities.

To the student who comes out of these courses, laser-based flow visualization and digital image processing will already have become "common practice", just as word processors and spreadsheets are now. The junior lab, AE3010, will give the student broad experience in actually conducting such experiments. A few of these students will take AE4010, the Advanced Diagnostics course, where advanced techniques will be taught with much greater rigor, and more challenging experiments will be attempted.

In AE4011, the Flow Control Elective, the projects will challenge the students to achieve desired objectives using tools such as acoustic excitation, mechanical flaps, edge modification, and surface tripping. The diagnostic techniques from AE3010 and 4010, combined with the theory of the other courses, will be integrated here to do what the engineer enjoys most: learn to control and improve useful devices and processes. A precious few will take up AE4900 Special Problems for independent research. The cycle is completed when the best experimentally-observed images are compiled and converted to demonstrations and problem-sets for the core courses. This is the mechanism for constantly advancing the curriculum. In brief, AE3010 will show students the beauty and complexity of fluid dynamics, as well as the bases for analytical methods. AE4010 will teach diagnostic techniques, and AE4011 will teach what is known about flow control. All courses will insist on careful observation, and use the question "why?" to demand careful interpretation. AE4010 and 4011 will teach "how". AE4900 will teach exploration of the unknown using tested facts, complemented by analytical and extrapolative reasoning.

New Features

What is new is that the student will learn by working with actual flow problems throughout the curriculum. The image sequences will try to tell the student "what will the flow really do" while posing questions that take intense analytical reasoning, justified by numerical results. (Can you assume that this is steady? Is that a vortex forming? How strong is it? Is this flow approximately irrotational? Let's try looking at vorticity contours. How turbulent is this flow? Is there substantial momentum transfer across the dominant flow direction? Is that shock steady? If not, why not? ) Secondly, they will get used to applying numerical techniques from the beginning (image analysis must use finite differences, interpolation, and numerical integration), so that the CFD teacher can teach more. Thirdly, the student can take home the "correct answer" in the form of flow images on diskettes, and try out a variety of solution approaches. Finally, these techniques allow for iterative learning, where one gets to improve one's comprehension of the subject matter through several cycles with no penalty for imaginative attempts. These are the ingredients needed for fast learning and development.

Progress To-date

Over the past seven years, we have observed the progress of over 25 Undergraduate Special Problem projects at the Aerodynamics research laboratories. These students have, over periods of one to two quarters, when they were typically taking 3 other courses, become valuable members of research teams, adept at flow visualization techniques. Their insight into fluid dynamics increased dramatically, as did their grades in subsequent courses.

Over the past three years, as planning for the new experiment has become more focused, several projects have served as test cases (Refs. 7-11). Recent studies of vortex flow over aircraft at high angles of attack, a rotor wake in forward flight, and vortex shedding from objects of complex shape have all used digital processing of flow images to extract quantitative information. Additional data points are the "independent proposal" presentations at the end of the AE3010 lab course each quarter: these have been real eye-openers on what the junior-level student can do.
Proof-of-Concept, 1990-91

In 1990-91, two junior-level students were recruited into research projects, to work on image-related problems. One became the vortex trajectory expert on a NASA Grant studying unsteady vortex flow over an aircraft at high angles of attack. The other researched, designed, and analyzed the image data from a continuing industry-sponsored project on vortex shedding from complex-shaped objects, correlating image-measured shedding frequencies and flow structures with hot-wire spectral results. We have been through the mechanics of acquiring, storing, transferring, analyzing, and reporting on the images. Neither student had taken any course on the various problems encountered, but over the course of a quarter, with little formal lecturing, each became superbly competent at his work, and in the process learned a great deal about everything else that was being done in the research labs. Each of these junior-level student projects resulted in a very significant improvement in our capabilities at the John Harper wind tunnel.

Implementation Plan: Video-Based Image Analysis

The key is the easy availability of accurate video camcorders, inexpensive frame grabbers and digitizing boards for personal computers, and the advent of the 1.44MB diskette, which permits storage of several 8-bit digitized images. These permit capture of flow images acquired in the "inaccessible" research laboratories for convenient analysis on small computers, and for wide dissemination. We are putting together a "library" of video image sequences. Samples from such a sequence are shown in Fig. 2. The development of the wake of an oscillating airfoil is shown, along with a wide-angle view of the wake. The double exposure apparent in the image is an artifact of the digitizing, and allows the odd and even video lines from two consecutive frames to be separated using a computer program. This is just an easy way to grab two consecutive frames. Another similar sequence has been acquired on natural vortex shedding from a cylinder, where the Strouhal frequency can be easily calculated from the images. Other images are discussed later in the paper.

Examples of Image Sequences and Analyses

The range of possibilities is unlimited. Here some examples are given, based on recent work at the author's laboratories.

Vortex Flow Over an Aircraft Model

Figure 3 shows the asymmetric vortex flow over a generic wing-body model, caused by forebody instability. This frame is from a sequence of vortex flow patterns recorded as the model moved slowly through the laser light sheet. The asymmetry was traced to the nose and solved by passive geometric correction. Vortex trajectories then digitized from the symmetric-flow videotape are shown in Fig. 4. Recently, Griffis has attempted to correlate the ensemble-averaged, digitized image intensity distribution from the seeding pattern with the velocity field, and has obtained some preliminary success.

Wide-Field Shadowgraphy

Griffis obtained wide-field shadowgraph images, frozen with 25-nanosecond resolution with a copper vapor laser, documenting the density gradients in the wake of a helicopter rotor. In the actual experiment, the research challenge was to stretch the technique to low Mach numbers, and some success was obtained even with rotor tip Mach numbers as low as 0.28. Later experiments were conducted with a hair dryer with much better success. This is a simple experiment to conduct and record, as long as there is a density gradient to observe. Future challenges will be in extracting actual density fields from the gradient images using image processing algorithms.

Karman Vortex Street

Griffis used images of a vortex street downstream of a round pipe, illuminated with a copper vapor laser sheet. He then compared frequencies computed two ways: first directly from the images, assuming that the vortex convection speed was the same as the freestream speed, and then by direct measurement of the spectral peak using time-series analysis of a hot-film anemometer signal. The difference provided a good means of calculating the convection speed of vortex centers, while seeing what causes the spectral peaks. This project led the student to investigate differences in shedding characteristics between objects of various shapes, as part of an industry-sponsored project.

The Roll-up of the Edge of a Vortex Sheet

Figure 5 (Ref. 13) shows the edge of the wake of a helicopter rotor, where the tip vortex core trajectory is seen to be modified by the roll-up of the inboard vortex sheet into a discrete structure. The associated phase-resolved velocity field is also shown, with the opposite signs of vorticity of the two structures evident.

Vortex-Induced Flow Separation

Figure 6 (Ref. 14) shows a newly-discovered result: when the vortices from a helicopter rotor interact with the flow over a wing at moderate angle of attack, massive flow separation results. This can be easily explained once one sees it happening, but shows the very large difference between what one would compute from "uniform downflow" rotor wake models, and reality. Again, sequences showing different phases of the interaction are on videotape, correlated with time indices.

Analysis Techniques

As seen from the vortex tracking problems and the intensity correlation problems above, digital image analysis is an active and growing capability. These are performed on the Macintosh II computers in the School's computer labs, or on 80486-33MHz computers in the wind tunnel control room. As such, they are commonly-available and
inexpensive capabilities. Other examples of analyses are given below:

**Starting of a Supersonic Tunnel**

Figure 7 shows two frames from a sequence taken during the starting of our blowdown supersonic tunnel. A color schlieren system was used. As a preliminary example of quantitative analysis, we attempted to get instantaneous Mach number at various points using the local inclination of weak disturbances. The images during starting have several zones of supersonic and subsonic flows, and as usual with such problems, we quickly found ourselves wondering about the several features which were observed.

**Velocity Extraction from Video Images**

Our recently-developed capability to perform Spatial Correlation Velocimetry (SCV) has opened new doors in quantifying flow images. We are now able to extract two components of the instantaneous velocity vector at several points in a plane using two consecutive video images (or even by odd-even decomposition of a dual-exposed video frame). Examples are discussed below.

**Stalled Airfoil in a Water Table**

Figure 8(a) shows the pattern created by chalk dust sprinkled on the surface of water flowing around a small plexiglass model of an airfoil in our undergraduate laboratory. Fig. 8 (b) shows the velocity vectors computed from these video images using a 16-MHz Macintosh II. Similar results are easily obtained for flows around cylinders and other objects, with a sequence of such plots showing unsteady phenomena.

**Plunging Wing and Wing-Canard Interaction**

Figure 9 shows samples from a video animation of velocity fields measured when an NACA0012 wing executed large-amplitude, arbitrary plunging motion in our large wind tunnel. In this case, the experiment required powerful large-amplitude, arbitrary plunging motion in our large wind velocity fields measured when an NACA0012 wing executed plunging motion and other objects, with a sequence of such plots showing unsteady phenomena.

**Cloud Motion**

A final example of such velocity measurement and flow analysis is the recent work of Goodson, who used the video camera and computer to study the motion of clouds on a warm Spring day. Again, this was part of an undergraduate Special Problem project, and required no lasers or wind tunnels to observe unsteady fluid mechanics on a grand scale.

As mentioned at the beginning of this section, there are no limits to the possibilities opened up by the video camera, with its 30Hz time resolution, freeze-frame options, and a computer with a digitizing board. Recent developments such as liquid crystal stress diagnostics and pressure-sensitive paints open up other possibilities similar to the velocity field measurement shown above. On a much simpler scale, a determined experimenter with quick reflexes and a sure hand can capture the detailed unsteady aerodynamics and vehicle dynamics of a bird or insect in maneuvering flight, and perform very quantitative analyses. The author recently had occasion to dissuade a young high-school scientist from her plans to stick pins into live butterflies in order to observe and revolutionize wing design: a butterfly in free flight would provide a much more useful test case, with the data capture being accomplished using a videocamera instead of less benign means. The results are awaited.

**SUMMARY**

The examples presented above are meant to trigger new thinking. The video camcorder, digitizing board and personal computer have opened up vast possibilities in capturing, transferring, and analyzing detailed bases of information on the dynamics of fluid flow. It is up to us to see how we can use these capabilities to revolutionize the teaching, learning, and application of fluid dynamics. The curriculum plan presented in this paper is one author's view of how to start within the constraints of the present curriculum, and still be able to make a large improvement.

**A closing note**

Towards the end of June 1992, the National Science Foundation has informed the author that the plans outlined in this paper have been funded for implementation starting this year. This places great urgency on these plans, and provides a unique opportunity for experimentation. Suggestions and comments are invited from the interested reader: a prime objective of the NSF project is to ensure the widest communication, discussion, application, and associated improvement of these ideas.

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**REFERENCES**