AC 2007-1873: APPLYING CFD AND NOVEL DEVELOPMENT IN ELECTROMAGNETIC FLOW CONTROL TO A MECHANICAL ENGINEERING SENIOR DESIGN PROJECT

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Applying CFD and Novel Development in Electromagnetic Flow Control to A Mechanical Engineering Senior Design Project

Abstract

A research project in electromagnetic control of hypersonic shockwaves for re-entry bodies is in progress at Alabama A&M University (AAMU). A group of propulsion students were asked to design a mechanical cradle to support a test object for an experiment involving electromagnetic control of shockwaves as a senior project. The thermal and mechanical design of this cradle required students to apply Computational Fluid Dynamics and novel development in electromagnetic flow control to complete the required design tasks. This paper describes the project and the assessment method used to evaluate student learning.

Introduction

Mechanical Engineering graduates must demonstrate: 1) an ability to design a system, component, or process to meet desired needs; 2) an ability to function in multidisciplinary teams and 3) an ability to use the techniques, skills and modern engineering tools necessary for engineering practice. One of the key challenges faced by the engineering educator today is how to provide a fast track for the project and design engineering experience while also providing a strong fundamental engineering education and solid preparation in engineering analysis and design in a four-year program.

The ME program at AAMU strongly encourages teamwork on class projects for courses in the major. This allows students to develop a design portfolio starting from the freshman year. Project training continues through their capstone design course. The projects assigned to students are often combined with on-going, externally funded faculty research projects.

A research project in electromagnetic control of hypersonic shockwaves for re-entry bodies is in progress at Alabama A&M University. During hypersonic re-entry, the air behind the bow shockwave around the leading edge of the vehicle is highly ionized due to the abrupt shock-induced temperature increase. As a result, the plasma electrical conductivity can become high enough to effect significant magnetohydrodynamics interaction. By super-imposing a magnetic field on this ionized region, it is possible to induce electromagnetic forces which can control the shockwave structure and, in turn, decrease heat and increase drag on a re-entry vehicle through the interaction of the charged particle stream and the electromagnetic field. It is clear that undergraduate mechanical engineering students cannot conduct the required full-scale research tasks within their senior year; however, it is possible to spin off some of the research elements so that the students can be trained in multidisciplinary design. For example, a mechanical cradle with a six-degree of freedom moving mechanism is required to support the test model in a vacuum chamber. Consequently, a group of Mechanical Engineering senior students were asked to design the required cradle as a senior design project. The design effort consisted of three parts: computational simulation of fluid and plasma dynamics coupling with an electromagnetic field, design of the cradle using the results from the simulation and experimental investigation using a hypersonic Arc Heater test facility. This research required integration of computational fluid dynamics (CFD), plasma dynamics, electromagnetics and mechanical design.

Background about AAMU and the SEAARK Approach

AAMU is a charted historically black university. It is located in the northeast side of Huntsville, Alabama, an important world center of expertise for advanced missile, space transportation and electronic research and development. Among the leading government and industry organizations located in this area are: the NASA Marshall Space Flight Center, the Army Aviation and Missile Command Center (AMCOM), the Redstone Arsenal Testing Center, the Boeing Company, Northrup Grumman, Lockheed Martin Aerospace and many others associated with high-tech. endeavors. These organizations require large numbers of engineers trained in the areas of manufacturing and propulsion.

In response to this requirement, the Mechanical Engineering program at AAMU was organized to provide two course-of-study options: manufacturing and propulsion systems. The faculty of the Mechanical Engineering (ME) department adopted a systems approach, denoted by the acronym SEAARK [1,2,3], for instruction and teaching. SEAARK stands for (in reverse order) Knowledge, Repetition, Application, Analysis, Evaluation and Synthesis. It covers the learning from the basic to the complex levels. The SEAARK approach for lectures is also utilized for class projects. This paper presents a case study in applying CFD and Novel Development in electromagnetic flow control to a Mechanical Engineering senior design project in the propulsion option.

Elements of the Senior Design Class

The Mechanical Engineering Senior Design Project consists of two classes, ME 470 and ME 475, in consecutive semesters. Table 1 shows the course syllabi for both courses.

Table 1. ME 470/ME 475 Senior Design Project Syllabi

	FALL SEMESTER (470) SPRING SEMESTER (475)
Catalog Data:	ME 470 *Mechanical Engineering Design Project* - 2 hrs. (Lec. 1 hr., Lab 1 hr.) Design or comprehensive analysis and development of an engineering product or process. The student is required to give an oral presentation of his/her work and submit an approved typewritten technical report.
Prerequisite:	Senior Standing and consent of instructor (Offered - consult advisor) ME 475 *Mechanical Engineering Design Project Continuation* - 3 hrs. (Lec. 1 hr.,Lab 2 hrs.) A continuation of ME 470. Prerequisite: ME 470 (Offered - consult advisor)
Text Book:	Instructor notes
Coordinator:	
Objectives:	The ME 470 and ME475 sequence constitute the capstone design experience. These courses emphasize either the thermal track or the mechanical track. The senior design project in mechanical engineering is

	designed to address integration of knowledge and skills acquired during the previous semesters in particular those courses of the junior and senior year. Course content includes programming or simulation or project practice to promote project-engineering skills. Students are expected to develop the senior design project with a systems perspective, so that they can analyze the problem from the perspective of other disciplines. The capstone design report shall address product realization process or PRP. Other issues to be addressed as appropriate are: economic impact, reliability, the impact of the engineering solution to society at large and the manufacturability of the proposed solutions. The student is required to give an oral presentation of his/her work and submit an approved typewritten technical report
Prerequisites	1. Senior standing.
Lesson topics are in support of program objectives and program outcomes.	
Grading Policy:	The oral presentation of his/her/their approved typewritten technical report is evaluated each semester by all the faculty members of the ME department . A brief presentation is given to members of the Industry and Government Advisory Board in the Spring semester if time permits it. The instructor collects all the evaluations, reviews and suggestions throughout the semester and meets with students to guide them and verify that the program objectives are met.
Computer usage:	As needed to meet project requirements.
ABET category content as estimated by coordinator:	
	Engineering science: 0 credit Engineering design: 5 credits.(ME470+ME475)

All senior design projects must include both thermal and mechanical elements and, if possible, include manufacture and test of the product. Students must propose three possible design solutions, evaluate these against, design constraints, and select the single, final design. All projects must be completed in two semesters. All outcomes must be measurable. Students are encouraged to submit a technical paper describing the design project to the AIAA, or ASME student / young professional sections for publication.

Electromagnetic Control of Hypersonic Shockwave Research

The authors have an ongoing research project funded by US-Army. The objectives of this research are to numerically and experimentally investigate the effects of electromagnetic fields on hypersonic shockwave structure for re-entry bodies and to critically evaluate system level technical issues. Experimental investigation will be conducted in an existing small-scale MHD-driven hypersonic wind tunnel at NASA Marshall Space Flight Center. A ceramic model body with surface mounted electrodes and an internal magnet coil will be instrumented and mounted on a rigid “sting” in the wind tunnel test volume for exposure to a short duration, high Mach number free jet flow. The principle test objectives will be to quantify the increased shock stand-off distance and the induced electric potentials in the shock layer during an electromagnet pulse. The results of the experiments will be compared against theoretical predictions for validation purposes and will be used to make a critical assessment of the technical feasibility of the application of electromagnetic fields on hypersonic shockwave structures for practical applications.

Applying CFD and Novel Electromagnetic Flow Control to the Senior Design Project

Computational Fluid Dynamics (CFD) is not a required course in the Mechanical Engineering curriculum at AAMU; therefore, it was necessary to train students to use a CFD analysis package for the required thermal system design and analysis. We understood that we did not have enough time to teach the CFD algorithm in design class so we invested lab hours to introduce the fundamental concept of fluid modeling and simulation. This included grid generation, solution of set of partial differential equations using a finite difference method, and application of a software packages for grid generation, boundary condition specification, simulation, and scientific data visualization. A group of propulsion students were introduced to using the modified WIND code to conduct a simulation of hypersonic plasma flow around a test article with a superimposed electromagnetic field. The first task the students had to do is to apply the CFD tool to simulate hypersonic ionized flow around the aero-electromagnetic test model in the full-size vacuum chamber. Thermal analysis of the flow field is used to analyze pressure and temperature on the test model. From these results the total force on the model was computed. The second task was to design a mechanical cradle based on the computed forces to support the test model in the vacuum chamber. Three possible designs were proposed. The best design was selected after a merit analysis. The third task was to produce the cradle and to test it in the vacuum chamber. It is important to understand that the senior students are experiencing the challenges of CFD modeling and application of electromagnetics for the first time in their two-semester work.

Figure 1 shows the experimental setting of the plasma research test fixture at the NASA Marshall Space Flight Center. As shown in Figure 1, the vacuum chamber is connected to the exit of the arc heater facility. The test article is located inside the vacuum chamber.

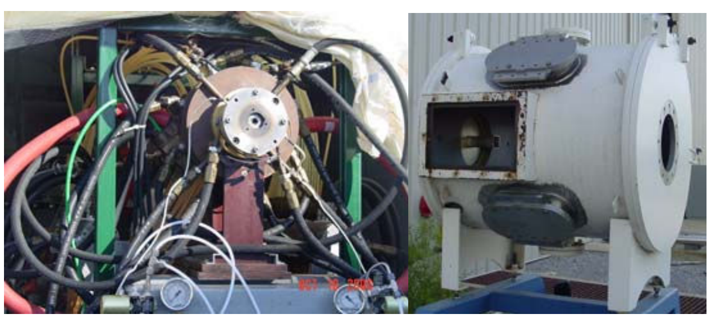

Figure 1. Experimental Setup for Electromagnetic Control of Hypersonic Shockwaves.

The group of senior propulsion students went to test site and measured the test chamber physical dimensions. Figure 2 shows the vacuum chamber CAD drawing and proposed test cradle as well as the computational grid inside the nozzle, near the test article and inside the vacuum chamber. The unit for physical dimension is the inch. Figure 3 shows the student simulation results using WIND code. Mach number and Pressure contours near the nose of the test article were plotted. Using the CFD data generated by WIND code, pressure at the surface of the test article was extracted to calculate pressure force acting on the test article. Table 1 shows the calculated force on the test article nose. This force acts on the test article nose in the horizontal direction, which creates a flipping or rotational force on the article.

The overall force is 23 N. This force is applied to the structural design of the test cradle. Figure 4 shows the manufactured test cradle.

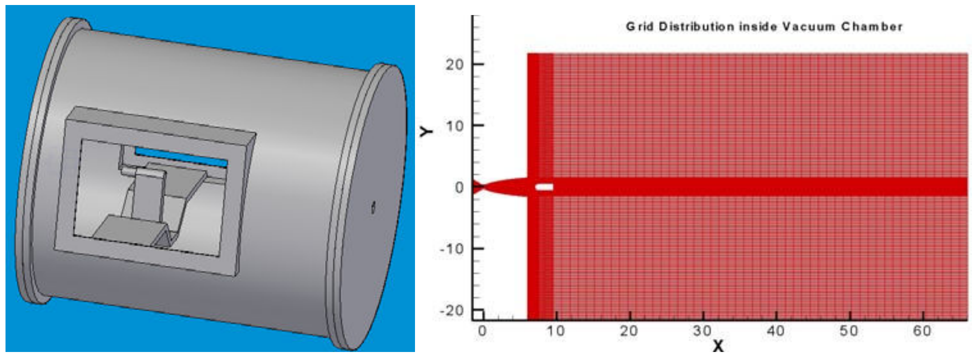

Figure 2. Vacuum chamber CAD drawing and Grid distributions based on the real physical dimensions.

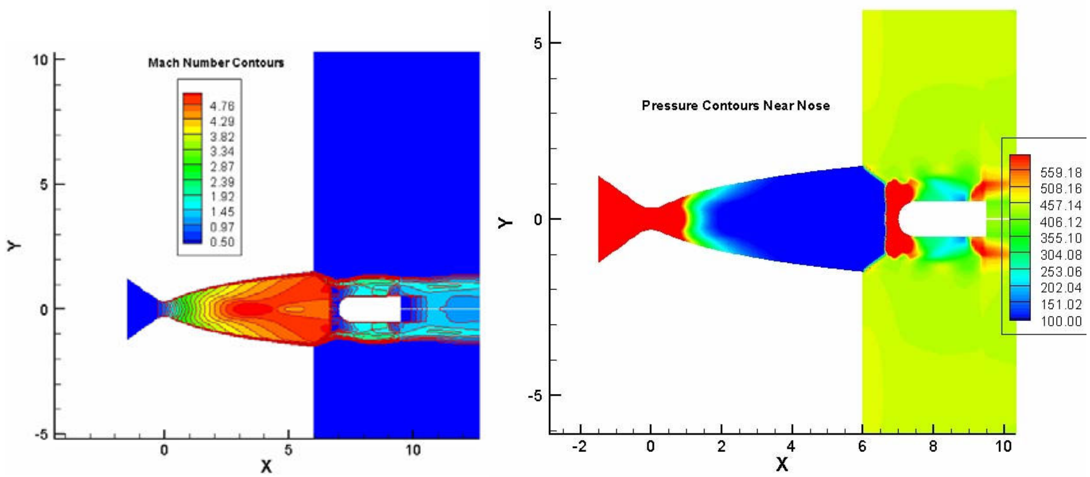

Figure 3. Mach number and pressure contours near the nose of the test article inside the vacuum chamber.

Figure 4. First production of test cradle inside the vacuum chamber.

Table 1: Calculated Flipping Force on the Test Article Nose.

i	Y (inch)	P (lbf/ft^2)	Area (m^2)	Average P	Fi	Force (N)
1	0.0000E+00	1.3718E+03	9.6270E-05	6.5510E+04	6.3067E+00	2.3681E+01
2	2.1794E-01	1.3647E+03	8.6145E-05	5.8077E+04	5.0030E+00	
3	3.0000E-01	1.0613E+03	7.6004E-05	4.8058E+04	3.6526E+00	
4	3.5707E-01	9.4616E+02	6.5874E-05	4.2953E+04	2.8295E+00	
5	4.0000E-01	8.4807E+02	5.5733E-05	3.8409E+04	2.1407E+00	
6	4.3301E-01	7.5635E+02	4.5613E-05	3.4193E+04	1.5596E+00	
7	4.5826E-01	6.7196E+02	3.5466E-05	3.0258E+04	1.0731E+00	
8	4.7697E-01	5.9199E+02	2.5339E-05	2.6515E+04	6.7186E-01	
9	4.8990E-01	5.1560E+02	1.5190E-05	2.2877E+04	3.4750E-01	
10	4.9749E-01	4.4003E+02	5.0746E-06	1.8953E+04	9.6180E-02	
11	5.0000E-01	3.5169E+02				

Assessment

Student learning can be assessed using both direct and indirect methods. The direct assessment tools include:

(1) Teamwork Assessment;
(2) White paper Proposal;
(3) Progress Report;
(4) Project Report and Oral Presentation/Final Defense

Table 2 shows the assessment for teamwork applied in this design class. Table 3 shows the assessment for the white paper proposal. Table 4 shows the evaluation criteria for the progress report. Each team has to defend their final project in front of all Mechanical Engineering faculties. Junior students are also invited to attend the presentation.

Table 2. Teamwork Assessment

1. Each group need to elect a project lead or group leader.
2. Group leader will receive 5 points bonus towards his/her final grade
3. Group leader is responsible for monitoring team project progress, accomplishment of team member assignment and delivering of the final report and product.
4. Team leader is the contact point for team.
5. All team members are required to deliver report and make oral presentation.

Table 3. Evaluation of White paper Proposal

Project Title and Team Members
Statement of the Work:
What are you trying to do;
Why are you doing the project (Why is there a need?) This include a brief literature review if applicable;
How to do it: Three possible designs, evaluate designs with constraints, select final design.
Describe strategy, method of attack. All proposed tasks should be measurable.
Where to do it: physical locations where project or testing will be conducted or take place.
Delivery product: At the end of the project, what will be delivered?
Proposed Timeline and Milestone: Example:
WORK BREAKDOWN STRUCTURE
Task 1. Analysis and Engineering
Task 2. Experimental Model Development
Task 3. Experiment

Task 4. R&T Roadmap Development
Task 5. Management and Reporting

	Week 1	Week2	Week3
Task 1			
Task 2			
Task 3			

Team Member Qualification
Proposed Budget: Be practical.
Maximum 2 pages, 12 pt Time New Roman font, 8.5” X 11” paper, single spacing, 1” margin top, bottom, left and right.

Table 4. Evaluation of Progress Report

Progress report: Cover
Abstract (Summarize Accomplishments)
Background (Why, description of entire project)
Achievements: What has been done and what have been accomplished. How did you accomplish it (in detail). Detailed results / Analysis / Design / Drawing.
Future Tasks

All team design projects are evaluated by Mechanical Engineering faculty in the final project presentation/defense. Faculty and students evaluate project deliverables and presentation based on criteria listed in Table 5.

Table 5. Project Evaluation Form

Project Presentation Evaluation Form

□ **Faculty** □ **Student**

ME Class: ______________________________
Class Presenter(s): ______________________________
Team Member(s): ______________________________
Project: ______________________________
Presented Date: ______________________________

		Rating: Poor (1); Fair (2); Good (3) ;Excellent (4)
Technical Presentation Contents	1. Were the objectives and purpose clearly stated?	
	2. Was the problem well defined?	
	3. Was the project properly justified (Why?) (Scientific, economic, political, value?)	
	4. Was the design, analysis and modeling understood?	
	5. Did the approach taken reach as part of a selection process?	
	6. Are the results technically and economically feasible?	
	7. Effective conclusions / recommendations?	
	8. Quality of the work or design.	

Presentation Style	9. Was the contents well organized?	
	10. Appropriate use of graphs, charts and board, audio, Video?	
	11. Was the message clearly delivered?	
	12. Teamwork was evident in the presentation (if applicable)?	
	Sub-Total: (Add scores from Line 1 to 12)	
Compliance Verification	**Mechanical Design Contents (0-100%)**	
	Thermal Design Contents (0-100%)	
Comments:		

As an indirect assessment, all students are encouraged to submit their design project results to a professional conference, such as AIAA or ASME for presentation and publication. External review of the project design is also encouraged if the project is related to research activities involving industry and government agencies. As a result of first semester senior design project, the propulsion team submitted a paper describing their design and analysis results to the 2007 AIAA Plasmadynamics and LASER conference. This paper was accepted for presentation and publication in June 2007.

Conclusion

A group of propulsion senior students applied CFD to provide analysis data for the design of a mechanical cradle required to support a test model used for investigation of electromagnetic control of shockwaves for hypersonic re-entry bodies. The senior design project was discussed. Assessment and evaluation of the student learning was discussed.

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