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A Multidisciplinary Hydroelectric Generation Design Project for the Freshman Engineering Experience

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A two-semester Introduction to Engineering course sequence at Norwich University has Mechanical Engineering (ME), Civil and Environmental Engineering (CEE) and Electrical and Computer Engineering (ECE) students together for the first semester, and they are separated into their disciplines during the second semester. A final project in the second semester was desired that could bring the students back together to make discipline-specific contributions to a multi-disciplinary project. The chosen project was a hydroelectric generation project in which the ME students designed a water wheel to work in a laboratory flume, the ECE students designed a permanent-magnet generator with wireless monitoring, and the CEE students designed a structure to support the wheel and generator. In addition to designing their respective components, the students had to communicate between disciplines to define interfaces and requirements for their designs so all the components could work together as a larger system. The first year of the project was successful in that the student teams were able to design working components that functioned together in a system to generate electricity, and the experience generated several lessons-learned that will be used to enhance the experience for the next class of freshmen. The paper will discuss the scope of the design problem and the resulting design solutions, the lessons learned, and the improvements for the second cycle of the project.

Introduction

As systems become more multidisciplinary, the graduating engineer is expected to work more often with experts outside their own domain. In many cases, this cross-fertilization between disciplines can open up new pathways to creative solutions to emerging problems. Moreover, being a critical part of a larger project promotes interdependence among the players on multidisciplinary teams, which tends to develop the self efficacy of the individual in terms of their own ability to contribute, recognizing the contribution of others, and the ability to “speak the language” of the other members and even make contributions in their domain.[1]

The emphasis of the project was on the engineering design process within a multidisciplinary team, while the technical scope was designed to be a vehicle for this process while introducing technical concepts that the students would study in depth later in their programs. The technical scope was therefore carefully constructed to provide a high probability of success. Therefore, the level of expectation was set relatively low for the performance of the system—it was expected to “work,” but only at a level that would be attainable through relatively straightforward design solutions.

The design problem

A power generation project was chosen because it has elements of electrical, mechanical and civil engineering that could be used as a basis for learning discipline-specific concepts at an appropriate level for first-year engineering students.

The facilities available for this project include a fluids lab with a flume that is 12 inches wide and capable of a variable flow rate up to several hundred gallons per minute. A flume with a pumping system is more reliable and controllable than the wind in the valley where the school is located, and it is in a controlled environment, so using the flume for a small hydroelectric generation project was chosen as an appropriate design problem.

The project was divided into three main parts for the three disciplines as shown in Figure 1 below. The ECE students were assigned responsibility for the generator and a wireless control system, the ME students were assigned the turbine design as well as the transmission to connect the turbine to the generator. The CEE students were assigned the system to mount the turbine and generator, and any structural modifications to the flume if necessary. The team sizes varied between the disciplines, as each instructor grouped the students according to their own class management approach. For instance, the ME discipline was the largest with three sections of between 16 and 20 students, and the ME instructor formed one team for each section to design one of two turbines or the transmission. In contrast, the ECE discipline was the smallest and the main ECE instructor invited a “guest” instructor for each course module, and for this four-week module the two instructors split the single class section into two teams of seven or eight students to work on the generator and the monitoring system.

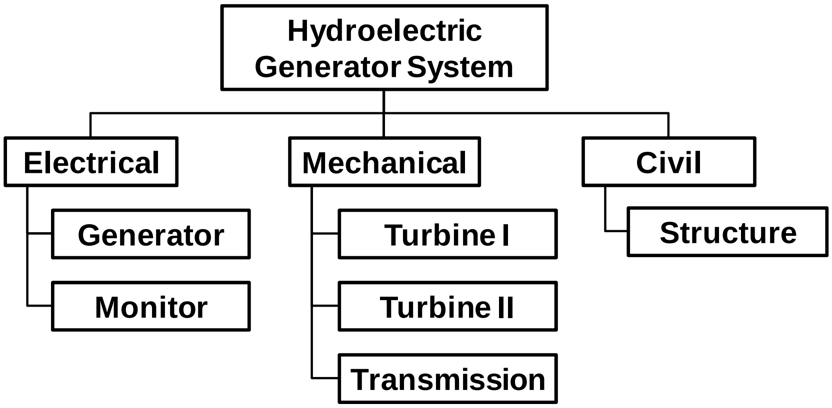

Figure 1. Top-level organizational structure for the generator project.

Electrical team

The generator design was based largely on a straightforward permanent magnet generator (PMG) plan that is designed to be built with basic tools that are likely to be found in communities in developing countries. The plans are available on line from Hugh Piggott,[2] as well as through the original sponsoring organization Practical Action (practicalaction.org). The PMG’s basic design is that of a rotor consisting of two steel plates with eight permanent magnets mounted on each plate with alternating north-south orientation, and a stator with six coils mounted in the gap between the rotating magnet plates. The rotor plates and stator are shown schematically in Figure 2. In the original design the coils were connected in series pairs so that the six coils produced a three-phase ac output, which was then rectified to produce a dc output. The output voltage could be increased by using three or four coils for each phase, resulting in a design with nine coils and 12 magnets per plate, or 12 coils and 16 magnets per plate, respectively.

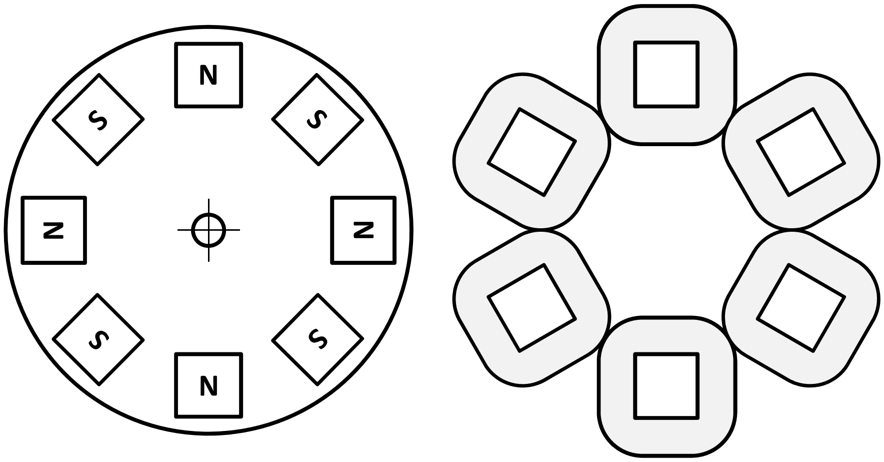

Figure 2. Schematic of one rotor plate of two with magnets (left) and the coils arranged in the stator (right).

The magnets are arranged so that the magnetic field between pairs of magnets across the gap moves over one side of a coil at a time, inducing a current in the coil that alternates direction. The arrangement is shown in Figure 3. If the relative velocity between the magnetic field and the coil (u), the segment of the wire bundle (l) with N turns that interacts with the field, and the orientation of the magnetic field (B_o) are all taken to be orthogonal, the peak magnitude of the voltage V_{emf} is simply

$$V_{emf} = uB_o lN \quad [V]. \tag{1}$$

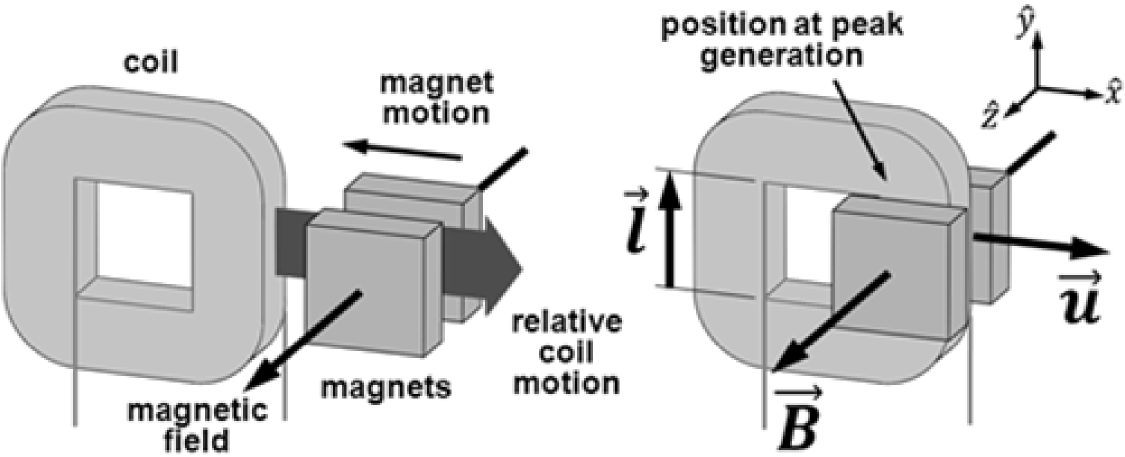

Figure 3. Basic interaction of a magnet pair and a coil in the PMG.

The scope of the generator design was essentially limited to optimizing V_{emf} in (1) by adjusting the variables. The velocity u was adjusted by choosing the radius to the magnets based on the geometry due to the number of magnets (8, 12 or 16 on a side) and their size (0.25, 0.5 and 0.75 inches square), and the rotational speed (limited to 1500 rpm). The interaction length l was set by the choice of magnet dimension, and N was limited by the geometry of the magnet dimension, the gap distance between magnets, and the wire gauge choice (between AWG-20 and AWG-30, taking current rating into account). The magnetic field B_o was a function of magnet type (limited by cost) and the gap defined by the coil thickness. There were several tradeoffs to be made within the constraints of cost and power output: for instance, B_o is larger as the gap gets smaller, but that limits the number of tuns N in the coil.

The magnetic field B_o was not a straightforward value to obtain algebraically, so the students built several prototype coils of varying thicknesses and wire gauges, and measured the V_{emf} using an existing rotor for which the gap could be adjusted. In this case all the variables in (1) were known except B_o, so the effective magnetic field could be solved as a function of the gap, and an equation could be fitted to the plotted B_o vs. gap data to be used in subsequent designs.

The resulting design called for nine coils of AWG24 wire, 0.75 x 0.75 x 0.125-inch rare-earth magnets.

The load for the generator was an automotive light bulb rated for 20 W. At a maximum design speed of 1500 rpm ($\omega = 157$ rad/s) the expected torque on the generator was $T = P/\omega = 0.13\ Nm$ before adding any friction losses. An estimate of the overall torque and rotational speed needed to be coordinated between the teams so that the mechanical system would deliver the necessary speed and torque to the generator shaft, and that the structure was designed to accommodate the mounting configuration and support the weight of the generator, turbine and transmission with the forces transferred from the operating flow.

The second ECE team designed a wireless system with the goal of monitoring the generator and controlling a set of relays to switch between delta and wye configurations of the three-phase generator. At slower speeds the phase voltage is lower, so the generator is wired in the wye configuration to maximize the output voltage, but at higher speeds the resulting higher voltage can be reduced by a factor of $1/\sqrt{3}$. This offered the students an introductory exposure to the design of a simple supervisory control and data acquisition (SCADA) system. The design of the wireless communication system centered on modifying open-source Arduino sketches for use with an XBee radio.[3] The measurement chosen for data acquisition was the angular velocity of the generator because of familiarity with a similar project earlier in the semester in which an optical photo gate was used measure the shaft speed on a motor. The team did not have enough time to define the final empirical thresholds for the switching network in addition to getting the Arduino boards to count revolutions to determine the shaft speed, and send and receive the wireless serial data, so only the speed monitoring was successfully demonstrated in the final project.

Mechanical team

The mechanical engineering teams were responsible for designing the turbine and the transmission required to harness the power in the flow and transmit it to the rotating shaft of the turbine at the required torque and speed. There were three sections of mechanical engineering students, so two were tasked with designing separate turbines, and one was tasked with designing the transmission.

The fluid dynamics aspect of the problem was focused on basic conservation of energy principles, and to limit the scope to an appropriate level, a basic undershot waterwheel was used. The students measured volumetric flow rate and open channel (flume) dimensions to calculate the available power in the water stream. Based on their research, they estimated a power transmission efficiency for the system to get an overall power conversion expectation.

Given the flow rate Q and the cross-sectional area of the open-channel flow A impinging on the paddle of the wheel, the velocity of the flow can be found using $v_{in} = Q/A$. The kinetic energy in the flow is then $E_{in} = mv^2/2$ where m is the mass representing the momentum that will be transferred to the wheel.[4] The following analysis is beyond the expected level of the average first-year student, but with some guidance, the more familiar principles can be highlighted, and the resulting equations can then be used algebraically to perform optimizations.

The incremental mass in the channel is given by $m = \rho A(\Delta l)$ where ρ is the density of the water, and Δl is an incremental distance along the channel, so the input kinetic energy is

$$E_{in} = \frac{1}{2}\rho A(\Delta l)v_{in}^2. \tag{2}$$

The incremental distance along the channel is related to the velocity by $\Delta l = v\Delta t$. To find the input power, the input energy is divided by the duration of the impulse, and using $\Delta l/\Delta t = v_{in}$, the input power is

$$P_{in} = \frac{1}{2}\rho A v_{in}^3. \tag{3}$$

The momentum is transferred to the wheel through an impulse of $F\Delta t$, so conservation of momentum requires that the momentum in the channel after the wheel will be less, implying that $v_{in} > v_{out}$. The velocity of the paddle on the wheel is taken to be v_{out}, and can be related to v_{in} through $v_{out} = cv_{in}$, where the constant $c < 1$. For a given impulse duration Δt and a smaller v_{out}, the equivalent mass describing the momentum transferred to the wheel is $m/\Delta t = \rho A(v_{in} - v_{out}) = \rho A v_{in}(1 - c)$. This assumes that A does not change, which is consistent with a simplifying assumption that the height of the flow, and hence the potential energy, remains constant before and after the wheel.

The output power can be found using $P_{out} = Fv_{out} = Fcv_{in}$. The impulse to the wheel is $F\Delta t = m(v_{in} - v_{out}) = mv_{in}(1 - c)$, and from that, and using $m/\Delta t$ from the argument above, the force is then $F = \rho A v_{in}^2(1 - c)^2$. The power out is then

$$P_{out} = \rho A v_{in}^3 c(1 - c)^2. \tag{4}$$

Finally, the power transfer efficiency can be estimated using $\eta = P_{out}/P_{in}$, or

$$\eta = 2c(1 - c)^2. \tag{5}$$

From (5) the maximum efficiency can be found to be approximately 0.29 for $v_{out} = v_{in}/3$. To relate this to the torque requirement T, the output power $P_{out} = T\omega = \eta P_{in}$ where $\omega = v_{out}/R$ with R being the radius of the wheel. Using $v_{out} = cv_{in}$, (3) and (5), the torque is related to the other parameters by

$$T = \rho A R v_{in}^2 (1 - c)^2 \tag{6}$$

where the torque includes the generator torque transmitted through the gears plus the total estimated torque due to friction in the system. From (6) the parameters can be adjusted to optimize the system.

Based on their previous calculations of flow rate and flow speed, students used gear ratios and required generator rotor speed to design their preliminary gear train. The rotational speed of the waterwheel is related to the generator speed by $\omega_W = (N_G/N_W)\omega_G$ where N_G/N_W is the gear ratio between the generator and the wheel. The transmitted torque is $T_W = (N_W/N_G)T_G$. Using these equations, a suitable gear ratio can be found. The final ratio used was $N_G : N_W = 10 : 138$.

Civil team

The civil engineering students were responsible for characterizing the flume, specifying the bearing supports to accommodate the expected forces on the waterwheel shaft, and designing the generator platform to be compatible with the placement of the wheel shaft location and the expected weight of the electronics and generator. This task required a great deal of coordination, as the several possible water wheel designs evolved rather rapidly, with attendant changes in configuration of the mounting and interfaces.

The flume was characterized for the flow rate given the head behind the sluice gate and the depth of the channel using Bernoulli's equation

$$\frac{P_1}{\gamma} + \frac{v_1^2}{2g} + z_1 = \frac{P_2}{\gamma} + \frac{v_2^2}{2g} + z_2 \tag{7}$$

where P_1 and P_2 are the gauge pressures at the head behind the sluice gate and at the top of the flow, respectively, both of which are taken to be zero, $\gamma = \rho g$ is the kinematic viscosity, and $v_2 \gg v_1$ so $v_1 \approx 0$. The flow was assumed to be uniform and any second-order effects are neglected to maintain an appropriate level for the students, as they had not yet had a fluid mechanics course. From those parameters, the velocity in the channel was found using

$$v_2 = \sqrt{2g(z_1 - z_2)} \tag{8}$$

Using a maximum head of 20 inches, a channel depth of 2 inches, the velocity was found to be $v_2 = 9.8\, ft/s$. With a channel width of 12 inches, the flow rate was $Q = 1.6\, ft^3/s$.

When collaborating with the ME turbine design teams, various depths of water flow and patterns of flow over the water wheel were considered, and from those, the expected available power was predicted.

Coordination between disciplines

This was probably the most significant part of the project from a learning perspective. Each team was expected to be the "expert" in their own domain, but they had to become familiar enough with the other domains, at least to a level at which they could communicate and collaboratively design a working interface between their subsystems. In addition to the requirements and constraints placed on the overall project by the customer and the derived requirements within the subsystem, there are interface requirements that must be negotiated. To handle this, each of the teams designated a leader/spokesperson to be responsible for cross-team communication. These students spent most of the design time with their colleagues in their own task, but they also met periodically to coordinate those interface requirements.

The ME's turbine design needed to be compatible with other ME team's power transmission mechanism, and both ME components needed to be compatible with the CE's mounting system. The CE's likewise had to manage the configuration compatibility between the ME's wheel and the ECE's generator, to include the shaft length, elevation, placement, bearings, and connectors. The ME's power transmission design also needed to be compatible with the ECE students' generator design in terms of speed/torque considerations in addition to the mounting configuration. What became immediately evident to all of the students was that they could not conduct their design tasks independently, but had to communicate with all of the other teams at every step of the way. The teams were still tempted along the way to say, "We're waiting for (fill in the blank) before we can (fill in the blank)," but they were reminded that all systems needed to progress concurrently due to time constraints and that no individual team could afford to wait for the other teams to finish before they could proceed. This created some stress as the teams had to deal with last-minute configuration changes due to availability of supplies as well as adapting interfaces that did not work as expected. The students were also reminded that this is frequently how a real engineering design project progresses. No single person or single team operates independently but relies on the other teams who also rely on them to meet their milestones and complete the project on time.

Results and Discussion

From a technical standpoint, the project was successful in that the core subsystems were designed and built, integrated into the hydroelectric generator system, and it produced enough power to energize the load. Many improvements could be made to the resulting system, but the main focus of this project was to learn to navigate through the process of carrying out a multi-team project across engineering disciplines.

Overall, this first time through this multidisciplinary design project proved to have some very rewarding aspects as well as some areas for improvement. The first thing planned to be improved is the problem definition. The project was not fully developed when it started, and the technical goals were not well defined, primarily because the capabilities of the different parts working in concert were unknown, and a late start in developing the project precluded sufficient time to test all the parts. The other immediate change to be made is to move the project earlier in the semester. It was originally deployed near the end of the semester as a four-week "capstone" project for the course so that other projects could be done before it that would develop some of the necessary background. This worked well for some teams, but not for others that had other end-of-semester requirements that generated conflicts at the end, and the final system test occurred on the last day of classes, lasting into the early evening. A final complaint was that the scope of some of the tasks, although technically appropriate, was too limited to engage all students in all groups. This was true for the larger teams across the disciplines, but the members of the smaller teams appeared to be more gratified with the increased engagement. This will be addressed by expanding the tasks to include more design options, and considering adding a measured amount of complexity to the turbomachine design to increase the number of turbine design options.

On the positive side, many of the students found the project to be enriching. There are no quantified data to present as evidence at this point to support an assessment, but aside from the issues mentioned above, positive anecdotal evidence exists to support continuing and extending the project. One conversation in particular involved a freshman who was offered a chance to transfer to a "more prestigious" engineering school, and when asked by a colleague at the end of the project if he was going to go, he said "are you kidding?" and then explained how he doubted he could get better hands-on engineering learning than what he was already getting. Assessment for the next implementation of this project will be more formalized, and formative assessment through a reflection assignment will likely be the instrument used. This appears to be an appropriate instrument for assessing the professional or "soft" skills within the small sample size (N ~ 80) that spans the three disciplines at Norwich University. Questions will be formulated to evoke responses regarding the communication process between teams, the allocation of (or "negotiation" for) requirements between the subsystems, and the role of individual contributions to the larger project.

Another positive observation was that the engineering process can be taught well without insisting that all students do all the same assignments. At the top level, this semester the engineering students were divided into their disciplines for the second course in the sequence rather than having all of them learn more about the tools used primarily in other disciplines than their own. They still learned similar general engineering concepts, and the joint project reinforced the multidisciplinary nature of their profession. The project took this a step farther by creating teams that were working on different tasks within their major discipline. Among the ME's there were some who worked on the turbine, and some who did not, and among the ECE's there were some who worked on embedded systems with wireless communication, while the others worked on the generator design. Although there was a little more prep time needed, the variety of a multi-faceted design problem was a refreshing break from the dogma of having everyone grind through the same lab exercises. Finally, the motivation of being responsible for a part of a larger system rather than having to answer for only one's own grade seemed to have a positive effect on the work ethic of the students who were engaged with the project.

Conclusions

A multidisciplinary design project consisting of a hydroelectric power generation system was developed in which teams from mechanical, civil and environmental, and electrical and computer engineering disciplines participated. The students were responsible for their parts of the system, but they also had to work with students from other tasks and disciplines to make sure their subsystems worked together. Along the way, in addition to being introduced to a broad spectrum of engineering concepts, they also gained an appreciation for having to depend on other teams and be depended upon to be successful in the process.

The project provided a venue to attempt to teach similar core engineering concepts while engaging in a diverse set of technical problems across the School of Engineering rather than isolating it in one instructor's class. The results were generally positive and sufficient to support repeating the process, but there were a few issues that were identified that will be fixed in the next cycle.

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