International Journal of Engineering Education Vol. 29, No. 2, pp. 380–387, 2013
Printed in Great Britain

0949-149X/91 $3.00+0.00

Design and Construction of a Boat Powered by Solar Energy with the Aid of Computational Tools*

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The senior design project in engineering curricula is undoubtedly one of the prime opportunities for future engineers to synthesize knowledge acquired during their college education. We adopt the perspective that product development is an engineering and social activity aimed to satisfy human needs eliminating the negative environmental impact. This definition is delivered in our students through design experiences aimed under a project-oriented design course. This article seeks to give an overview of this project and to summarize the experience of the past two years that has led to improvement in the designing experiences in the capstone project. The project actively uses CFD (Computational Fluid Dynamics), CAM (Computer Aided Manufacturing), FEM (Finite Element Method) and CAD (Computer Aided Design) software as tools for enhancing the innovative capacity of senior year engineering students. Seniors working collaboratively were asked to design a solar-powered boat while taking hydrodynamic, energy and economic factors into consideration. We show how computational tools accelerate decision making processes in design while suggesting promising directions for the students to follow. All this is done while adhering to the fundamental principles in engineering that will lead to a feasible solution. Student creativity was channeled appropriately through CFD, FEM, CAM and CAD tools and new ideas were rigorously and rapidly tested at an early stage in the project allowing for a wide exploration of ideas and concepts. An important result of this capstone activity is the realization by the students of the importance of specialized engineering software in achieving a successful design. The objective of this paper is to present and discuss results obtained while observing students work with computer tools as a way to enhance their creativity in the context of developing their senior design project.

Keywords: innovation; prototype; computational tools; design; solar-powered boat

1. Introduction

Students from the engineering area, as an important part of their education and training, enroll during their senior year in a design course as required by ABET (American Board of Engineering and Technology) [1]. The main goals of the senior design project are for the student to develop skills and abilities such as engineering problem solving, creative reasoning, innovation, inventive design, team work, multidisciplinary work, and self-learning, as well as using computer software to aid in the design of innovative prototypes.

Tecnológico de Monterrey [2] is the largest private university system in Mexico, it is accredited by the Southern Association of Colleges and Schools (SACS) [3], and the engineering programs at Campus Monterrey are accredited by the Engineering Accreditation Commission of ABET. In our School of Engineering, the senior design course has consisted recently in developing diverse projects that include the building of prototypes that help students develop skills valued by the automotive, aeronautic, and naval industry. Among these prototypes we can mention: an off-road vehicle for the BAJA SAE México competition [4]; a RV-10 aircraft was assembled using Active Learning and Reverse Engineering techniques [5, 6] as well as numerical tools to perform structural and aerodynamics analysis of the aircraft; and a boat powered with solar energy to compete in the Solar Splash Event [7].

This article presents the experiences and the work of engineering students from Tecnológico de Monterrey (ITESM) during the past two years in developing the concept and following through the realization of the solar boat prototype aided by different computational tools. Participating mechanical engineering seniors were asked to perform an assessment of the impact that Project Oriented Learning Aided by Computer Software had throughout the process. This qualitative observation by our students is helping faculty in our department structure future curricula.

2. Design requirements

The design and construction of electromechanical prototypes is one of the major areas of interest of mechanical engineering students. Although many undergraduate curricula include the application of mechanical design software that covers fundamentals at different levels, the design and construction of electromechanical prototypes had remained out of

* Accepted 19 October 2012.

the scope of the mechanical engineering curricula in our university in the past years. Therefore, this paper presents the experiences of a course that aims to give an educational space to the students to design and construct an electromechanical prototype and, in particular, to improve the skills of the students relative to the detailed design of a solar powered boat. The boat needs to comply with all the regulations established by the Solar Splash Event, an international championship of universities organized by IEEE and ASME [7]. Solar Splash lasts 5 days in which the teams compete in several events such as: a 300 m sprint, slalom and endurance. The design, workmanship and technical report are also considered in the global evaluation. There are constraints to boat size, total power supplied by the photovoltaic panels, and the battery capacity.

3. Methodology

Considering the Solar Splash regulations throughout the whole process from conception to realization, Project Oriented Learning (POL) was the guiding pedagogic approach [8–10], with the aid of computational programs of CAD, CAM, CFD and FEM. In the POL technique, a project is assigned with a specific goal, in our students' case, to enter a solar powered boat to the Solar Splash competition. The purpose of POL is that students learn as they develop and design the prototype, with the instructor as a facilitator. It is a student-centered learning technique that involves interdisciplinary and team work. The POL is implemented in the senior design course that is conducted in 15 weeks of one semester with two hours of faculty/student meetings per week. The senior course is totally project oriented where the first three weeks are devoted to plan the activities of the semester and to review fundamentals concepts of mechanical design and solar energy conversion. Also, there is a training period where the students learn how to use specialized software. The strategy and the advances of the project are reviewed by the professor. During the last twelve weeks of the semester, students work completing the boat with the implementation of the propulsion mechanical system and of the electrical diagram to store and distribute the electrical energy. Every design concept is evaluated analytically and computationally using engineering software for CAD, CAM, CFD and FEM. To integrate all these computational tools in the creation and design of this prototype the following methodology was employed as shown in Fig. 1. The next section explains each step of this methodology.

4. Design and prototype creation

4.1 Concept development

The students were organized by teams of 3 to 4 students and they were assigned to present proposals of different preliminary designs. The engineering requirements for the design of the boat were selected with the assistance of QFD (Quality Function Deployment). The QFD results [11–12] and sketches of the boat were presented to a committee of advisors consisting of mechanical engineering faculty and other experts in order to discuss the pros and cons of the designs. After this feedback process, the preliminary designs were modified and three prototypes were selected. The DelftShip software [13] was employed to create a preliminary design of the hull boat and a CAD program was employed to generate the drawings of the prototypes. Fig. 2 shows a preliminary design of the hull and the CAD drawing.

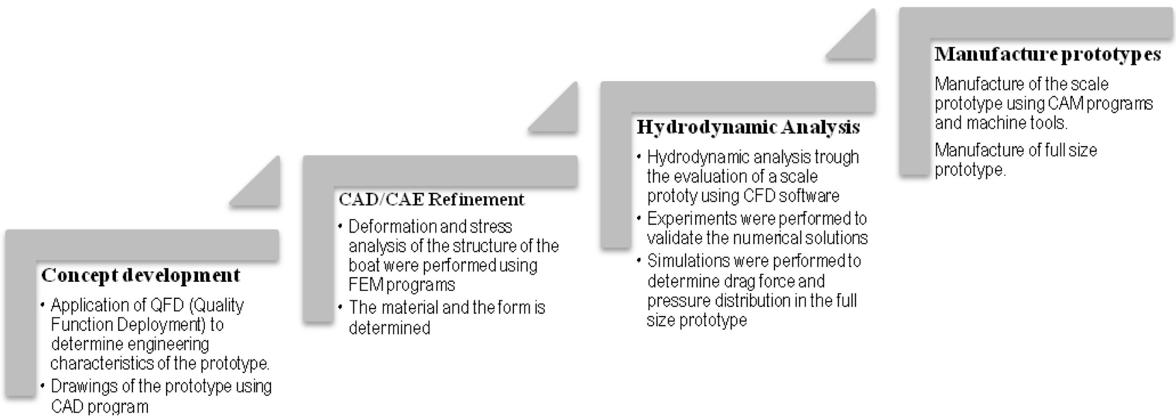

Fig. 1. Methodology employed in the project.

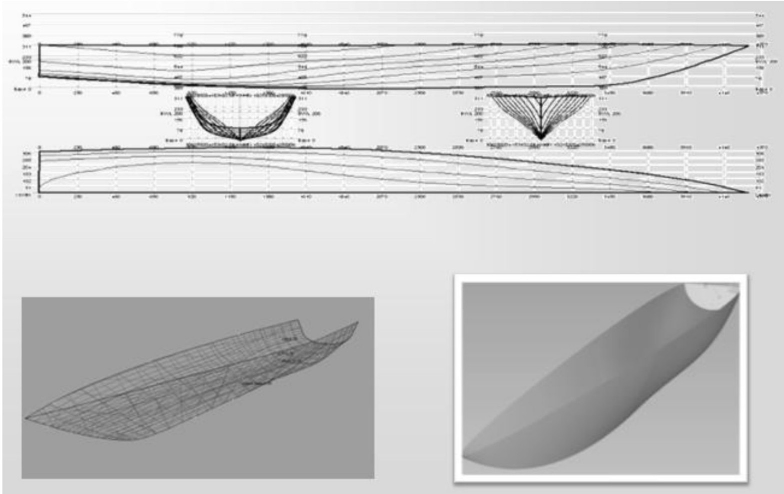

Fig. 2. Preliminary drawing of the hull of the prototype.

4.2 CAD/CAE refinement

A stress and deformation analysis with a FEM program was performed to determine that the structure of the boat can withstand the stresses produced by the forces due to the water pressure and the outboard motor. The results of the stress and deformation analysis were important in the selection of the material and the design of the hull skeleton. The CAD/CAE/CAM development is shown in Fig. 3.

4.3 Hydrodynamic analysis

CFD Simulations helped the students evaluate the hydrodynamic performance of the three prototypes. The drawings of the prototypes generated in the CAD program were imported into the CFD program. The geometry of the prototype was subtracted from a large parallelepiped to create the domain that represents the flow of water around a boat. The domain was divided in a finite number of small control volumes using a grid generator program. CFD software [14] based in the finite volume method was used to solve the governing equations (Navier-Stokes, continuity, etc.) for the problem of flow of water about the boat. Pressure distributions, drag force and the velocity field were obtained from the numerical simulations for different boat velocities.

Experiments were performed in a hydraulic channel with a scale prototype to validate the CFD results. Particle Image Velocimetry (PIV) [15] allowed visualization of the flow around a scale boat prototype. PIV consists of adding small tracer particles to the fluid that moves with the flow in a region selected for the analysis. This region is then illuminated with a laser beam and a digital camera captures pictures at short time intervals. A computer program with a special algorithm correlates the motion of the particles to obtain the instantaneous velocity fields of the flow. This information is very useful to study the flow pattern of a

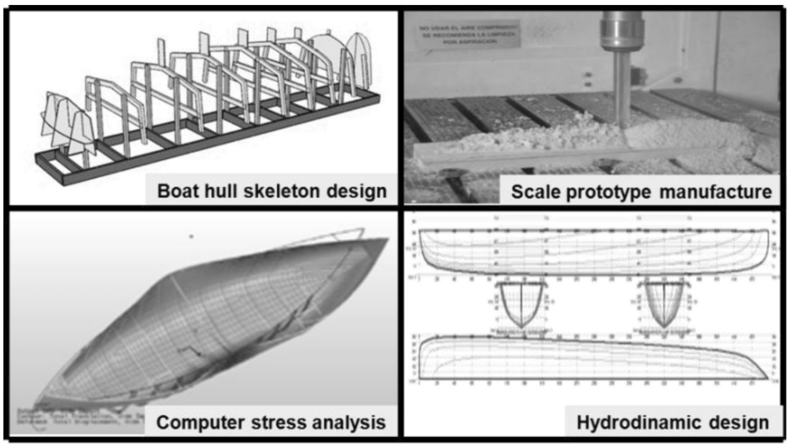

Fig. 3. CAD/CAE/CAM product development.

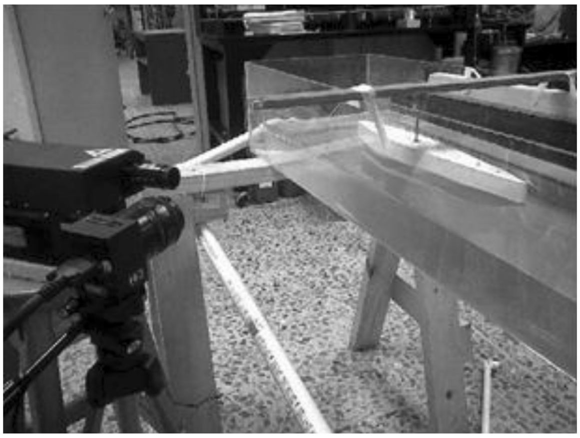

Fig. 4 Hydraulic channel and PIV system setup

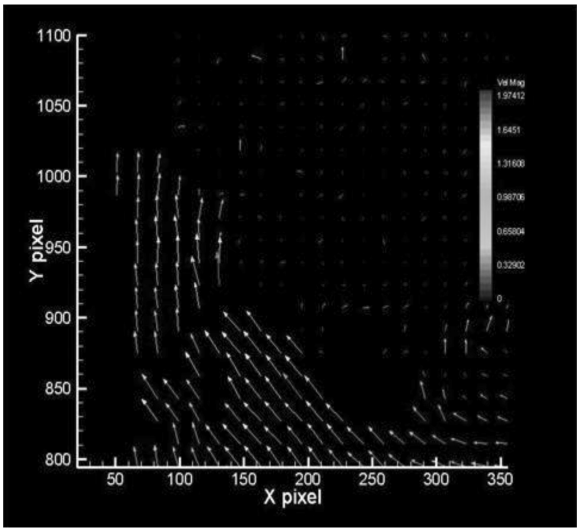

Fig. 5. PIV image of the instantaneous velocity distribution at the rear part of the prototype

particular configuration and design. Fig. 4 shows the PIV system (laser and digital camera) and the channel with the scale prototype. The instantaneous velocity field on the rear part of the prototype obtained with the PIV system is shown in Fig. 5. The magnitude and direction of the velocity vectors of fluid are represented with arrows, and it can be observed that the fluid is flowing around the rear part of the boat. Numerical simulations were performed to study the hydrodynamics in the full size

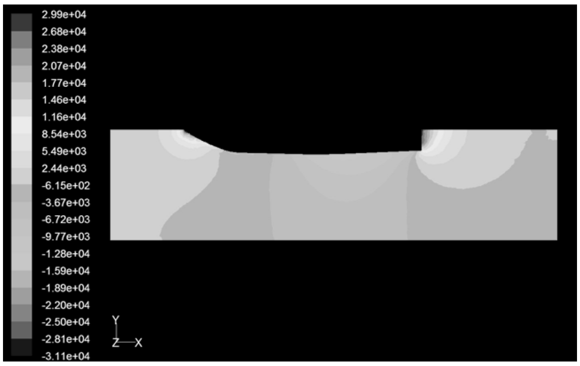

Fig. 6. Contours of velocity magnitude (m/s) of the water for the solar boat prototype.

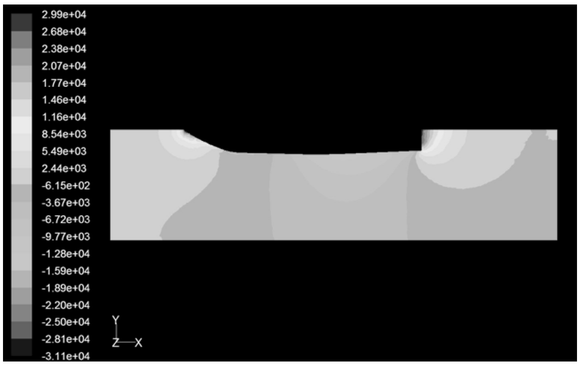

Fig. 7. Contours of static pressure (kPa) of the water for the solar boat prototype.

prototype. A cross sectional plane (side view) with the contours of velocity magnitude (m/s) of water for one of the prototypes is shown in Fig. 6. The pressure distribution (kPa) in the flow for the same plane is shown in Fig. 7. In these simulations the boat is fixed and the fluid is moving around it. For constant velocity this is equivalent to the situation were the boat is moving. The velocity of the fluid is near zero at the front of the hull and the pressure in this region reaches a high value. As the fluid moves under the hull, the fluid is accelerated and the pressure decreases to a low value. From the numerical and experimental analysis, the prototype with the minimal drag force was chosen. Fig. 8 shows the final design of the prototype while competing in the 2011 Solar Splash event.

Fig. 8. Final design of the prototype

5. Discussion

The students used various computational tools during the development of the solar boat prototypes. The use of specialized CAD, CAM, FEM and CFD engineering software was instrumental in creating and designing innovative prototypes. For instance, using the software and applying the constraints imposed by the Solar Splash regulations, some parameters were fixed to create preliminary designs of prototype. Also, a committee consisting of faculty members and experts, with the assistance of QFD, selected three prototypes. Another computational tool used was the Delft Ship Marine Software for easily creating drawings of the hull. The dimensions and the displaced volume were introduced to the program that generates a hull drawing that can be later modified. This drawing can be imported to a CAD program to clean the geometry. Compared with previous semesters where the use of specialized software was less frequent, the computational tools significantly improved the creativity of the students in the design of the prototypes. In the first year, mainly CAD tools were employed in the development of the prototype. Only one design was proposed and most of the time was spent in building, testing and modifying the prototype to improve its hydrodynamic performance (reduce drag force, increase stability and maneuverability, etc.). In the second year, when more computational tools (CAD, CAM, FEM and CFD) were employed, the number of designed prototypes increased and the students could be more focused in enhancing their creativity than in drawing the geometry and testing the prototype.

After this preliminary selection process, it became necessary to select the best prototype for the competition. Besides of the design restrictions imposed by the regulations, it was imperative to consider economic aspects, feasibility of construction and the estimated time to complete the prototype. The budget assigned to the project was limited, some materials and production methods were not available, and there was a due date to have the boat ready for the competition. Considering these aspects, it was decided to perform experiments and numerical simulations to reduce the cost of the process, minimize the weight of the boat without affecting the safety factors and accelerate the construction process. Scale prototypes were manufactured with the aid of CNC tools and experiments were performed in a hydraulic channel to study the hydrodynamics of the flow around the prototype. Due to the large difference of scales between the full size prototype and the scale models, dimensional similarity was not achieved. However, the experimental data of the scale model was useful to validate the CFD results of the simulation. After the CFD software was calibrated with the results of the scale model, it was possible to run simulations of fluid flow for a full size prototype with just changing some scale factors in the input parameters of the software. This is another example of the importance of the computational tools in the innovative design of the prototypes. To perform experiments in the three full size prototypes would have been economically unfeasible.

Light and inexpensive materials were selected to manufacture the boat. Wood and fiber glass were selected due to their relative low price and weight. Ribs made of wood were employed to reinforce the structure of the hull. FEM software was very important in reducing the amount of materials used and to guarantee that the boat could withstand the stresses produced by the water pressure and the loads generated due to the motor operation. The students evaluated different strategies of manufacture design reducing the cost and time of construction.

We have been mentioned several advantages of using the computer and computational tools in the creative design of the prototypes. However, there are some disadvantages that must be mentioned. Although, the students have taken engineering courses in the areas of materials, mechanics, fluid dynamics and numerical methods, they have relatively little experience and knowledge in the use of specialized engineering software (CAD, CAM, CFD and FEM). Therefore, a training period is required (from two weeks to a couple of months) in order for the students to take advantage of all these computational tools. A solution that has been implemented to accelerate this training process is to incorporate graduate students in the senior project with the purpose of assisting the undergraduate students. The role of the professor is of an advisor, a supervisor and a facilitator as the project progresses.

It has been illustrated in this project that the computers and computational tools play an important part in the formation of students to enhance the creativity and innovation of the prototypes. However, an important challenge is to measure the impact of these computational tools with appropriate and repeatable means. Different methods and means have been employed to try to measure this impact, although the authors consider that there is room for improvement. As a part of the tasks assigned to the students, they perform a mid-term and a final presentation. Also, they must submit a final report and a poster describing their work and presenting their results. A committee of three professors evaluates the report, the oral presentations and the poster following the guidelines of evaluation

Table 1. Rubric to evaluate the effect of the computational tool in the design creativity

Concept	Grade
Specialized computational tools were used in design of the prototype and during the development of the project	
The design of the prototype was improved due to the application of computational tools	
The selection of the specialized software was appropriated and the students know how to use correctly.	
The use of the computational tools allows to explore more modifications in the design of the prototype	
The use of computational tools enhance the creativity and innovation of the students in the design of the prototype	

1 completely disagree, 2 disagree, 3 undefined, 4 agree, 5 completely agree.

rubrics designed to assess different skills such as the application of engineering concepts. Table 1 presents a rubric designed to assess the use of computers and computational tools in the creativity and innovation of the prototypes, where a numerical value is assigned to quantify the impact of these tools. Also, a survey has been designed in order to obtain a feedback from the students about how essential the use of computers and software were to improve their creativity and innovation (Fig. 9).

TECNOLÓGICO DE MONTERREY, CAMPUS MONTERREY

Department of Mechanical Engineering

COMPUTATIONAL TOOLS CONTRIBUTION IN PROTOTYPE DESIGN SURVEY

This survey is to assess how the use computational tools contribute to enhance the creativity of the student in the design of prototypes. We need your help to make the results of this study comprehensive and accurate. The information you provide will be kept stickily confidential and examined only by the professor. Thank you very much for your participation.

Student ID:__________ Name:________________________ Date:__________

Project Name:____________________________ Professor:______________

1. **Specify the type of specialized engineering software employed during the design of the prototype (CFD (Computational Fluid Dynamics), CAM (Computer Aided Manufacturing), FEM (Finite Elements Method) and CAD (Computer Aided Design)).**

   ☐ None ☐ Only CAD ☐ CAD and CAM ☐ CAD, CAM and FEM or CFD.

2. **How difficult was to learn the use of specialized engineering software during the project?**

   ☐ Very difficult ☐ Difficult ☐ Moderate ☐ Easy

3. **On average, about how many hours a week did you spend using specialized engineering software during the project?**

   ☐ 1-2 hours ☐ 3-4 hours ☐ 5-6 hours ☐ > 6 hours

4. **What percentage of specialized engineering software was employed during the development of the prototype?**

   ☐ < 25% ☐ 25-50% ☐ 50-75% ☐ > 75%

5. **How did you consider that the use of specialized engineering software contribute to the creativity and the innovation of the design of the prototype?**

   ☐ Very much ☐ Moderate ☐ Some ☐ Not much or none

Fig. 9. Survey to evaluate the effect of the computational tools in the design creativity.

6. Conclusions

In light of recently revised accreditation criteria and the call from industry on what they need from engineering graduates, it would appear that these demands are unlikely to be satisfied by a traditional engineering curriculum and "chalk and talk" pedagogy. In this work, we present results of our experience in teaching the senior design project with a strategy of Project Oriented Learning with the evaluation of engineering design through the application of simulation software. A group of students were exposed to an engineering challenge to innovate and create prototypes for engineering. The methodology proposed in this work achieved several goals. First, the students were challenged with an interesting project, where their goal was to enter and compete in the Solar Splash event, following its rules. Second, the students were exposed to modern computer based engineering tools and the effect of these tools on their creativity was carefully observed. We can conclude that computer software becomes an advantage in promoting and enhancing student creativity as he/she works on the capstone project. For the solar-powered boat project, the use of this software has increased year after year given its positive impact on students' output and performance. In this work, a rubric and a survey are presented as a first attempt to assess the effect of computers and engineering software in the innovation and creativity of the students. However, more information is needed to assess and quantify the impact of these tools in developing creativity in the students when designing prototypes. This is ongoing research that is carried out in our Department.

Acknowledgments—The authors gratefully acknowledge support from Tecnológico de Monterrey through the Research Chair in Solar Energy and Thermal-Fluid Sciences (Grant CAT-125).

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