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# Creating a Functional Model of a Jet Engine to Serve as a Testbed for Mechanical Engineering Students' Capstone Design Work

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# Creating a Functional Model of a Jet Engine to serve as a Testbed for Mechanical Engineering Student's Capstone Design Work

**Yasser Al-Hamidi, Shameel Abdulla and Ibrahim Hassan**

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## Abstract

A gas turbine is an internal combustion engine that converts natural gas or other liquid fuels to mechanical energy, to drive generators or to provide the energy in water desalination or in petrochemical plants. Jet engines are gas turbines optimized to produce thrust from the exhaust gases. The design of jet engines involves all of the fields of mechanical engineering, but thermodynamics, heat transfer and vibrations are of particular importance to the engine design. In this paper, we present the work done by a group of senior mechanical engineering students as part of their MEEN 404 experiment design course project. Students were asked to slightly modify an open-source simplified jet engine CAD model for 3D printability, build and test the 3D printed functional model in different compressor and turbine configurations. For that, the students had to go through the entire design process, from functions through requirements, through alternative designs to be able to integrate the newly modified parts into their testbed. They had to equip the system with all the necessary sensors and instrumentation to control and monitor the engine while conducting many tests to study the cost, efficiency, and performance over a range of parameter values and environmental conditions such as the number of blades, blade angle of attack, and outlet nozzle size. This project was a good tool to promote student's engagement and development, advance their critical thinking, and improve their problem solving and leadership skills. The project was also of a great help to students in understanding many mechanical engineering topics covered in other classes, especially after being complemented by a workshop hosted by General Electric (GE) at Qatar Science and Technology Park, where students received a hands-on training session on regular maintenance work carried out on aircraft engines.

## Introduction

The jet engine is a marvelous piece of engineering that encompasses many fundamental engineering principles. Model jet engines have been used in laboratory setting to enhance students' learning experience (1). The primary objective of this project was to help the students understand the challenges and requirements to design an experiment. The students were asked to work on two different aspects of the jet engine: Its performance characterization and its vibration analysis. As the semester progressed, they were able to gain in-depth knowledge about these topics. Building a jet engine was not an objective, hence the students found an online scaled version (2) that they downloaded and modified for their experimental needs. The project was split into three parts: Model selection and alteration, Assembly and design reiteration, Experimental setup and testing.

This paper will try to detail out the experiments and outcomes achieved by the students as they completed the objectives for their MEEN 404 course.

## The University and Students

Texas A&M University at Qatar (TAMUQ) is an international branch campus, with more than 8,000 miles away from the main campus at College Station, Texas. Despite its location in the Middle East, students at TAMUQ are required to complete identical coursework as their peers on the main campus, including courses on American politics and American history. The student body is comprised of students from around the world, but primarily students come to TAMUQ from the Arab Gulf region and Asia. TAMUQ offers Bachelor of Science degrees in chemical, electrical, mechanical and petroleum engineering. The university maintains an enrollment of around 550 students, of which 58% are male and 41% are female [4]. Nearly all of the students at TAMUQ speak English as their second or third language. The faculty of the university is as diverse as the students, with faculty from the United States of America, Jordan, Lebanon, Egypt, Greece, France, and elsewhere. TAMUQ is located in Education City and funded by the Qatar Foundation, a non-profit organization founded in 1995. Education City hosts the branch campuses of five other American universities, including Georgetown School of Foreign Service, Carnegie Mellon University, Northwestern University, Virginia Commonwealth, and Weill Cornell Medical College. Education City is a bustling community of students and faculty in all disciplines (3).

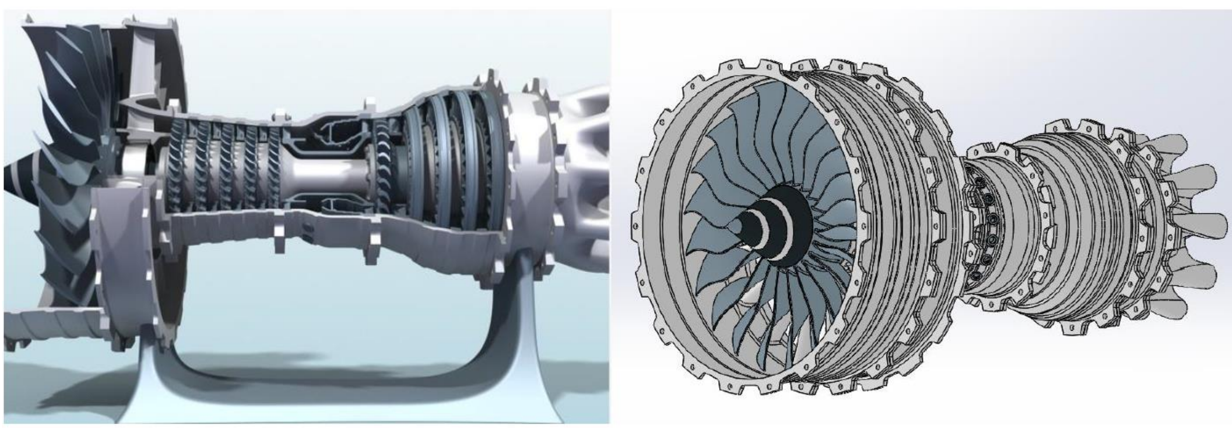
## The Project

Students in the MEEN 404 course project are required to identify topics and develop experiment designs that include establishing the need, functional decomposition, requirements, conducting the experiment, analyzing and interpreting the results and writing the final report that documents all of these aforementioned sections. In this paper, we discuss the work that has been done by two teams (5 students each) who worked on the jet engine project. The first team's main objective was to conduct an envelope analysis and determine the damage index on the jet engine, while working with different faulty bearings. Their study would allow them to diagnose the jet engine for faulty bearing by analyzing the vibration of the jet engine. The second team used compressed air to mimic internal combustion and to power their engine, and a fan to simulate airflow during flight. Their main objective was to study the thrust generated by the engine at various inlet pressures and various inlet air flow rates. Both teams faced many challenges during the semester to build their test setup and to achieve their objectives, which will be covered in details in the rest of the paper. However, the weekly meeting with the course instructor and technical lab coordinator were very helpful in providing sufficient guidance to sort our most of these issues, and ensuring that the teams progress in their work on a regular basis.

## Facilities

During the first phase, the students spent a good amount of time researching about feasible 3D models that they could download and print in the university's Rapid Manufacturing Facility. The Rapid Manufacturing Laboratory at TAMUQ, which hosts a number of machines that facilitate and help students in their course and senior design projects. It provides the means by which students can print their prototypes or functional parts both in metals and plastics, so they get an idea and feel of their final product. This lab has a total of eight 3D printers out of which four are plastic FDM (Fused Deposition Modeling) 3D printers with different build envelops and resolutions. These printers are capable of printing different kinds of plastics, which include: ABS-M30i, ABS, PC-ABS, and PC-ISO.

The two groups had to communicate and select one design to work on. The criteria that were to be fulfilled while selecting the design were: 1- It should closely resemble a real jet engine model. 2- It should be printable (or require only minor modifications)/ 3- It should be a CAD file so that the students can use their skills in SolidWorks to work on the model. Even though 3D printing is a very versatile manufacturing process, the students still had to face some design challenges such as thickness of the parts and tolerances of the parts that fit together. Fig. 1 below shows the jet engine CAD model which both teams agreed upon.



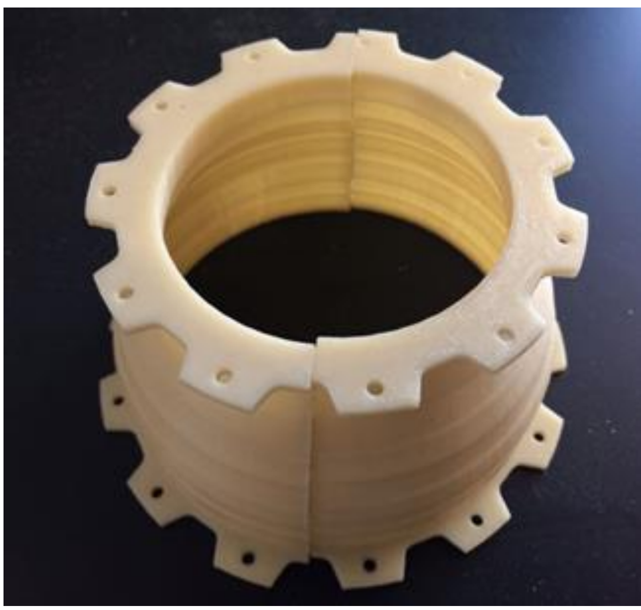
(a) (b)

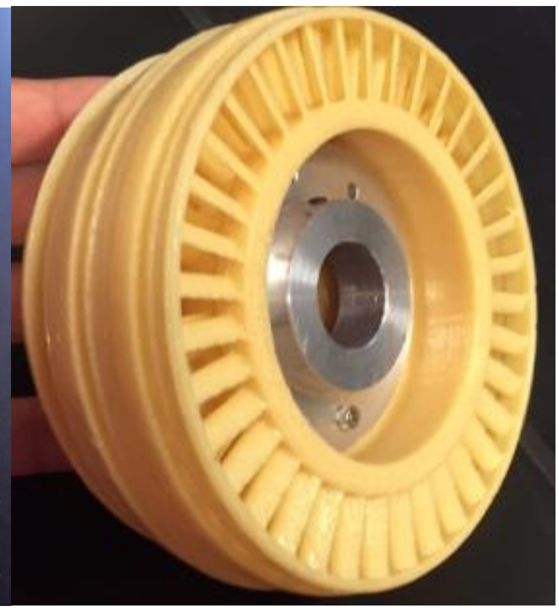
Fig 1. (a) The jet engine model selected by the students. This was a model purposed for showcasing and was cut in order to show the internal workings (b)The students then modified it to create a closed system.

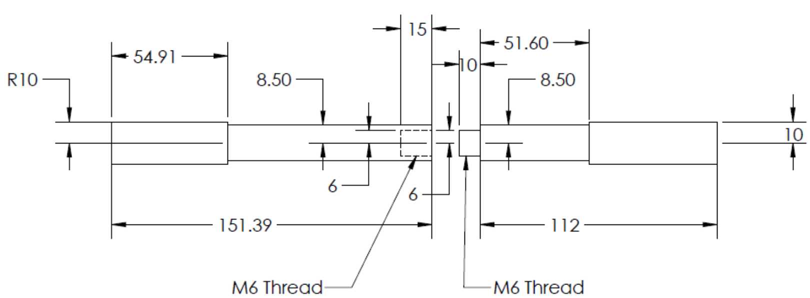
The students had to modify the design considerably in order to accommodate the auxiliary devices they would connect to the engine model such as the source of power and the sensors. The performance team decided to power the engine with compressed air. Therefore, they had to ensure that the design is completely closed, and that it has the necessary connecting ports to accept compressed air into the combustion chamber. The vibration team had to ensure that they could connect the electric motor to the jet engine. Hence, they modified it differently than the performance team. The vibration team did not need a closed casing. They however required the front and back of the engine to be open such that that they could mount the entire assembly on a rotating shaft. Therefore, they decided to get rid of the fan cone and the exit nozzle.

Once the students had the model ready for print, it was 3D printed in ABS plastic**.** The students spent two weeks assembling the printed parts. During the assembly, they faced challenges that they couldn't perceive using the CAD software. Some parts needed to be split in order for them to be assembled properly (Fig. 2 a). Some parts such as the shafts and flanges were redesigned and made from aluminum to help the students to connect the 3D printed parts to the machine easily

(Fig. 2 b). This allowed the vibration team to lower the tolerance for the outer diameter of the shafts. To carry out the vibration analysis, the vibration team had decided to use an existing vibration analysis rig from GUNT (Fig. 3). The rig, which included the data acquisition and required vibration sensors, provided students with a flexible and modular learning platform to conduct their vibration analysis. It also helped them to link practical work on the experimental setup and the theoretical/analytical aspects of diagnosis thus fostering integrated learning. When used in conjunction with the 3D printed parts, the full experimental setup significantly sped up the students' understanding of machine diagnosis.


(a)


(b)



(c)

Fig. 2. (a) Some parts had to be split in order to assemble them properly. (b) & (c) Some elements were redesigned and milled from aluminum in order to reduce lead time on manufacturing and to get better tolerances.

## Project Challenges

The main challenge for the students was that the topic chosen was relatively new to most of them. None of them had a turbomachinery "elective" course, by that time. This required them to investigate deeply about it. They spent the first portion of the semester trying to understand the different characterizations of a jet engine. By the end of phase 1, they had a better understanding of what needs to be done in order to make the project as meaningful as possible.

The initial plan was to have one 3D printed jet engine, and have the students install their sensors and actuators on to the same system. However, this proved challenging since both the teams wanted to choose a different method of actuation, and different configurations. Since the CAD designs were ready, it was decided to 3D print another setup so that the groups could work independently.

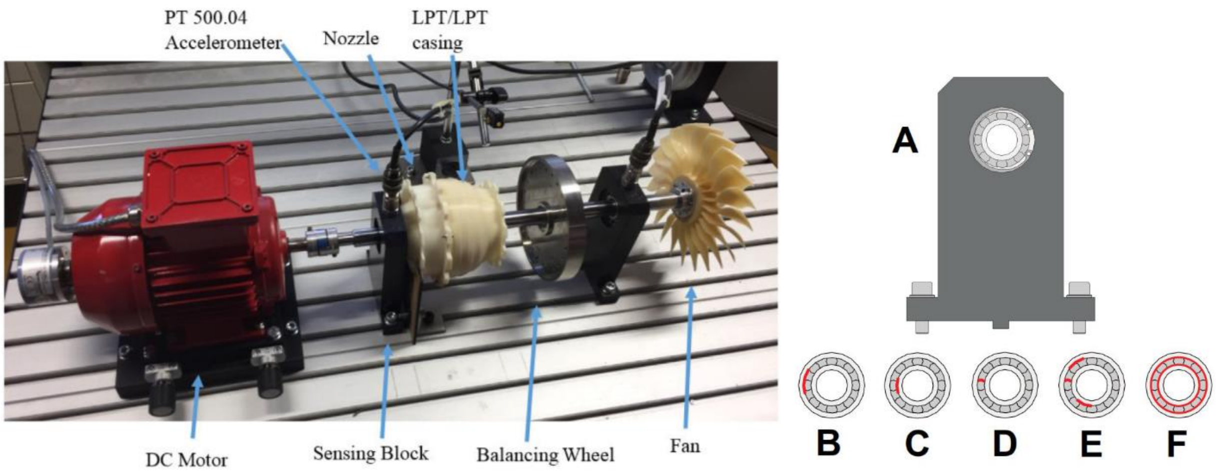
The other challenge students faced was the time required to get the finished 3D printed parts. The 3D prints usually have support material. The support material is removed by dissolving it in a hot chemical bath which took some considerable amount of time. Therefore, in order to reduce time needed to print all the parts, the students decided to redesign the model such that some parts like the shafts and flanges could be manufactured from aluminum using traditional manufacturing techniques such as the lathe and the milling machine. This also taught the students the technical drawing skills needed to communicate with the machinist.

**Experimental setup and testing**

Since the model is expected to rotate at considerably high speeds, making sure the experimental setups were safe was a high priority. Hence, to ensure that students are aware of all hazards involved in their experimental setups, they were asked to submit a project safety analysis (PSA) for their projects. The PSA provided students with the opportunity to identify potential risks and hazards, implement safe standard operating procedures, and implement necessary safeguards to mitigate consequences. To work safely, both teams decided to use the GUNT machine, which had a hood that can be closed while the experiment is run such that, in case the 3D printed model fails and breaks apart, the projectiles will be contained within the setup.

The vibration team also benefited from the speed-controlled DC motor which comes with the GUNT machine to control the speed of rotation of their jet engine, since the speed of the engine was a control variable for their experiments (Fig. 3 a). The laboratory trolley mounted with aluminum t-slots made it very easy for students to assemble their engine setup. Moreover, the setup had a set of sensors that the students found very useful in completing their objectives. The software was also available that would provide them with the required damage index for different test runs. Their experimental goal was to conduct envelope analysis on the jet engine for different types of faulty bearings (Fig. 3 b). This analysis would allow them to characterize the fault in a bearing using just the vibration data.

The second team of this project wanted to mimic the internal combustion using compressed air. They required that the jet engine to be closed with a casing unlike the vibration team. They also had a blower in front of their model to provide a constant flow rate of air through the engine. The compressed air was directly injected into the combustion chamber using a series of pneumatic pipes and connectors. A pressure regulator was used to control the pressure of the compressed air. Hand held sensors such as a laser tachometer, an air velocity meter and a micro-manometer were used for measurements.




(a) (b)

Fig. 3. (a) The experimental setup for Vibrational analysis. The printed parts are coupled with the test rig from GUNT. (b) The types of bearing faults that the team studied.

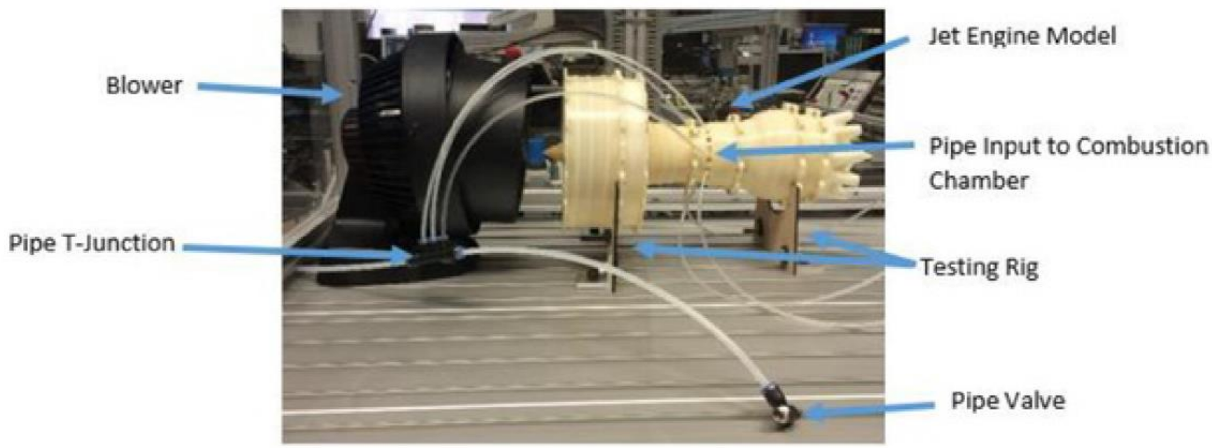



Fig. 4. The experimental setup used by the performance team. The pneumatic lines provided compressed air for mimicking combustion and the blower provided a constant airflow to mimic flight.

**Results and Analysis Made by the Students**

The work objective of the vibration team for this project was to assemble the inner spool of the 3D printed jet engine on the GUNT Hamburg machine, balance it, and then study its vibrations for different faulty bearings through envelope analysis. The team had 6 weeks to conduct the experiment, collect the data and analyze them, after they complete the setup of the jet engine. The faulty bearings were taken from the GUNT machine which has five different faulty bearings (B, C, D, E and F while bearing A has no faults). The difference between the bearings is the location and severity of the faults, which is reflected in the envelope analysis plots for each bearing. The GUNT software generated the plots for the envelope analysis by interpreting the data from the PT 500.04 accelerometer.

Initially the vibration analysis was performed on a healthy bearing (bearing A) which was used as a reference to aid in analyzing the effects of such faulty bearings on the vibration characterization of the inner spool. Figure 5 below shows the envelope spectrum of the healthy bearing. As shown in this Figure, the damage index of the healthy bearing is 0.67, which is almost negligible.

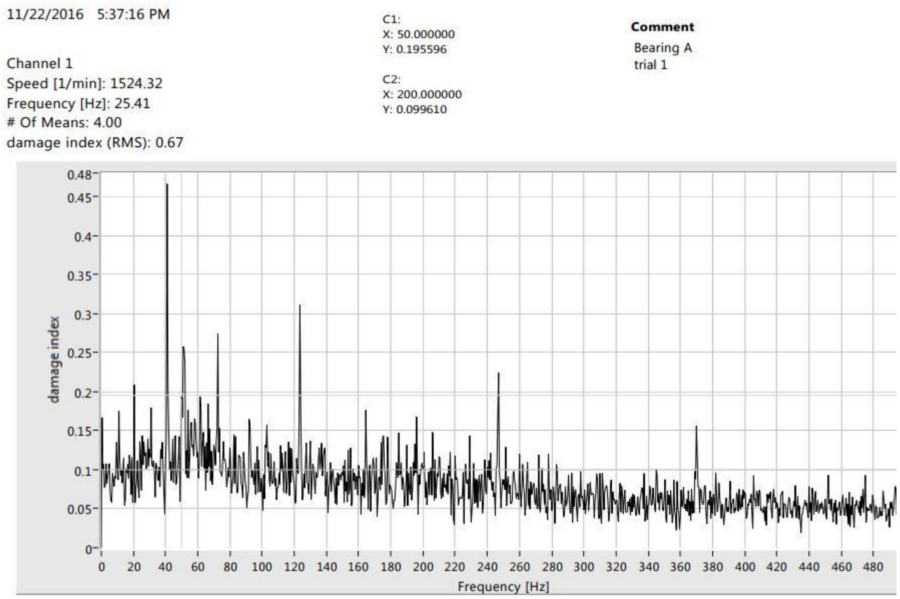



Fig. 5. Envelope spectrum of a healthy bearing.

Figure 6 below shows the envelope spectrum of bearing B, which has a damage in the outer ring:

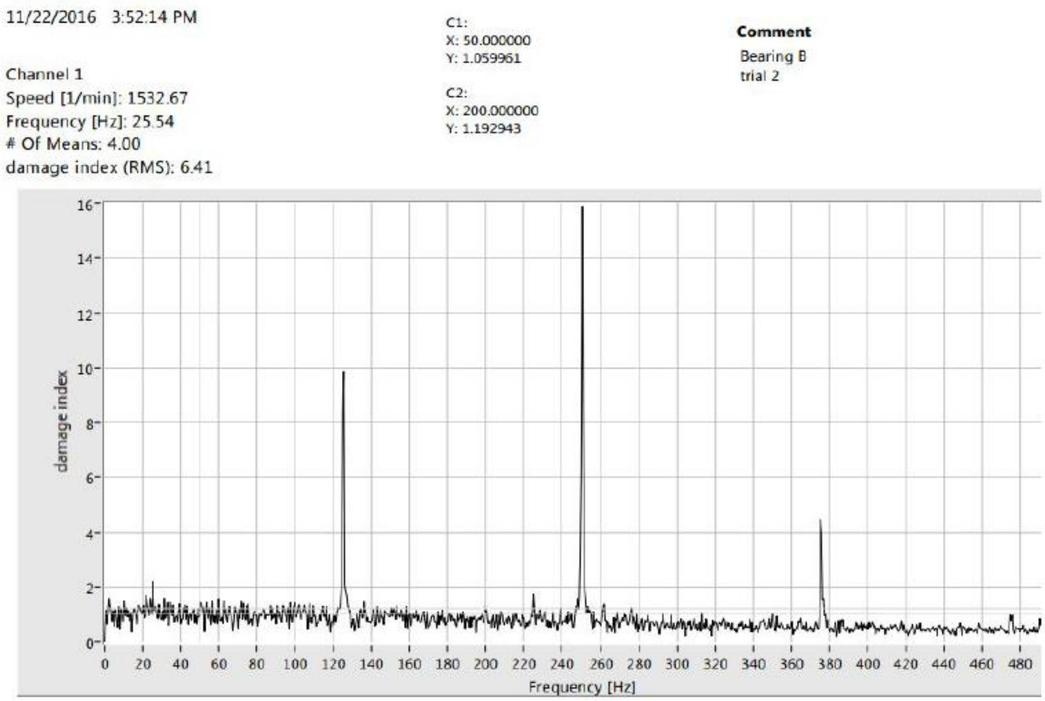



Fig. 6. Envelope spectrum of a bearing with a damage in the outer ring

For each faulty bearing, three trials were performed and the damage index was recorded for each of them. To validate the data, the mean and standard deviation for the damage indices of each bearing were calculated and used in the ANOVA analysis of the results. This study aided in detecting and determining the severity and location of the faults in the bearings for not just the 3D printed engine but even real engines. Using the results that were collected in phase 3, the team are able to identify the type of fault (if any), severity and location of the fault for any unknown suspicious faulty bearing. This reduces the time and portability of damaging other parts of the jet engine during operation, since this is a non-intrusive technique to detect the damage of the bearing. The other team of this project performed the thrust measurements. The volumetric flow rates at the inlet and exit of the model jet engine were recorded along with the velocity measurements. These values were measured for the four cases (Case 1: No Blower, Case 2: Blower Speed 1, Case 3: Blower Speed 2, Case 4: Blower Speed 3) and the thrust values for each case were measured. The rotational speed of the outer fan of the model jet engine (Low Pressure Fan) was also measured for each value of inlet pressure of the compressed air for the four cases. The compressed air input was varied from 0.5 bar up to 4.5 bars with increments of 0.5 bars. The tabulated values for the thrust measurements in the report submitted by the students showed results with high uncertainties. Students explained the different sources or errors and future work to correct it.

## Learning Assessment and Conclusions

The assessment of this experiment was made through exams, oral presentations, and a final report. Overall, the two groups for this experiment showed no notable difference in learning compared to the other groups of this course, assigned to different projects. However, when one looks at the jet engine project students, it appears that they benefited more from the assigned multi-disciplinary hands-on project. Students were able to appreciate the knowledge they had in previous engineering courses, e.g. how to measure vibrations, how to select shaft bearings, how to 3-D print complex systems and so on. The students were also able to test the performance of the engine and better understand the implications of using compressed air to simulate the combustion of hydrocarbons in turning the turbine blades. Once the engine started functioning, the students were able to identify the shortcomings of the design, to make modifications and to find alternatives to the issues. During the process of iterative improvement of the engine and the experimental setup, the students were able to attain critical knowledge of safe experimentation procedures, equipment procurement options, and data analysis. Following is a sample of the self-evaluation by the students: “the project gave myself along with the team an opportunity to better understand the jet engine in motion, the experimental process, and the data analysis process. I researched how 3D printing is turning from a method of prototyping to rapid manufacture, especially in parts that are too complex to machine easily, like turbine blades”.

In conclusion, the students completed their course objectives successfully. They also met the ABET criteria put forth for the course, e.g., to be able to justify the experimental needs and specify clear objectives, and to identify the variables of interest and the needed sensors to measure them. They were able to apply their knowledge of mathematics, science and engineering to tackle the challenges in their assigned project. Since the two teams had to work together in some aspects of the project, they learnt key communication skills. They also learnt how to use statistical tools such as ANOVA to analyze and understand the data they recorded.

As a future work, the authors believe that 3D printing should be used as a key tool in all engineering courses. Most of the time, students are limited to experimenting with existing setups. Going through the process of actually designing the experimental setup will allow the students to enhance both their design skills and their engineering knowledge. It also allows them to be creative within the time frame of a semester. Jet engine in general is a rich piece of engineered product that shows many engineering principles that the students could investigate, study and improve. As a future work, this would involve design analysis where the students can change the blade design, number of stages or even come up with completely new designs that they could quickly prototype and experimentally evaluate.

# 1. References


1. *Laboratory Experience With A Model Jet Turbine.* **Matsson, John.** Salt Lake City, Utah : ASEE Conferences, 2004.

2. **Shakal, Chris.** 3D Printable Jet Engine. *Thingiverse.* [Online] February 9, 2016. http://www.thingiverse.com/thing:1327093.

3. *The STEM Loop: Undergraduate Engineering Students Create a STEM Children's Book.* **Seawright, Leslie and P.E., Ibrahim Hassan.** New Orleans, Louisiana : ASEE Conferences, 2016.