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HOW IS FLUID MECHANICS TAUGHT TO BIOLOGISTS?

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ABSTRACT

An understanding of fluid mechanical concepts is important for a variety of biological areas from biological oceanography to locomotion (swimming and flight) to cardiovascular physiology to diffusion within cells and across cell membranes. While graduate students in biomechanical areas are usually encouraged to take courses within engineering schools, the interests of undergraduate biology majors are often best served by courses in physical biology taught within biology departments. These physical biology courses not only cover fluid mechanical topics in a biological context, but cover that subset of fluid mechanical topics of most immediate biological relevance at a level of mathematical, physical, and chemical background normally attained by biology majors. An example of a laboratory exercise in insect dispersal/drag using a terminal velocity assay is briefly discussed.

INTRODUCTION

Biology curricula do not always contain courses in general biological fluid mechanics, although there are probably a greater number and diversity of such courses than is known by some members of the engineering faculty. For example, departments of oceanography or biomedical engineering will usually have courses in biological fluid mechanics, although these particular cases are likely to cover completely different topics (e.g. wave mechanics vs. non-Newtonian flow). Undergraduate biology students are usually required to take physics rather than engineering courses as part of their physical science instruction. These introductory physics classes may cover hydrostatics but will rarely cover moving fluids of any sort. Thus, the typical biology undergraduate may have had more exposure to special relativity than to fluid mechanics and is not well-positioned to understand or develop an interest in fluid mechanics.

A course in fluid mechanics appropriate for biologists should not be thought of as simply a “watered-down” treatment of the same material given to engineering students, but as a qualitatively different course. This is perhaps best explained by a counter-example. Imagine an aerospace engineering student interested in learning something about animal flight. That enthusiasm would be considerably diminished if the student was advised that in order to properly understand animal flight, one should first spend years studying physiology, behavior, evolutionary mechanisms, and population genetics to develop a better understanding for force production by the muscles, skeletal mechanics (implications of external vs. internal skeletons), fuel availability and type (running on sugars vs. fats, mechanics of circulatory and respiratory systems), historical design constraints (imposed by evolutionary history), non-aerodynamic factors (such as appearing attractive to the opposite sex), and natural variation. An analogous situation is encountered by biology students taking engineering courses; much of the more biologically-relevant fluid mechanics is taught in the more advanced classes with many prerequisites. This is why topics in biological fluid mechanics may often be more successfully taught in a biology department for a biological audience.

Much of what is written here reflects the bias of my own training and teaching experiences, which are from the perspective of general comparative (non-medical) biomechanics. Courses I have taught include a general undergraduate course in comparative biomechanics, an advanced seminar in animal flight (team-taught with my colleague Dr. David Alexander), and an advanced seminar in insect morphology (also team-taught).

WHY SHOULD A BIOLOGY STUDENT BE INTRODUCED TO FLUID MECHANICS?

Organisms are filled with fluid compartments and are surrounded by fluids (air or water). Thus, the way in which an organism can move, obtain nutrients, exchange heat, and sense information about its environment are all affected by fluid mechanical properties and behavior; knowing something about these properties will help a student to understand the functional design of organisms and how this affects where and how they can live (the biological subdisciplines of physiology and ecology). In addition, students of the biological subdisciplines of cellular and molecular biology rely heavily on separation techniques such as centrifugation and electrophoresis, and would benefit greatly from understanding the physical phenomena underlying these techniques (e.g. material found in Probstein, 1989).

DIFFERENCES BETWEEN FLUID MECHANICS COURSES TAUGHT IN BIOLOGY DEPARTMENTS AND ENGINEERING DEPARTMENTS

Biologists often find it particularly helpful to teach solid and fluid mechanics together. This is because of the scarcity of “rigid” body parts that form the usual physical boundaries in introductory fluid mechanical problems. The material properties of the biological organism or its parts will often have a significant effect on the fluid flow. Biological organisms or their parts can be squishy and stretchy and slimy; biological materials are often highly heterogeneous and may have time-dependent material properties (Wainwright et al. 1976; Vincent, 1990). The sorts of conditions that are common in biological systems are in fact not usually covered until more advanced courses in the engineering curriculum. For example, biological fluid mechanics can be unsteady and non-Newtonian with fluid-solid interactions. An undergraduate biology major taking an introductory course in fluid mechanics is unlikely to encounter much information that will relate directly to the biological systems of interest to that student. For these reasons, biologists often find it more useful to teach the undergraduate biology majors fluid mechanical topics in a biological mechanics course within the biology department rather than encouraging students to pursue courses through the usual engineering curriculum. In contrast, graduate students pursing advanced degrees in biological fluid mechanics are often encouraged to take the appropriate engineering course sequences (whether offered within aerospace, chemical or mechanical engineering departments).

Biological systems are typically more complex in geometry than engineering problems, particularly those for which analytical or numerical solutions are available (Figure 1). Thus a biologist is often at a loss as to how to apply an engineering equation when a measurement such as surface area can be problematic to estimate. This is one of the reasons why the level of mathematical treatment is often at a simpler level for a biological audience. A student who laboriously struggles to understand the Navier-Stokes equations feels cheated when the equations are not directly useful and do not promote understanding. In fact, memorizing some equations can lead to a false sense of understanding. Along these lines, Cussler (1997) suggests that the simplicity of the math describing steady-state diffusion across thin membranes may actually inhibit a true understanding and appreciation for this process (p. 18). In the context of biological fluid mechanics an appreciation for the physics is more important than an appreciation for the math. A biologist will usually have had calculus, and possibly more statistics than engineering students, but will be less familiar with manipulations involving complex numbers, Bessel functions, or Fourier transforms. This is why many of the biological fluid mechanics texts (Denny, 1988; Denny, 1993; Vogel, 1994) are written at a mathematical level that many engineers feel is limiting or too simple for engineering students (Schetz and Diplas, 1998). It should be noted that there are mathematically more advanced treatments in many aspects of biological fluid mechanics (e.g. Cheer and van Dam, 1993; Ellington and Pedley, 1995; Fung, 1997). This difference in mathematical background or expectations makes team-teaching for students from biology and engineering more difficult.

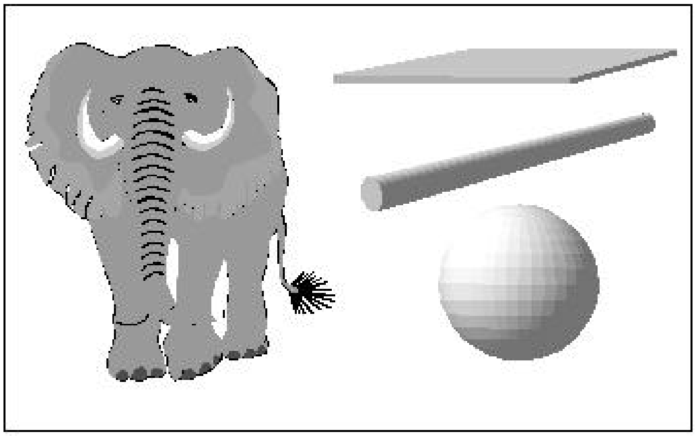

Figure 1. Biological structures (example on left) are usually more complex in geometry than boundary conditions in engineering problems (examples on right).

There is also a difference in the topics of direct interest to biologists. For example, obvious topics of less interest to biologists would include supersonic flow and rarified gas dynamics (but see Pickard, 1974). Topics of special interest to biologists are unsteady flow, oscillating flow, fluid-solid interactions, and low *Re* flow. Topics of probably equal importance to biologists and engineers include dimensionless numbers, Hagen-Poiseuille flow, drag, pressure, diffusion, and heat and mass transfer. The techniques that particularly enhance learning are likely to be similar for biology and engineering students: physical modeling, flow visualization, and computer simulations.

WHY WOULD AN ENGINEER CARE ABOUT BIOLOGICAL COURSES IN FLUID MECHANICS?

Biological systems provide instructive examples or counter-examples for engineering students (Gordon, 1978; Alexander, 1983; McMahon and Bonner, 1983; Fletcher, 1992; Pennycuick, 1992; Berg, 1993). This may be particularly true for engineering areas converging on aspects of biological design such as building small flying machines. The extent to which “biological inspiration” has truly been influential in human engineering efforts has recently been scrutinized by Vogel (1998), who demonstrated that the actual number of documented cases of technological transfer from the natural world is fairly small. This is not to suggest that biological systems are not relevant or interesting, but simply that the constraints influencing biological functional design are rather different from those operating in human technology. A general acknowledgment of the value of cross-talk between disciplines is demonstrated by initiatives in interdisciplinary training such as the National Science Foundation’s Integrative Graduate Education and Resarch Training (IGERT) award.

Biologists tend to borrow heavily from techniques developed by engineers, and are therefore less likely to be able to provide novel fluid mechanical techniques for use by engineers. However, because biologists have different needs (such as more stringent requirements for non-toxic fluids compatible with living organisms), they may be sources for permutations on established techniques, such as the use of fluids different from those commonly used in engineering circles, e.g., dextran solutions for swimming microorganisms (Sleigh, 1962; Podolsky, 1994), Karo® syrup for physical modeling (Loudon et al. 1994), or whole milk for analysis of wave propagation (Denny and Loudon unpublished).

I conclude with an example of a laboratory exercise that has been helpful in teaching biology students some fluid mechanical concepts in a biological context.

EXAMPLE OF A FLUID MECHANICAL LABORATORY EXERCISE FOR BIOLOGISTS: TERMINAL VELOCITY ASSAYS FOR INSECT DISPERSAL AND DRAG ESTIMATES

The fluid mechanical concepts that may be emphasized in this exercise are : parachute design, drag, force balance, center of drag vs. center of gravity, stability, scaling factors, orientation of small objects, dimensional analysis, buoyancy, estimation of velocity, and propagation of error.

One laboratory exercise that I have had biology graduate and undergraduate students do is to determine the terminal velocity of insects or their component parts under a variety of conditions. The biological context has ranged from insect dispersal to drag on objects of complex geometry (such as highly branched insect antennae) that are difficult to estimate otherwise.

The basic idea is very simple: the object is dropped in a convenient fluid (air, water, ethanol, glycerol) and its terminal velocity measured. Once the object has reached terminal velocity, the net force on the object is zero and therefore the gravitational force, buoyancy and drag will all sum to zero (Figure 2). The gravitational force is estimated from weighing the object. The buoyancy may or may not be appreciable in a particular context and that can be an informative force for the student to estimate. In order to estimate the buoyancy the volume (or the density and mass) of the object must be known. For biological objects with densities somewhere between pure water and glycerol, the density can be estimated accurately by placing the object in a beaker of water and changing the density (e.g. by adding glycerol) until the object becomes neutrally buoyant. Naturally one must perform the appropriate controls to ensure that the density of the object has not been changing by immersing it in those fluids.

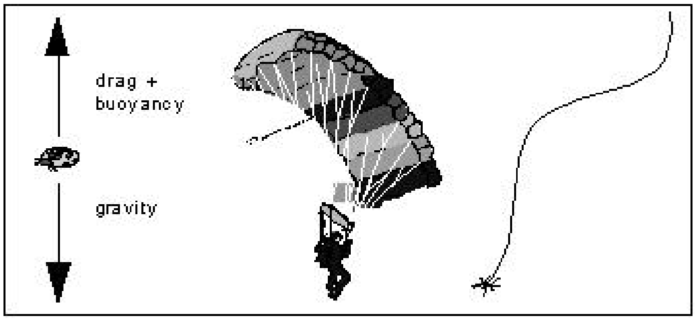

Figure 2. When a falling object reaches terminal velocity, the forces will cancel and the drag may be calculated from the forces due to gravity and buoyancy (left). Effective parachute design is size dependent (center and right); many small arthropods (right) use single filaments of silk when they “balloon.”

Methods of determining terminal velocity

The most simple and least expensive way to estimate terminal velocity can be done using a stopwatch to time how long it takes the object to fall a series of known distances. From the time interval between release and impact, and the total distance traversed, one can estimate the average velocity during the fall (an unknown fraction of which is traversed at terminal velocity). If this average velocity so estimated is plotted as a function of increasing falling distance, the curve will asymptotically approach the magnitude of the terminal velocity. Naturally the accuracy of such methods depending on the speed of the fall (reaction times of students using stopwatches is typically on the order of a few tenths of a second). I have found that teams of students in a stairwell with stopwatches can make surprisingly accurate determinations of terminal velocity of individual insects. Alternative methods include videotaping the object falling, and then using a motion analysis program (such as Motus software available from Peak Performance, Inc., Englewood, CO) to digitize its movements and estimate velocity from the changing position on successive frames. It is quite simple to automate the timing of the fall if the object may pass by light sensor-detector arrangements or if its release and fall may be sensed and timed by appropriate detectors. An assortment of spheres of known densities and sizes (control objects) are available, for example, from Small Parts (Miami Lakes, FL).

Regardless of the details of the way in which terminal velocity is estimated, it is still computed by dividing a measured distance by a measured time interval. These sorts of differential quantities are of course subject to large associated errors, which are useful for the student to estimate (also see Walker, 1998). Estimation of the acceleration, and its associated uncertainty is even more instructive in this regard.

Insect dispersal and parachute design

Insects come in a variety of shapes and sizes. The smallest insects are readily wind-dispersed. Since many of these small insects (such as aphids) are important pests, it is of interest to determine to what extent they will follow the prevailing wind currents, and an assessment of their terminal velocity is one useful indicator in this regard. In addition, many insects and other small arthropods (such as young spiderlings) exhibit a behavior called "ballooning," where they disperse with a "parachute" consisting of a single long filament of silk (Figure 2). Clearly the geometry of an effective parachute is size dependent. Larger objects such as parachuting human beings cannot be effectively slowed using parachutes of the same design used by small spiders. These contrasts in size-dependent functional design are both interesting and informative to the students. The functional behavior of silk strand parachutes can be easily estimated in a laboratory where different lengths and widths of filamentous material may be used to slow a falling object.

Useful references on falling objects (low *Re*) and terminal velocity include Hoerner (1965), Ward-Smith (1984), Diamond (1989), Barth et al. (1991), and Denny (1993). More complex permutations on this theme can easily be added by using objects that spin or tumble as they fall, or objects that oscillate.

OTHER RESOURCES - WEB SITES

Web sites that may be helpful to visit include:
BEMS (Biological and Environmental Mechanics) at
http://quarles.unbc.ca/bems/bems.htm
and a list of societies in Biomedical Engineering at http://fairway.ecn.purdue.edu/BME/societies.html.

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