2006-26: LIFE IN MOVING FLUIDS: INTRODUCING CLASSICAL FLUID MECHANICS INTO BIOENGINEERING

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Life in Moving Fluids: Integrating Classical Fluid Mechanics into an Undergraduate Bioengineering Program

Abstract

A new course that seeks to link classical fluid dynamics with living systems has been developed and offered as part of the bioengineering program. A fully integrative approach was taken throughout the semester with the focus remaining fixed upon the impact that fluid dynamics has on life and living systems. A wide range of activities are integrated into the course with the most non-traditional being a compassion practicum and the creation of a visual art project.

Key words: fluid dynamics, living systems, and integrative schema

Introduction

Advances in the fields of biology, mathematics and physics have resulted in the development of a new field of engineering, commonly referred to as bioengineering. This field encompasses the areas of biological, physiological, medical, and social systems as well as other fields in which the design, development or modification of complex, knowledge-intensive systems is a requirement. Bioengineering is similar to traditional fields of engineering in that all engineering programs educate individuals in the art of product and process development for the improvement of human health and quality of life. However, bioengineering is unique because of the need to understand the emergent properties of living systems. Living systems, unlike most man-made products and processes, are composed of large numbers of "self-replicating" components, which undergo "self-organization." These features provide living systems with most of their fascinating and complex properties and are the primary focus of bioengineering studies.

The goal of the undergraduate bioengineering program at Binghamton is to provide students with the opportunity to develop an understanding of how emergent properties arise in living (i.e., complex) systems and, therefore, how the properties of living and biomimetic systems can be regulated and modified. The course, Life in Moving Fluids, focuses upon bridging the gap between classical fluid dynamics and biology/zoology. Concepts such as, for example, inviscid flow, boundary layer theory, vortex dynamics, and dynamic similarity are used to explore the relationship between fluid flow and biological design. The two most important fluids in the study of life on Earth are air and water. Thus, the course explores not only their physical characteristics but also how the physics of air and water have influenced and constrained biology. The course is offered as a technical elective in the newly formed bioengineering program at the State University of New York at Binghamton.

Upon completion of the course, students are expected to be able to:

- Describe the differences in physical characteristics between air and water and how those differences impact life.

- Use classical deterministic tools to describe the motion of air and water n living systems.
- Describe the importance of spatial and temporal scales and scaling.
- Describe the physical characteristics and the importance of vortex rings and vortex dynamics.
- Describe the differences between laminar and turbulent flows and the impact of those differences on living systems.
- Develop modeling ability in classical fluid dynamics as well as in living systems.
- Use Mathematica to solve complicated deterministic equations as well as for developing simulations.
- Develop approaches suitable for solving open-ended problems using an engineering design methodology.
- Develop an appreciation for the impact of engineering and technology on the health of the Earth's ecosystem.

Student Population

Students in the bioengineering program at Binghamton have a very different background in mechanics as compared to students in mechanical, chemical or aerospace engineering. Students are not required to take the traditional statics and dynamics series of courses nor are they required to take foundational courses in either continuum mechanics or thermodynamics. The challenge then becomes to develop and teach a course which focuses on some of the important aspects of classical fluid mechanics particularly in their effects upon living systems and to present the material in such a way that is rigorous yet accessible. Also, and equally as important, the course should serve as a catalyst to encourage further future study by the students in related subjects. As Binghamton is a relatively small engineering school, it was also important to offer the course as a possible technical elective for students who major in mechanical engineering and have had the traditional prerequisites for classical fluid mechanics.

The course was first offered in the spring semester, 2005. The total student population equaled 38 with 21 bioengineering majors and 17 mechanical engineering majors. The incoming cumulative grade point averages of both sets of students were approximately the same (2.86/4.00 vs. 2.88/4.00).

Approach

The approach taken in this first offering of the course was integrative in structure and included as well current movie titles to generate in-class discussions and follow-up critical review essays. A mind-map of the course topics and activities is presented in Figure 1.

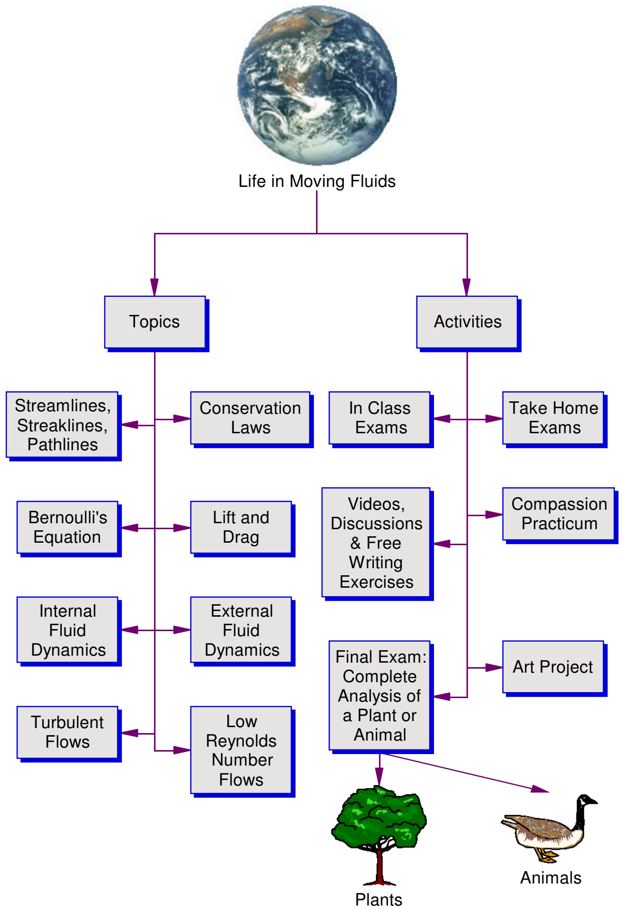

Figure 1. Mind-map of Topics and Activities

At the outset, students were challenged to look at the kinds of fluid phenomena in the two most common fluids for living systems here on Earth: air and water. They were given copies of photographs taken of sugar maple forests during the early fall season and of Monet's famous painting, "Water Lilies." The students were asked to keep the following questions in their minds throughout the semester:

- Why are there so many more small leaves on the sugar maple trees as compared to water lilies?
- Why do tree trunks branch most often into two separate branches, rather than three or more?

These questions were returned to again and again throughout the semester and merit some further explanation. The question of the size of leaves on plants in the air versus those in water point to issues related to both external and internal fluid mechanics. Considering the external flow field, questions related to behavior, growth alterations in response to drag as well as changing shape link the fluid principles directly with the behavior of living systems. Secondly, considering the internal flow, the focus becomes the circulatory and respiratory systems. The tree trunks branching question served as a springboard for study of the first and second laws of classical thermodynamics in that the analysis revolves ultimately on the issue of calculating the minimum energy required to pump the required oxygen.

Two primary texts were used which served to introduce the various topics and make the necessary connections to living systems.[1-2] Once the importance and relevance were established, the necessary mathematical foundations for many of the equations simply stated in the texts were explored and developed. This approach was taken for a range of different topics involved in mass, heat and momentum transport. The following examples will hopefully add clarity to the instructional format used.

Both texts described a series of useful equations with minimal derivation for flows in circular and non-circular pipes. After introducing the equations, students were guided through a careful development of the appropriate Navier-Stokes equations, necessary simplifications and assumptions and resulting solutions for the laminar flow case. The discussion of pipe flow also served as a jumping off point for discussions of fully developed flow fields and, thus, to the generation of momentum and thermal boundary layers along the walls of the pipe or channel. Once again, students were carefully guided through the development of boundary layer equations using both the differential and integral formulation. Boundary layer analysis allowed the class to consider the physical situations and adaptations of a vast multitude of organisms, specifically *craspedophilic* creatures or those typically found at the interface between plants and animals. In addition, with an understanding of velocity gradients, we could then focus on settling phenomena for example of spores in the atmosphere as well as suspension feeding by some swimming fish, tadpoles and whales.

The study of flows in pipes the served as a starting point for an introduction to dimensional analysis and order of magnitude analysis as well as turbulent fluid dynamics. This was accomplished through identification and discussion of the importance of the Reynolds number. After the introduction of the Reynolds number was made, the focus was then turned to dimensional analysis and the Buckingham Pi Theorem as a means to develop important dimensionless groupings of parameters. A wide range of such groupings was then developed from pressure, drag and lift coefficients to Nusselt and Grasshoff numbers. The dimensional analysis linked easily to heat transfer phenomena including conduction, convection and radiation.

Subsequent to the discussion of the various parameters, attention was then focused on turbulent flows both from a conceptual perspective but also from a more mathematical foundation as the velocity decomposition was introduced which led to the Reynolds' equation and its attendant closure problem. Various schemas used to solve turbulent flow problems were discussed including Reynolds stress models, large eddy simulations and vorticity transport models. The study of turbulent flow allowed the class to focus its attention on the importance of vortical structures in nature including the often occurring three dimensional characteristic of the vortex structure, the affects on the diffusion of passive contaminants and the dissipation of kinetic energy.

A mind-map that outlines the approach taken in this course for this one topic, pipe flows, is shown in Figure 2. Similar approaches were taken with other important topics including lifting living bodies, gliding and soaring as well as the thrust of flying and swimming.

Interspersed with the technical content, a series of videos were introduced including the PBS "Origins" series,[3] and "Winged Migration."[4] "Origins" served as a starting point for discussing the differences between our most common life supporting fluids, air and water and also a discussion of the origins of both. The modern theory of the origin of water (i.e. transported in the form of ice by comets) proved to be most energetic. "Winged Migration" brought the importance of external aerodynamics and the persistence and stubbornness of life to the forefront of awareness. After each video presentation, the class was then asked to reflect on what they had seen in a free writing format.

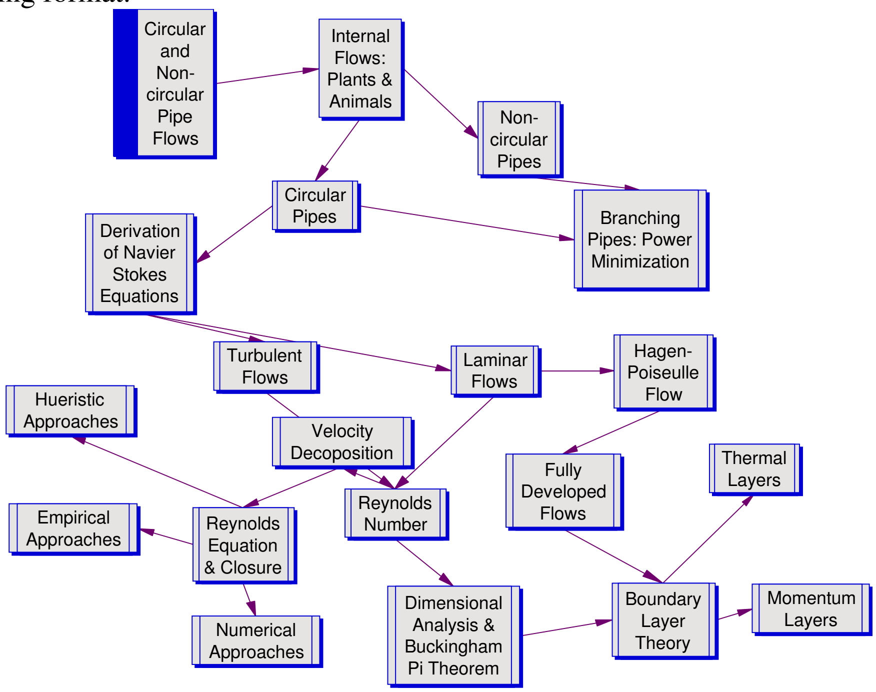

Figure 2: Integrated Approach Used in Course: Circular and Non-circular Pipe Flows

Compassion Practicum: Making Peace with the Earth

A practicum is defined in the dictionary as "the part of the course that deals with practical work." A Compassion Practicum then is a practical work that demonstrates a willingness to promote compassion and peace and to act on one's intentions. Action is the key word. As part of this course, students are required to do something tangible and meaningful for the Earth, which demonstrates commitment to promoting and/or restoring the health of the planet. Students must follow a formal design methodology, which is described in course. At the completion of chosen action, students submit a 300-word reflective essay on the entire experience. A partial list of some of the action taken is provided:

- Organized recycling efforts in college dormitories
- Organized recycling efforts in various apartment complexes
- Binghamton University Nature Sanctuary clean-up
- Organized leaflet distributions highlighting various issues
- Organized letter writing campaigns to protest various issues

The compassion practicum was linked to the final two course learning objectives: (1) develop an ability to solve open-ended problems using a design methodology; and (2) develop an understanding of the impact engineering and technology have on the health of the Earth.

Art Project

One of the assigned texts for this course is the Gallery of Fluid Motion.[5] As a graduate student, I was first drawn to the study of fluid dynamics, particularly turbulence, because of its incredible elegance and beauty. As part of this course, students are challenged to produce their own unique and creative work of art that demonstrates their understanding of and appreciation for the fluid dynamics of Nature. Students may choose any visual art medium. In addition, a 300-word essay describing the creative work is required. A partial list of some of the works of art is provided:

- Multiple photographic collages of turbulence and vortex rings
- Real time flow visualization experiments
- Videos of birds in flight, swimming porpoises, aircraft in flight, and ocean/beach interactions
- Pencil, ink and acrylic paintings

Student Performance and Reactions

Statistical analysis of the results from the two different sets of students is presented in Table 1. The results suggest that the lack of exposure to traditional prerequisites in fluid mechanics, namely statics and dynamics, continuum mechanics and thermodynamics did not put the bioengineering students at a significant disadvantage. Their scores were slightly lower overall with slightly greater standard deviation and skewness values. Here the mean, standard deviation and skewness all are calculated include data for all exams. It should also be added that the mechanical engineering students all had taken their discipline-specific fluid mechanics course and were seniors. The bioengineering students were all at the junior level.

Engineering Major	Number of Students	Final Mean (%)	Final Standard Deviation	Final Skewness
Bioengineering	21	84.5	6.87	-0.1
Mechanical Engineering	17	87.2	5.20	-.01

Table 1. Overall Performance of Students: Bioengineering vs. Mechanical Engineering

The reactions of students are assessed through exit interviews and university wide student evaluation forms. Summaries of the results from the student evaluations are shown in Table 2. The maximum score is 4.0/4.0. These results are above the average response for the bioengineering program and the engineering school during that particular semester and thus are considered to be an indication that the course was relatively well received by the students. Exit interviews confirmed this positive overall response. Students were more enthusiastic of the compassion practicum than any other activity in the course while they were least enthusiastic of the art project. It is useful to discuss what is meant by the various terms used in Table 2. Course satisfaction refers to how satisfied students felt with the course, that is, did the course meet or exceed their expectations? In addition, students herein are asked to judge whether or not they can actually do at the end of the course what the syllabus indicated they would be able to do. Technique effectiveness asked student to judge how effective the instructor was in communicating the information in a meaningful way as well as how well the instructor kept the student's interest. Overall effectiveness includes a range of different parameters including the course objectives, the learning environment established within the classroom, the generated excitement for the course material and the desire to continue study in this academic area.

Engineering Major	Number of Students	Course Satisfaction	Technique Effectiveness	Overall Effectiveness
Bioengineering	21	3.25	3.55	3.35
Mechanical Engineering	17	3.35	3.65	3.55

Table 2. Overall Performance of Students: Bioengineering vs. Mechanical Engineering

Final Thoughts

The first offering of the present course has been judged a success by the bioengineering program and will be offered in subsequent years. During its next scheduled offering, a more liberative pedagogy will be utilized in an effort to increase to an even great extent student ownership of the education process. Liberative pedagogy, first formally developed by Freire, forces students to make decisions not only about course content and direction but also the manner of assessing their particular learning.[6]

The course has a rather unique status in the engineering school at Binghamton. Its place as a suitable technical elective for non-bioengineering majors has vacillated back and forth. This seems more a function of concerns over academic "turf" among other departments than concerns over the course's actual technical content. At the present time, the course is once again being reviewed for technical elective status for all engineering disciplines offered at Binghamton.

References:

1. Vogel, Steven, Life in Moving Fluids: The Physical Biology of Flow, Princeton University Press: Princeton, New Jersey, 1994.
2. Denny, Mark, Air and Water, Princeton University Press: Princeton, New Jersey, 1995.
3. Samimy, M., A Gallery of Fluid Motion, Cambridge University Press: Cambridge, Ma., 2004.
4. Winged Migration, SONY Pictures, 2005.
5. Origins, WGBH PBS Boston, 2004.
6. Freire, Paolo, Pedagogy of the Oppressed, Continuum International Publishing Group: New York, 30th Anniversary edition, 2000.