Bringing an Integrative Modeling Experience to a Freshman Biomedical Engineering Course

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Abstract –

As an integrating lab experience in our Fundamentals of Bioengineering freshman course, we have included a Major Project that ties together many of the principles of biomechanics and bioelectricity covered in the lecture. It uses the human systemic cardiovascular system as a model. During the first half of the semester, students solve finite-difference equations describing the flow of blood in the cardiovascular system using Matlab. During the second half, teams of two students each assemble an electrical circuit analog of the same system. With the models, they make measurements of pressure and flow for both healthy cardiovascular parameters and for several common diseases.

Introduction –

We developed our two freshman biomedical engineering courses around three goals: 1) to introduce beginning students to our Department and the field in general; 2) to teach basic concepts and principles that underlie several specialties in biomedical engineering; and 3) to challenge the students with real-world problems, giving them a chance to assess their interest and skill level early in their academic careers. The purpose of this paper is to describe how we addressed these goals in the first-semester's class by incorporating a major modeling project that integrates the material covered during that semester.

We require two Fundamentals of Bioengineering courses in the freshman year. The first class (the topic of this paper) covers biomechanical and bioelectrical subjects, while the second semester covers biochemical and cellular topics.[1] The first semester's class is organized around a set of fifteen fundamental laws and principles related to biomechanics and bioelectricity—given in Table I—which meets one of the goals listed above in the course's design . Each topic is covered as one unit in a complete set of notes and homework problems supplied to the students. Each unit takes about one week to cover and is done in traditional lecture fashion (three per week). Weekly homework assignments, four quizzes, and four exams are given.

It is widely accepted that well designed lab experiences reinforce and strengthen the learning of engineering concepts.[2,3] An important component of our class is the Major Project, a hands-on lab experience in two parts that takes all semester to complete and that ties together most (about 80%) of the principles covered in lecture. The human cardiovascular (CV) system is an excellent example to illustrate biomechanical and electrical concepts. It encompasses fluid mechanics, including conservation laws, but also illustrates tissue elasticity, muscle action, and power and energy principles. Moreover, there is a close analogy between the ventricle-driven flow of blood through the vessels of the human circulation and an electrical circuit with resistors and capacitors. The Major Project pulls these various parts together for the students.

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Table I – Laws and Principles Covered in the Course Units

1. Basic Concepts: Numbers, Units and Consistency Checks 2. Darcy's Law (membranes) 3. Poiseuille's Law (flow through tubes) 4. Hooke's Law (elasticity and compliance) 5. Starling's Law (cardiac adjustment) 6. Euler's Method (finite-difference solutions) 7. Muscle, Force and Leverage 8. Work, Energy and Power	9. Ohm's Law (current, voltage, resistance) 10. Kirchhoff's Laws (circuit analysis) 11. Operational Amplifiers (gain, feedback) 12. Coulomb's Law (capacitors, fluid analogs) 13. Thevenin Equivalent (1^{st}-order time constants) 14. Nernst Potential (cell membranes) 15. Fourier Series

Elements of the Major Project –

A simplified lumped-element model of the human systemic circulation, Fig.1, is provided to each student. The same model is used as a starting point by all students in order to facilitate uniformity in helping debug their individual solutions and to keep the model complexity consistent with the time available for the solutions. As can be seen from Fig. 1, several approximations have been made, such as including only the systemic portion of the CV system with one heart chamber, lumping similar branches together, ignoring inertial effects, and assuming blood is a Newtonian fluid.[4] In conjunction with lecture discussions of general techniques of physiological modeling, the essential process of making assumptions in modeling—including what is gained and what is lost in the process—is covered.

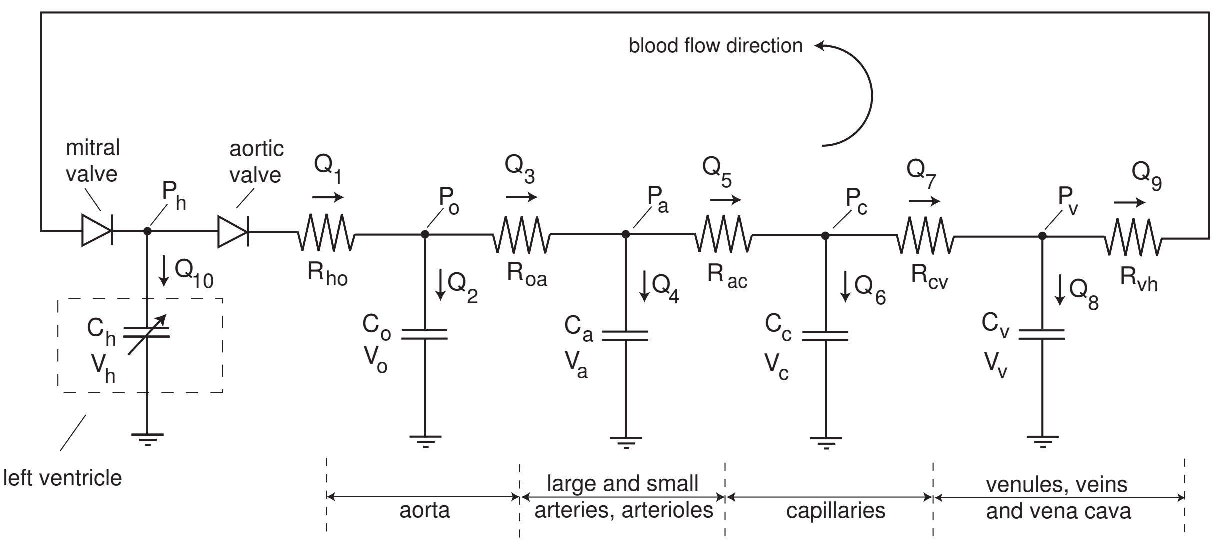

Fig. 1 - Simple model of cardiovascular system.

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Part 1 – Matlab Simulation –

During the first half of the semester, each student writes a Matlab program to solve for the pressures and flows at key locations around the systemic circulation using a finite-difference time-domain technique (based on Euler's method). All relevant equations are presented 'just-in-time' in lecture[5] as needed to solve various stages of the lab project, and all equations are given in easily understood finite-difference form rather than differential form, as appropriate for the first semester freshman status of the class.

Each student calculates the model parameters (the various vessel compliances and resistances, for example) using tables and graphs of human data. Due to varying interpretation of the graphical data, every student comes up with somewhat different, but still valid and usable, values compared to other students. Similarly, each student's Matlab program has individual variation, but all can be made to work if based on correct equations and assumptions. All calculations and programming are recorded using proper format in the student's engineering-style lab notebook, and individual progress and results are checked during four scheduled checkoff periods in the lab. An example of a typical Matlab graph of the pressure waveforms for one heart cycle assuming healthy CV parameters is shown in Fig. 2.

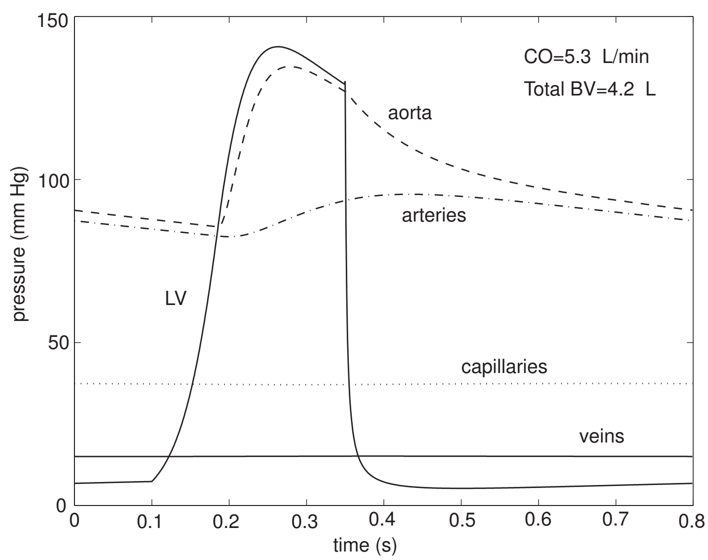

Fig. 2. Typical plot of pressures during one heart cycle at five nodes around the systemic CV loop using Matlab simulation.

After obtaining computer simulation results for typical healthy human CV parameters, the students must research three common CV abnormalities: anaphylactic shock, left heart failure, and hypovolemia. Each student must describe the physiological cause of the abnormality, the likely symptoms, what changes need to be made to the model parameters to simulate the disease, and (upon running the modified model) what effect the disease has on blood pressures and cardiac output. Again there is considerable variability in student answers, depending upon the presumed severity of the disease, but most are valid responses. Importantly,

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simulation of these diseases enhances the students' interest and adds a real-world context to the exercise, meeting another of the goals of the class listed in the Introduction.

Part 2 – Electrical Analog Circuit –

The model in Fig. 1 is directly translatable to an electrical circuit by exploiting the analogy between fluid variables and electrical variables[6] (pressure and voltage, flow and current, compliance and capacitance, etc.). During the second half of the semester, the students work in teams of two to assemble and test an electrical circuit based on Fig. 1. They choose electrical values (capacitance and resistance) corresponding to the related fluid parameters used in Part 1, and assemble the components on a prototyping breadboard. A typical completed circuit is shown in Fig. 3.

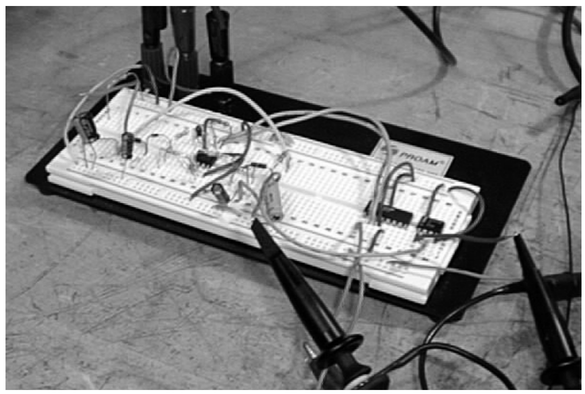

Fig. 3. A circuit model of the human systemic CV system exploiting the analogy between fluid and electrical quantities.

The most complex part of this circuit is the module that represents the left ventricle of the heart. Physiologically the heart's ventricles exhibit time-varying compliance, changing from high compliance during diastole to low compliance during systole. The electrical analog of the ventricle is provided by a capacitance-multiplier circuit using two operational amplifiers driven by a function generator (the 'pacemaker'). The use of op amps is covered in one of the units of the lecture. When the student circuits are complete, the teams use a dual-channel oscilloscope to measure voltage waveforms at various nodes of the circuit corresponding to blood pressure waveforms at related anatomical locations.

After measuring and recording waveforms for a healthy CV system, the students model two more disease conditions, atherosclerosis and aortic valve regurgitation, by modifying appropriate electrical components in the circuit. The students research the causes and symptoms of the diseases to determine which parameters to change. They run the modified circuit and plot (by hand) the resulting pressure waveforms in their lab notebooks. Again, these real-world disease simulations add interest to the lab exercise and present a learning opportunity regarding CV health that hopefully will be useful later in the students' lives.

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Student Evaluations –

Evaluations of the class and the Major Project have reinforced the fact that the project is a valuable part of the class. In an end-of-semester survey in fall 2001, 83 students (out of 107 students enrolled) responded. When asked about the benefit of the laboratory project to the goals of the class, the score was 5.70 out of 6.00. When asked about the overall effectiveness of the course, the score was 5.72 out of 6.00. Several students commented on the effectiveness and real-world nature of the Major Project exercise. In a similar survey taken the next year in fall 2002, the question about the benefit of the laboratory project to the goals of the class scored 5.53 out of 6.00, and the question about the overall effectiveness of the course scored 5.81 out of 6.00. Again several comments praised the Major Project effectiveness.

Conclusions –

The Major Project has now been an integral part of the class for four years. It has been improved from year to year (by giving the students more human data from which to calculate their model values, and by slightly simplifying the electrical circuit) as experience is gained with its implementation. Based upon student evaluations and feedback, it remains a backbone that ties together and supplements in a practical way many of the rather abstract bioengineering principles and concepts taught in the lecture. An extra benefit of using the CV system as the model system is that students can relate their own and their family's health to results obtained via the modeling.

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