Finite Element Analysis for Biological Engineering Applications: A Web-Based, Distant Education Venue

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Abstract

A web-based computational analysis course (URL http://cfdlab.engr.utk.edu/551w) was recently developed at the University of Tennessee to enable the accessibility of the general concepts of finite element analysis for the engineering sciences. This rigorous, first-level graduate course addresses computational methods that easily adapt to a wide range of curricula. Specific examples of biological problems are discussed. These problems include transport phenomena in biochemical and biological systems solved with the finite element method presented in this web-based course using readily accessible computational software, i.e., MATLAB® [1].

I. Introduction

Computational Mechanics for the Engineering Sciences is offered at the University of Tennessee in Knoxville (UTK) for students across engineering and science disciplines. The course introduces the finite element method applied to a wide array of engineering and natural science problems with focus on transport phenomena and solid mechanics, i.e., computational continuum mechanics [2]. Momentum transfer problems include the application of conservation principles to steady-state and unsteady conditions for one-dimensional and n-dimensional systems. The final topic in the course covers an unsteady convection-diffusion problem of n-dimension solved with the application of varying non-uniform meshes. The ability to alter the uniformity of the solution meshes allows for greater computational speed for demanding problems where mesh refinement may be efficiently applied. Fundamental heat transfer phenomena is covered in great detail to introduce n-D steady and unsteady applications.

This course was developed over several years with increasing emphasis on converting homework and laboratory assignments via html documentation. This led to the recent comprehensive effort to create a distant education venue with live, streaming video made possible by recent technological advances with digital video. Obtaining reasonable resolution and sound quality requires large amounts of digital information to be stored, which is also eventually archived for later viewing. However, the end user receives only instantaneous streaming video and sound; therefore, receiving the web-based course does not require storage space on the receiving computer. Requirements include only a computer with an adequate processor, RAM and a modem (28.8 K minimum) or LAN connection to internet services.

Because of many recent advances in finite element methods and corresponding software, a broad range of applications including areas of transport phenomena have become evident. The course takes the interactive approach that allows students to simultaneously view the live, video-streaming lecture, on-line course notes and graphical displays, while interacting through a live chat room.

Recently a large number of institutions have developed programs of study with an emphasis on the interface of engineering with the biological sciences. Some of these include areas of biomedical, biochemical, environmental, biomechanical, biological and agricultural engineering. The mathematics associated with biological systems is complicated by the heterogeneous nature of these systems that requires the rigorous solution techniques of computational analysis. Finite element theory achieves the greatest solution accuracy for many complex systems. Also, the natural applicability of finite element analysis for solving multidimensional problems makes this technique a highly desirable tool to tackle the complexity associated with biological systems.

Computers having access to the internet are becoming as common at home as the television and are nearly mandatory in the workplace. Therefore, the relative ease in accessibility to state-of-the-art technological information is rapidly taking place. This opens up many important avenues for students and professional engineers in the engineering sciences to acquire the necessary tools to solve complex problems associated with their fields. For instance chemical engineers may attempt solving many processing problems that often require solutions to the conservation laws concerning simultaneous effects of heat, mass and momentum transfer with endo- or exothermic reacting systems in mixing operations within a chemical reactor.

Bioprocess and food process engineers often deal with complex heterogenous systems characterized by non-Newtonian behavior. Solution integrity becomes of great concern for the systems of partial differential equations describing these challenging effects to better simulate these systems in the design process. An example is the design of a fungal bioreactor that address variable cell-dependent, non-Newtonian flow for submerged cultures requiring varying degrees of oxygen, which depend primarily on cell morphology and concentration. Simultaneous convective heat transfer effects may occur due to many possible biochemical reactions within microorganisms. In the past, problems of this origin were restricted primarily to supercomputers. Recently, with the advent of competitive technological advancements for desktop computers combined with user-friendly computational software, the problem-solving tools are rapidly becoming available to the engineers' desktop [3].

II. Discussion

The students on the receiving end of this course may come from departments of engineering, mathematics, computer sciences and natural sciences with specific interest in computational analysis of applied problems within their field. Biological, biochemical and biomedical engineering naturally fits this mold very well with a wide range of applications in processing, biomechanics, bioremediation, physiological engineering, etc. The student should have a fundamental understanding of the conservation principles in continuum mechanics and higher mathematics including matrix algebra and partial differential equations. A numerical analysis course beforehand is useful for grasping concepts early on, which may later distinguish the improvement in solution accuracy compared with finite difference or finite volume methods.

A biological engineering graduate student at Louisiana State University successfully completed all requirements for the course. Another student is currently enrolled to complete the course based on the video archives recorded during the previous semester. With increasing demands on students enrolled part-time with full-time jobs, as in the case with the second student, the distant education setup with unlimited accessibility to streaming video lectures present a valuable alternative for successful course completion. The student may easily access the lectures from home or the workplace according to their schedule with only the loss of the live interaction via the chat room.

Registration for this course occurs in three basic steps. First, the student on the receiving end applies to the University of Tennessee as a transient student, which is accomplished online at http://marge.cas.utk.edu/gradschool/. Second, a transient student certification form is sent to the student and must be signed and approved by the graduate school dean at the student's university. Third, the student may then register and pay for the course electronically. The final grade and credit hours will appear on the student's UTK transcript. These hours are then transferred to the student's university.

The first laboratory topic requires the student to define a problem of interest that requires a solution obtained by numerical analysis. The background and problem objectives are stated. The potential partial differential equations and appropriate initial and boundary values that define the problem are then introduced. This allows the student a flexible approach towards the ultimate goals of the course, to learn the finite element method and, most importantly, to apply the method to real-world problems. With emphasis placed on this problem, the students tend to better envision a useful end result that accompanies the basic elements of the course. The practical knowledge obtained by learning the finite element method may then be applied to computational analysis aspects of the student's thesis, dissertation or related topic.

The remaining laboratory topics in the course begin with a given problem that the solution is obtained from a MATLAB® template. The students alter the given template program to achieve the laboratory objective that may include obtaining the necessary mesh refinement for error quantization or changing the system's physical or chemical properties. These templates were written for the general heat transfer and computational solid mechanic problems discussed earlier. The codes may be modified to fit related problems, i.e., mass and momentum transfer phenomena that may pertain to the students' interest. Within each template, a library of matrix information is routinely called to solve the necessary linear algebra determined by the problem statement.

Some past successful laboratory topics with applications in biological or biochemical engineering pertained to modeling bioreactor systems for bioremediation of toxic compounds that include toluene, trichloroethylene (TCE) [4] and para-xylene [5]. Degradation rates of TCE were approximated for both biofilm and bioreactor systems defined by Fick's Second Law of diffusion of metabolite within the biofilm and a mass balance for the bioreactor system. The bioreactor mass balance included convection, dispersion within the liquid system, mass transfer between the liquid and biofilm, and mass transfer between liquid and gas phases. The model for this continuous bioreactor system also determined the effect of recycle ratio for system dilution. The degradation of para-xylene was modeled for a continuous radial-flow bioreactor. The mass balance for this unsteady-state system included a radial diffusion term, radial velocity term and a growth kinetic term based on Monod kinetics that also compensated for cell death within the reactor.

One student proposed a problem that considered the extraction of surface information by computer imaging to obtain a 3D surface reconstruction that may be applied to selection of products (3D objects) for quality control [6]. The selection process was applied to sweet potatoes in this model approximation. Another problem included the modeling of radial diffusion of caffeine (guaranine) from the seed of a Brazilian native fruit, guaraná. Other potential problems include the modeling of gas concentration profiles in modified atmosphere packaging [7], or modeling diffusion-reaction conditions within an enzyme reactor.

III. Summary

In summary, a web-based course was developed to teach the finite element method with aid of comprehensive laboratory exercises. This course was successfully taught as a live distant education venue to biological engineering graduate students at Louisiana State University. Applications of the finite element method to biological engineering are unlimited as problems become more demanding for the successful design of technologies for biological systems. Fortunately, with computational analysis tools becoming accessible to the engineer's desktop, complex problems may now be addressed in ways not previously possible. Therefore, the need for learning the appropriate computational analysis tools will be necessary for the biological engineer to handle complex problems in much greater detail. Also, time and location restraints for professionals or part-time graduate students with full-time jobs make the need for a convenient and effective distant-education courses a useful alternative.

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