AC 2012-3222: IMPLEMENTATION OF A NEW MECHANICAL ENGINEERING PROPULSION DETAIL DESIGN CAPSTONE COURSE

Prof. Brenda A. Haven, Embry-Riddle Aeronautical University, Prescott

Brenda Haven teaches thermodynamics and three jet propulsion courses at Embry-Riddle Aeronautical University (ERAU). Prior to coming to ERAU in 2008, Haven retired from the Air Force after 25 years working as an engineer in support of the F-15 fighter, advanced turbine engine research and development, and as a professor at the Air Force Academy.

Prof. Michael Kenneth Fabian, Embry-Riddle Aeronautical University

Michael Kenneth Fabian teaches thermodynamics, jet and rocket propulsion, and thermal power conversion courses at ERAU. He retired from the Air Force after 25 years and worked on advanced rocket engines, jet engines, and directed energy weapons. He was Program Manager for the first Lamilloy turbine, Branch Chief for world's first cryogenic full-flow rocket cycle, Deputy Director for Propulsion Directorate developing next generation jet engines with three flow paths instead of turbofan's two paths, and Faculty Advisor for ERAU Jet Dragster Project, Formula Research Club (March race car chassis), University Space Launch Initiative Club. He has a Ph.D. in aerospace engineering, University of Notre Dame, 1995, M.S. in aeronautics and sstronautics, University of Washington, 1989, (Oates Fellow), and a B.S. in aeronautical engineering, U.S. Air Force Academy, 1984. Email: fabianm1@erau.edu.

Mr. Alexander James Herring, General Electric - Aviation

Alexander James Herring is a graduate of Embry-Riddle Aeronautical University, Prescott, with B.S. degrees in aerospace engineering and mechanical engineering. Currently, he is working for GE as a turbine engine component designer.

Marissa Pinnola, Purdue University

Marissa Pinnola graduated from Embry-Riddle Aeronautical University, Prescott, with a B.S. in mechanical engineering in 2011. She is currently a student at Purdue University working towards her M.S. in mechanical engineering. Her current research focuses on forced response issues in high-speed axial compressors.

Mr. Devan Berg, Embry-Riddle Aeronautical University

Devan Berg is a recent mechanical engineering graduate of Embry-Riddle Aeronautical University. Currently, he is seeking full-time employment within the aerospace industry. Specifically, he would like to make contributions toward the advancement of the gas turbine engine.

Implementation of a New Mechanical Engineering Propulsion Detail Design Capstone Course

Abstract

This is one of two papers describing the propulsion capstone design experience at Embry-Riddle Aeronautical University in Prescott, Arizona. In 2007, we began accepting freshmen for the first time into our Mechanical Engineering (ME) program. In the 2010-2011 academic year, we offered for the first time the new ME capstone design courses with concentrations in either air-breathing propulsion or robotics. This paper describes the propulsion detail design course; a second paper will focus on the initial propulsion preliminary design course[1].

The first graduating class of ME majors included three students in the propulsion track. The propulsion detail design course follows the preliminary design course which involved aero-thermodynamic propulsion system design and matching to an aircraft system. The detail design course focused on propulsion component design, hardware fabrication and component testing. This approach, using student created hardware, is unique in propulsion capstone design. This paper discusses the team's efforts in the detail design of rotating components, the fabrication of a prototype first stage jet engine compressor blade using rapid prototyping techniques, the development of in-house aluminum casting techniques, and the subsequent vibrational analysis and the use of Campbell Diagrams. In addition, the assessment of the course outcomes: demonstrating communication competence and proficiency in engineering design via a capstone experience with comments by members of our Industrial Advisory Board will be discussed.

As this was the first time the course was offered with a small group of students, this paper will also discuss the lessons learned as well as future adaptations that will be implemented as the population of students within the propulsion track increases as the overall ME program grows.

Introduction

The Mechanical Engineering (ME) program at Embry-Riddle Aeronautical University (ERAU) in Prescott, Arizona, is a four-year undergraduate degree program. The ME program was ABET accredited in 2011. Similar to the other Prescott ERAU engineering programs, the emphasis is placed on faculty-student interactions, design experiences, hands-on learning and a capstone two-semester design, manufacturing and testing sequences during the senior year. The engineering capstone design course sequences have historically had a first semester Preliminary Design course that focused on overall system analysis and computer modeling. This course was followed by a Detail Design course focused on specific components of the system from the first semester but with an emphasis on building and testing the component or components. The new

Mechanical Engineering program for the air-breathing propulsion track is following the same approach. The first semester preliminary design course is described in another ASEE paper. The capstone detail design course will be described in this paper. With the resources available at our university, we could not fabricate an entire jet engine so specific components were examined for construction and testing feasibility.

First offering of the ME Capstone Detail Design Course

Since the ME propulsion-track students had previously taken a basic course in airbreathing and rocket propulsion which covered jet engine cycle design point analysis and off-design point engine operation, and an advanced propulsion course that covered component design, they were well prepared for the first capstone preliminary design course to do cycle analysis, component matching and airframe integration for a turbojet-powered area-defense fighter. Since the emphasis on the follow-on detail design course involved component manufacturing and testing, a first stage compressor blade was chosen to be examined from a production and testing viewpoint. The university has a few rapid-prototype machines, two high-temperature ovens that are used for our materials courses and also a large shaker table for the structures and instrumentation courses. This combination meant that it would be possible to create a full-scale model of a compressor blade, to melt material to cast compressor blades and to test and analyze the vibration modes of the resultant parts. There is also a commercial casting operation, the Bronze Smith, in our community that was willing to help the mechanical engineering department show students the steps in the ceramic-shell lost-wax casting method. Most university capstone propulsion courses stop at the analysis level so the addition of hardware fabrication, testing and analysis made this propulsion curriculum unique. The opportunity for students to take the design out of the computer and on to the test bench improved their understanding of the design process. The course timetable and deliverables were the responsibility of the students, helping to transition them to an engineering employment experience.

Course Structure

The *Propulsion System Detail Design* course is a 4 credit hour course that meets twice a week for a total of 5 hours per week of lecture and laboratory time. The detail design course lectures covered component specific issues that had not been examined elsewhere in the curriculum. The first offering of the jet engine detail design course focused on compressors and rotating machinery. The lectures were front-loaded in the course to cover concepts of production engine families, compressor stall and surge, vibrations and Campbell diagrams, aeroelasticity, acoustics and secondary flows. A field trip to the Bronze Smith casting facilities was also included since none of the students had any experience with casting methods. The remainder of the course involved laboratory work sessions to build test hardware and fixtures, conduct computer analysis of the compressor blade and potential vibrational interactions with other engine components, cast blades, test the blades on the vibration table, analyze test results, prepare for an early Critical Design Review and also a Final Presentation to an industry panel.

Due to the first offering of the course, a parallel approach was used to allow students to work through testing and analysis issues earlier in the semester. An aluminum non-cambered first-stage compressor airfoil with the team's mean-line chord length and overall tip length was manufactured in-house on our milling machine to be the "work-horse" blade. This approach allowed the shaker table mounting fixture to be evaluated and the data acquisition systems to be tested and compared to ANSYS analysis of the vibration modes prior to the production of the "actual" cambered and twisted compressor blade. This approached allowed testing issues to be resolved and streamlined in parallel to the lengthy casting development process.

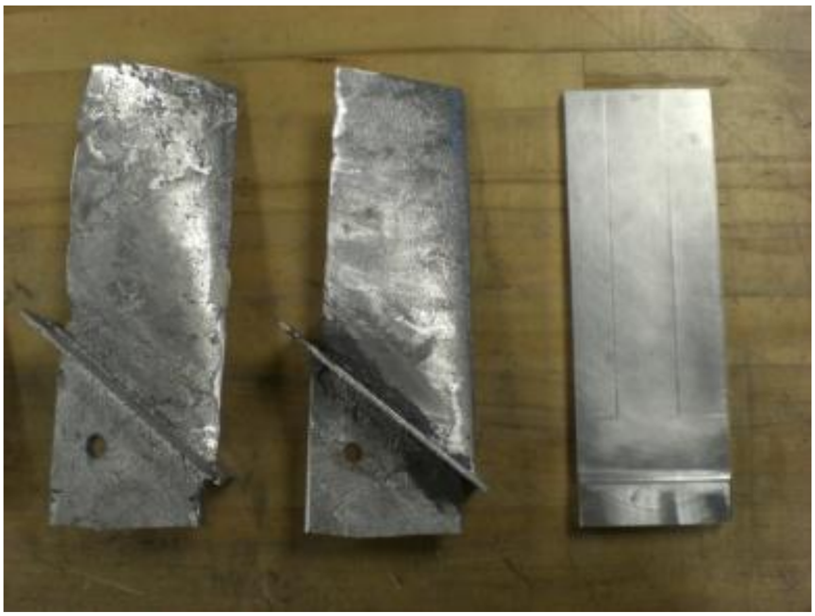

Figure 1. Cast Cambered and Twisted Compressor Blades compared to the flat "work horse" blade.

Course Content

The course lectures and laboratory activities will be discussed below:

Lectures

Lectures were limited to two hours per week for the first three weeks so the students could use the remaining laboratory time to work on long-lead items for their project. Since the students had just completed an aerothermodynamic design of a propulsion system in the preliminary design course, the concept of engine families (e.g. J85/CJ610/CF700) was presented. Due to the large capital cost of producing their new turbojet engine for a proposed area defense fighter, it was important to remind the students that their proposed engine design would be more successful if the engine core could also be used for perhaps a turbofan, turboprop, or turboshaft application to help better amortize production facility costs. Early history of compressor blade mounting methods, early blade failure modes and a review of modern manufacturing methods allowed the students to get some context of the project they were attempting. Compressor maps and the implication of compressor stall and surge were examined. While not possible in a university environment, large-scale testing facilities like the USAF Compressor Research Facility are used to map actual compressor performance and examine stall and surge conditions. A recurring issue for jet engine rotating machinery has been vibrations. Early steam turbines had similar problems and the Campbell diagram was initially developed to compare vibration modes of blades to potential excitation sources like support struts or adjacent stationary compressor vane rows[2]. The students learned how to interpret and also to create a Campbell diagram for their specific blade. They learned how to avoid vibration issues either through upfront design changes or changes in the engine control logic to avoid dwelling at certain rotational speeds that might excite engine vibrations. The ERAU Industrial Advisory Board requested that ME propulsion track students have some understanding of aeroelasticity and flutter since this is another problem area in the development of new engines[3]. Aeroelasticity is a coupling of unsteady aerodynamic lifting forces on compressor blades due to local flow velocity and angle of attack changes coupling with the blade structure. If properly designed, most aeroelasticity and flutter issues can be avoided. With ever tightening environmental regulations, jet engine acoustics represents an area that ME propulsion track undergraduates should have some understanding of the design issues. Although the mathematics of jet-engine acoustics is considered to be at the graduate level, the design philosophy and solution methods can be presented at the undergraduate level. The simplified flow models used to do the preliminary design of the engine components did not include what are known as secondary flows. Secondary flows are flow patterns created within jet-engine rotating machinery due to blade tip-wall clearances and boundary layer interactions that create horseshoe vortices around flow obstructions. In an academic environment, secondary flows are an area where students can examine issues through wind tunnel flow visualization techniques. This area might be developed in future years.

Casting Facility Visit

The Bronze Smith in neighboring Prescott Valley offered to have the students visit their facility to see all of the steps in the lost wax method of casting and also to see actual bronze casting pours. The students first visited the art studio portion of the facility to see finished sculptures and the level of detail possible thorough the lost wax method. In the main casting facility, the students saw the rubber molds created around a statue; the wax copy created in the rubber mold; the riser tubes to avoid casting voids; the numerous layers of coatings on the outside of the wax mold starting with a near talc layer to capture fine surface details to finally multiple gritty sand layers to give structural integrity to the mold; the removal of the wax layer in a furnace; the heating of the mold just prior to pour and the melting of the bronze in a natural gas furnace. The tour finished with the pours of a half dozen castings by a three-person crew in protective suits. The students were extremely motivated from the visit and had additional questions about casting techniques.

Initial Laboratory Efforts

Since the capstone project is student based, the team determined an initial schedule for the project and created a Gantt chart (named for Henry Gantt) which included project milestones and also a critical design review, a final presentation and a final report. The students quickly designed a “work-horse” blade using readily available 6061-T6 aluminum that was a flat plate of the same length as their first stage compressor blade. It had the same average chord length and the average thickness of their first-stage compressor blade. This simplified geometry could be quickly manufactured by the engineering college machinist. It would be used to test mounting fixtures the student also created and take an initial set of data on the school’s shaker table. The actual compressor blade design with blade camber and blade twist from root to tip was too complicated to be machined on-campus. A CATIA drawing of the actual blade was created and put into a format to be used by the university rapid prototype machines and off-campus milling machines. A local machine shop had done machining for other campus engineering and capstone projects so they were contacted about using their multi-axis milling machine to fabricate the compressor blade. Unfortunately, their estimated cost to manufacture an aluminum compressor blade was $4,000 which greatly exceeded our course project budget of $1,000. Since a machined blade was not possible, the students examined casting methods and materials. The students looked at bismuth alloys due to their low melting point and also aluminum alloys. Potential casting methods included the lost wax method and the “green sand” method which utilizes a moist clay-based sand material for the mold.

A test plan was developed for the work-horse blade so any testing and analysis issues could be resolved prior to the testing of the actual cast blade. The test plan included all procedures to mount the blade on the shaker table, conduct vibration testing on multiple axes, and a method to reduce the data and compare it to the analytical Campbell diagram. ANSYS modal analysis of the work-horse and actual cast blade allowed the team to determine the optimal locations to place the accelerometers to measure the bending modes on the shaker table.

The students created Campbell Diagrams plotting rotational speed versus frequency. The plots show the calculated vibration modes of the compressor blade and bending-mode natural frequency changes due to stiffening with increased rotational speed. These ANSYS-based natural frequency curves were cross-plotted with potential excitation sources like a one-per revolution inlet distortion or twenty-excitations per revolution due to the inlet guide vanes. If the potential vibration excitation source frequency coupled with the natural frequency of the compressor blade at a common engine RPM like idle, cruise or maximum power, then there is a strong likelihood of compressor blade failure similar to the famous Tacoma Narrows suspension bridge failure.

Material Selection

Since multi-axis machining of a blade was not possible, the students evaluated various materials including bismuth alloys and also aluminum alloys. Bismuth alloys have very-low melting points but lack the strength characteristic of aerospace materials like aluminum and titanium. Aluminum A-356 was chosen due material strength characteristics being similar to titanium blades and its use as a casting material. The melting point is 1375˚F which was within the capability of the university's high-temperature ovens.

Critical Design Review

A panel of current and retired faculty members reviewed the team's results for the work-horse blade testing and their plan for the casting and testing of the actual cambered and twisted blade. The rapid prototype model of the compressor blade was completed just in time for the Critical Design Review. It helped the panel see the scale of the proposed casting concept. Overall the panel was impressed with the quality of the results to date and cautioned the students about the hazards of casting molten aluminum.

Casting Compressor Blades

The students created a 14" x 8" x 6" metal frame for their casting mold using welded plate steel. Indexing pins were added so the mold frame could be easily split to remove the rapid prototype part, creating a void in the casting assembly. Pour and riser vent holes were created to avoid incomplete casting issues. Many teething problems were solved during the casting process. The total time required for a pour was approximately 9 hours due to the slow melting process in the high-temperature ovens and multiple attempts to cleanly split the casting case to remove the rapid prototype part and reassemble the mold. After the pour, the mold was left to cool overnight and opened the following morning. Unfortunately the students chose to cast in a horizontal axis rather than a vertical axis like the local Bronze Smith operation. This caused some of the sand collapse issues and also caused void fill problems on many of their casting attempts. The aluminum material had trouble moving 10 inches horizontally to fill the last corners of the blade. Frequent sand collapses force the team to start again packing the green sand into the mold. The students eventually realized their error and compensated by heating 2 crucibles of material to pour and also slightly tilting the mold to have gravity help fill the void. If they could have done it over again they would have cast vertically.

Figure 2. Student getting crucible to pour into sand casting mold below

Vibration Testing

The students used the university shaker table to conduct measurements of the vibration modes of the cast twisted and cambered compressor blade. Based on ANSYS analysis, 6 locations were determined to get the best vibration data using the accelerometers. Since the data acquisition system could only take three channels of data, all test were run at one set of locations and then run again at the second set of accelerometer positions. The shaker table sweeps through a range of frequencies until it either reaches the table maximum frequency or it reaches a table g force limit. Unfortunately, many of the tests with the actual compressor blade hit the g limit at lower frequencies than desired. This meant the students had to analyze the data below that frequency and estimate the vibrations at higher frequency by how well the instrumentation results matched the ANSYS vibration estimates at the lower frequencies and extrapolate the expected potential higher frequencies.

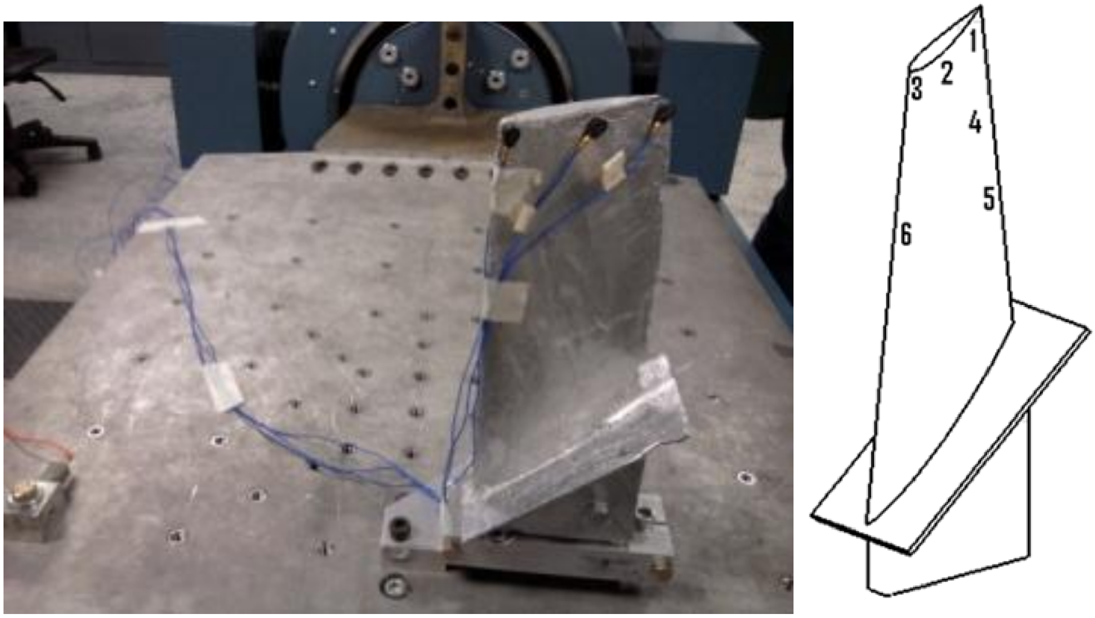

Figure 3. Actual blade instrumented on vibration shaker table and instrumentation locations

Analytical Results

The vibration analysis showed that the second bending mode of the actual compressor blade would potential couple with an excitation source that provided 2 disturbances per engine revolution at 8,000 rpm on the turbojet engine. For instance, if there were two engine support struts to position the front bearing cavity, these struts would provide a blade vibration excitation source. Fortunately, this rotational speed did not match idle, cruise, or max power operating speed so the engine fuel controller could operate to avoid staying at 8,000 rpm to try to prevent any vibrational issues. A potentially bigger problem was the 9^{th} bending mode of the compressor blade matched with the potential excitations of the 20 inlet guide vanes of the aircraft cruise throttle position of 6782 rpm. Higher order bending modes tend to have very small vibration displacements but if this occurred at the cruise condition where the aircraft would spends hours of flight time, the blade could fail due to high cycle fatigue similar to bending a paperclip a small amount millions of times. Either the compressor blade would need to be redesigned, the number of inlet guide vanes would have to change, or a slight variation in cruise speed would be needed to avoid the vibrational issue. The semester ended before the students could do the next iteration of potential designs to prevent the vibration issue.

Student Leadership Opportunities

Since there were only three students in the first offering of the course, each student was designated Design Team Lead (DTL) for one-third of the semester. The DTL had to provide weekly status reports, to conduct team meetings to keep the program on track, to monitor the project schedule and to also rate himself/herself and their team-members' work efforts. As the course student-count grows, the opportunity for every member to be the leader will be lost since very-short leadership schedules add confusion to the team. In addition to the weekly status report written by the DTL, a Top Issue Paper was submitted each week. This paper documented the biggest issue the team had to wrestle with during the past week and how they investigated and moved forward on the technical, financial and schedule impacts of the issue. The Top Issue Paper was written each week and it was a weekly rotated duty among the team members. Often the top issue was not in the work domain of the designated writer so he/she had to collect the facts and resolution method from the other team members. The collection of top issue papers helped the students see how the project evolved over the semester. The College of Arts and Sciences provided a professor to act as a consultant to instruct the student how to prepare proper weekly status reports, top issue papers and a final report. Additionally, the professor coached the students on critical design review and final presentations to improve quality.

Project Costs

Table 1 shows the actual costs for the project with a $1000 project budget. The rapid prototype cost is a materials-use fee based on volume of material consumed.

Table 1: Project Costs

Item	**Cost (USD)**
3-D Printed Model Compressor Blade	260
Aluminum A-356	55
Graphite Casting Crucible	41
Green Casting Sand	75
Casting Safety Suit	205
Casting Safety Hood	169
Mold Frame Steel	17
Re-sealable Casting Sand Bucket	2
Total	$823

Communication Outcomes

The students provided oral presentations for their Critical Design Review to a faculty panel and their Final Presentation to an industry panel. Additionally, the students conducted individual oral defenses of their portion of the capstone project to a panel of two propulsion faculty members. This allowed the students to individually present their contributions to the project and provide recommendations for future versions of the course. Weekly status reports and top issue papers tracked the project throughout the semester. The students completed a final report documenting their project results and provided recommendation for future classes.

Industry Panel Comments

One of the strengths of the capstone program is having engineers from industry evaluate the final presentation for all capstone design courses. They provide their assessment of the student's performance in the areas of Technical Accuracy and Completeness, Organization and Development of the presentation material, Neatness and Professionalism, and use of Visual Aids and Presentation skills. These areas are rated by the panel on a scale of 1 to 5, 5 being the highest level of performance. The results of the four-member panel are given below:

Table 2: Industry Panel Scores

	Average Score out of 5
Technical Accuracy and Completeness	3.9
Organization and Development	4.4
Neatness and Professionalism	4.6
Visual Aids and Presentation skills	4.5

This panel scores indicate technical accuracy as the weakest area, the students finished casting the best compressor blade with less than 1 week left in the course so the data analysis could have been better given more time. The rest of the scores are typical of our other capstone design courses.

Overall the industry panel was very impressed with the accomplishments of three students in a first-time offering of the capstone detail design course. The panel had suggestions for areas that would have improved the presentation clarity and also vibration analysis tips. The panel was also very interested in the student's view on what they like the most and the least about the course. Universally, the comments were that casting materials is more time consuming and harder than the students expected. The students thought the hands-on aspect of building and testing representative jet engine hardware was the best part of the course.

Lessons Learned

Capstone engineering projects involving hardware fabrication, testing and analysis take longer to accomplish than the students tend to realize. Ambitious concepts are difficult to complete in one semester and as a result data analysis and final reporting tend to suffer. One solution was the use of a frontrunner test article that allowed the students to eliminate many testing and analysis problems earlier in the course than if they had waited to produce their final "actual blade" and then begin testing and analysis.

Part of the student learning process involves having difficulties along the way. It would be very easy for the professor to direct the design effort but it is better to let the students struggle with how to move the project forward and get valid results. The early lecture material gave the students the “tools” but they had to learn how to use the tools during the semester. The open ended nature of the project made the students uncomfortable but also helped them mature for real-life engineering.

Much of the infrastructure for the capstone project already existed for other engineering courses. By working with other faculty to tailor a propulsion project to the campus capabilities, it allowed students to propose, fabricate and test a representative engine component within the constraints of an academic environment. They learned about and resolved problems that would not have been apparent in just a “paper” or “computer” study. Hopefully the discovery process will serve the students well in future engineering efforts.

Future Work and Summary

The 2012 offering of *Propulsion System Detail Design* has 11 students so two component areas will be examined: the compressor/fan and the afterburner. The compressor or fan blade effort will be expanded since many of the initial casting issues have been resolved by the first class of ME students. In addition to the vibration testing, the university tensile testing machines may be able to test the load strength of the blade mounting dove tail and provide a comparison to analytical results. Additionally, an in-house water tunnel can allow the exploration of secondary flow issues in vane/blade rows. A small section of the afterburner will also be constructed since the university has a small turbojet engine that could have an afterburner added and also has a ramjet test rig with a very large blower to create the required ramjet airflow conditions. Either approach will allow students to create a test rig/assembly and to determine the required instrumentation to test ignition and stable combustion of their afterburner design.

Undergraduate capstone design courses in air-breathing propulsion like those at the USAF Academy[4] and ERAU Daytona Beach[5] tend to stop at the thermodynamic analysis level. The opportunity for students to take a portion of their design to the next level of hardware construction and testing greatly improves student enthusiasm for engineering and gives them hands-on experience that is valuable to propulsion and power generation industries and research facilities.

Acknowledgements

Mr. Ed Reilly at the Bronze Smith, Prescott Valley, Arizona provided a facility tour and answered numerous student questions on casting.

Dr. Angela Beck, College of Arts and Sciences provided tremendous support for student presentations and written documents.

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