DEMONSTRATION OF THE DESIGN OF A FIRST-STAGE AXIAL-FLOW COMPRESSOR BLADE USING SOLID MODELING THROUGH A CLASSROOM PROJECT

Breon Williams, Brandon Howard, Xiaoqing Qian and Z.T. Deng, Alabama A&M University

Abstract

This paper presents a classroom project to design and analyze a first-stage axial-flow compressor blade using performance analysis, blade design, and solid modeling tools. Step-by-step instructions were used to provide a sample blade design project template. The first step of the design project was to conduct a parametric design-point performance analysis of the axial-flow compressor of a single-spool gas turbine engine to produce 12,500N of thrust at sea level. A performance analysis suggested that an axial-flow compressor with a pressure ratio of 6 and a mass flow rate of 38.7kg/s was required. The second step of the design project was to evaluate the compressor design using a simplified design tool. An initial six-stage constant mean radius axial-flow compressor was adopted. The Compressor Preliminary Analysis Program (COMPR) software package was used to calculate the blade profiles and flow angles for the rotor and stator of each stage at different radial based on a free-vortex design. The third step of the design project was to conduct a three-dimensional CAD design of the first-stage rotor blade using SolidWorks based on the blade profiles obtained in the second step. The fourth step of the design project was to conduct a stress analysis on the assembled first-stage rotor with 1508 rad/s rotation using ANSYS. Results indicated that for the initial design configuration, the maximum principle stress inside the blade exceeded the material limits for rotational speed of 1508 rad/s. As a result, the rotational speed of the first-stage rotor was reduced to 1370 rad/s. This reduced the total pressure ratio for the first stage and it was calculated that 7 stages of an axial-flow compressor would be needed to meet the design specifications. This paper provides a template for designing the first-stage compressor blade with emphasis on application of solid modeling using Solid Works and ANSYS.

Introduction

According to the Accreditation Board for Engineering and technology (ABET) requirements [1], all mechanical engineering students should be able "to design a system, component, or process to meet desired needs within realistic constraints such as economic, environmental, social, political, ethical, health and safety, manufacturability, and sustainability". Students also should be able to "use the techniques, skills, and modern engineering tools necessary for engineering practice". One way to teach design and analysis is to do classroom projects using solid-modeling tools such as, but not limited to, SolidWorks [2] and ANSYS [3]. Design of an axial-flow compressor's first-stage blade provided a good teaching example in solid modeling.

Axial-flow compressors are used in medium- to large-thrust gas turbine jet engines. The compressor rotates at very high speeds, adding energy to the airflow while at the same time compressing it into a smaller space. The design of axial-flow compressors for aircraft engines is a great challenge, both aerodynamically and mechanically [4]. Obtaining a high temperature rise in a stage is desirable to minimize the number of stages for a given overall compressor ratio. High blade rotational speeds, high axial air velocity, and high fluid deflection in the rotor blade will produce a high temperature rise in a single-stage compressor [5] and, in turn, produce higher compressor pressure ratios and performance for gas turbine engines. However, these factors were limited by blade material, structural stress, and aerodynamic load. For example, the first-stage compressor blade normally has large blade height and experiences large centrifugal stress due to its high speed of rotation. It also experiences high aerodynamic loads from high axial velocity. The design of the first-stage compressor blade requires solid modeling with the capability of structural and thermal analysis.

One of the senior mechanical engineering classes, ME 412-Analysis and Synthesis of Gas Turbine Engines and Components, taught at Alabama A&M University, is designed to provide students with a basic working knowledge of aerothermodynamics of gas turbine engine propulsion with a focus on component performance characterization and compressor and turbine design. Students are required to analyze on- and off-design performance and to characterize the operation of gas turbine engine propulsion systems and components. At the end of the one-semester course, students are required to complete a semester classroom project to design and analyze a first-stage compressor blade. Over the years, it has been found that students entering gas-turbine theory class did not have enough training in solid modeling and analysis. In order to complete the design process, it was necessary to spend a significant amount of time teaching the prerequisite materials such as using SolidWorks and ANSYS to conduct solid modeling. However, the goal of the gas-turbine theory class was to learn engine performance and compressor design. A significant amount of time should be spent on performance prediction and design analysis. It was necessary to develop a sample project template to conduct solid modeling and analysis so that learning efficiency could be improved.

The scope of this study was to provide students with a quick and handy sample project template to conduct first-stage compressor blade design using SolidWorks and ANSYS tools. The sample project could be extended to provide a quick tutorial reference for other solid-modeling and analysis applications throughout the mechanical engineering curriculum.

Classroom Project Definition

The ME 412 classroom semester design project was to design a first-stage compressor blade of an axial-flow compressor for a low-cost turbojet engine to deliver 12,500N of take-off thrust at sea level. For the first step of the design, students were required to conduct a gas-turbine engine parametric performance prediction (cycle analysis) and select engine component design parameters using the well-known software PERF [6]. PERF is a user-friendly program for calculating the variation in an engine's performance with changes in flight condition and throttle. The theoretical background of engine performance prediction, PERF, is described by Mattingly [7]. For the second step of the design, students were required to use COMPR software [8], apply the constant tip radius design, calculate the mass flow rate, number of stages, stage and overall pressure ratio, hub and tip radius of each stage, and mean radius flow angle for each stage. Hub and tip flow angles and reaction for each stage were analyzed based on the free-vortex velocity distribution. Students were also required to sketch flow path areas and radii for all stages. COMPR is a multistage axial-flow compressor design. This program calculates the mean-line design of multistage axial-flow compressors. Blade geometry and profiles were calculated based on axial-flow compressor analysis in Elements of Gas Turbine Propulsion [7]. COMPR can analyze the three fundamental types of mean-line design: constant hub radius, constant mean radius, and constant tip radius. Each of these designs can be analyzed using the user-selected swirl velocity distribution including free vortex, exponential, and first power. For the third step of the design, students were required to use SolidWorks and ANSYS to complete the first-stage three-dimensional blade design and rotational structural stress analysis.

Blade Design and Analysis

Preliminary cycle analysis on performance calculations using PERF indicated that a single–spool, all-axial arrangement was satisfactory for providing the required engine performance. The compressor pressure ratio was 8 and the turbine inlet temperature was 1200K. The design conditions were P=1.01bar and T=288K. Assume the absolute velocity entering the first-stage rotor has a zero-degree angle (Alpha Angle) with the axis, the axial velocity entering the first-stage rotor would be 150m/s, and assume the rotational speed N=240 rev/sec. Further assume that the hub-to-tip ratio for the first-stage rotor is 0.5, the mean radius for the first-stage rotor is 18cm, the work done factor is λ=0.93 for each stage, and the polytropic efficiency of the compressor is 0.90.

Starting from the preliminary analysis results, the design and analysis of the first-stage compressor blade is divided into four steps: 1) Apply the gas-turbine engine performance analysis tool, PERF, to refine parametric studies of engine components and obtain critical design-point performance parameters for an axial-flow compressor; 2) Recalculate the required number of stages And conduct compressor design using COMPR, obtain blade geometry and three-dimensional blade profiles; 3) Conduct solid modeling using SolidWorks to construct a three-dimensional blade for the first stage of the compressor based on blade profiles; 4) Conduct a stress analysis using ANSYS for the blade design, then modify and improve design parameters in step 1 according to the results of the structural analysis to complete the design.

<u>Step #1</u>: Refine/reselect design-point thrust and performance calculations using the gas turbine engine performance analysis tool, PERF, compressor parametric studies were conducted. Choosing the design parameters listed in Table 1, a performance calculation was conducted, as shown in Figures 1(a) and 1(b). The goal was to reach a thrust of 12,500N at sea level.

<u>Step #2</u>: Obtain first-stage blade profiles using the simplified version of the compressor design package, COMPR, conduct the compressor-blade profile design using COMPR based on the design-point analysis results obtained in the performance prediction.

1. Open the program Compressor Preliminary Analysis Program (COMPR) in Figure 2.

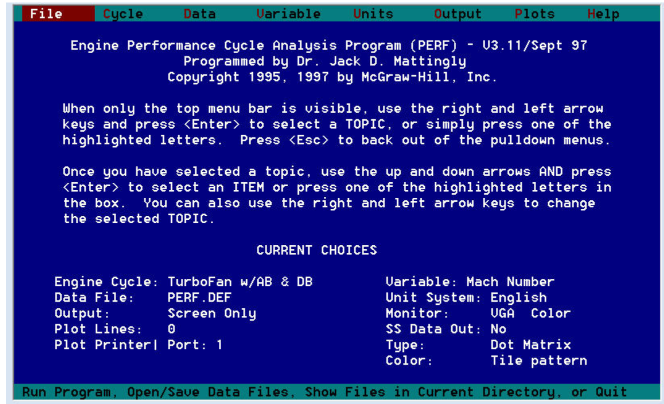
Table 1. Design Point Parametric Analysis Using the Performance Calculation Tool

Mass flow rate	16.99kg/s
Number of stages	7
Overall pressure ratio	8.0
Turbine inlet temperature	1200K
Design Point Ambient Pressure *Pa*	101,000 Pa
Design Point Ambient Temperature *Ta*	288K
First Stage Hub radius	r_h= 0.12m
First Stage Mean radius	r_m= 0.18m
First Stage Tip radius	r_t= 0.24m
First Stage Hub/Tip	0.5
Height of First Stage Blade	120mm
Chord of hub, mean, tip	49.2mm
First Stage Rotor angular velocity	1508 rad/s
Polytropic efficiency of the compressor	0.9
Work done factor	λ= 0.93
Axial velocity	150m/s
Absolute velocity axial angle	0°
Thrust	12,500N

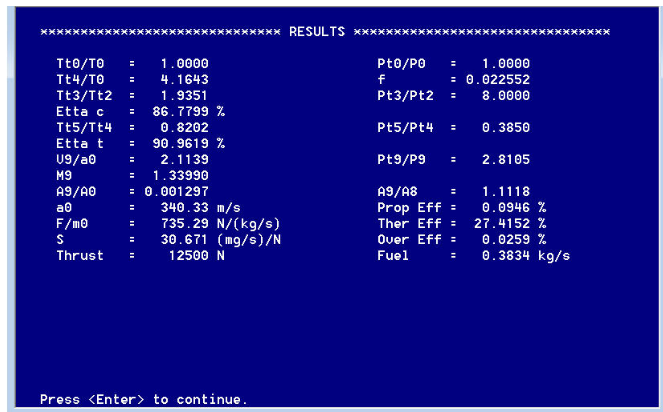
2. In the design-type section on the front screen of the program, select that it is a mean radius design. Ensure that the unit system is in metric by selecting SI Metric.

3. In the View/Edit Data section select initial. Once in Initial, change the data areas to number of stages to 6, mass flow rate to 17 kg/sec, Rotor Angular Velocity to 1508 rad/sec, and Alpha 3 for last stage to 0, as in Figure 3.

4. After ensuring that the initial conditions are correct, close the Initial Data window and return to the front screen of the COMPR Program. On the front screen, select the Perform Calculations button. A Constant Mean Radius Design window will appear; input the desired tip radius of 0.24 meters and click OK, as in Figure 4.



a) **PERF Software Interface**



b) **PERF Results Window**

Figure 1. The Graphical Interface Using Performance the Calculation Package

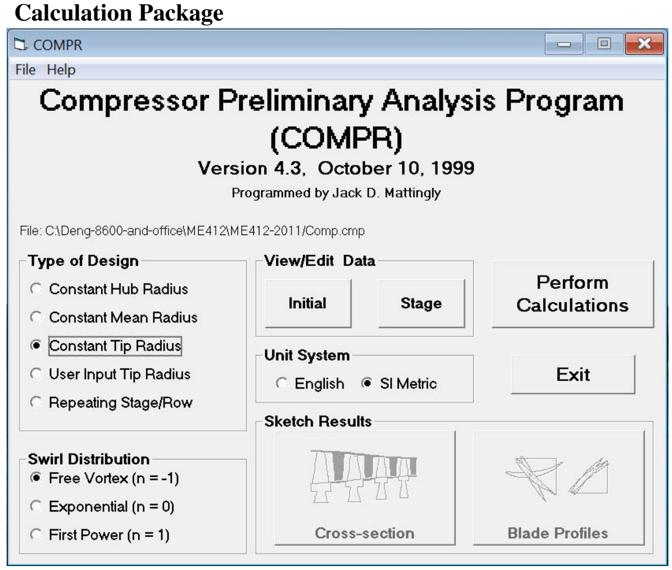


Figure 2. COMPR Design Program Initial Screen

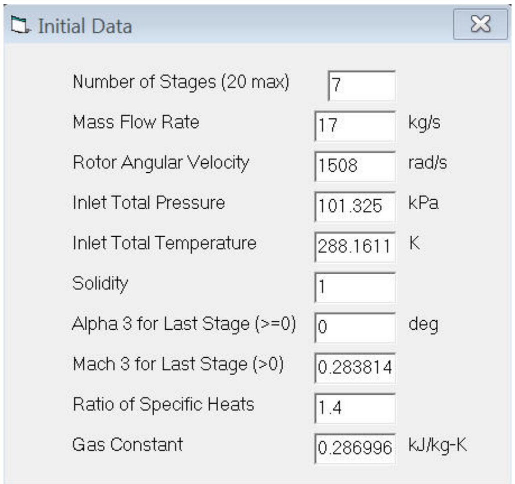


Figure 3. Initial Data Screen from COMPR for Setting the Initial Conditions of the Compressor Inlet.

Figure 4. Constant Tip Radius Design Window from COMPR

5. After verifying that the Design Mean Radius is ok, the Calculations for each individual stage data will appear in the Results window. To continue to the next stage's data, click on the Next Stage button located at bottom of the Results window. Repeat this for the remainder of the stages, as in Figure 5.

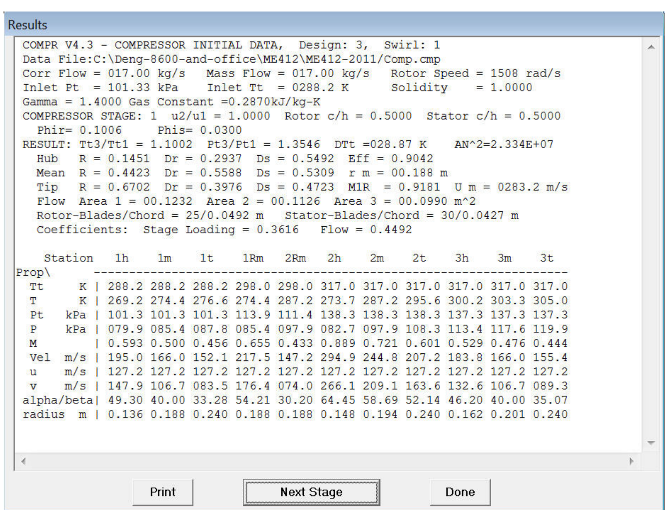


Figure 5. Stage 1 Data from the Results Window of COMPR

6. Clicking "Done" will close the Results window after all of the results from each stage have been reviewed. Once back at the front window of the COMPR, the student should notice that the Sketch Results section of the program has turned to color. Clicking Cross-Section will open the Sketch Pad window that has a cross-sectional area of the general sketch views of how the compressor's cross-sectional area changes, as in Figure 6.

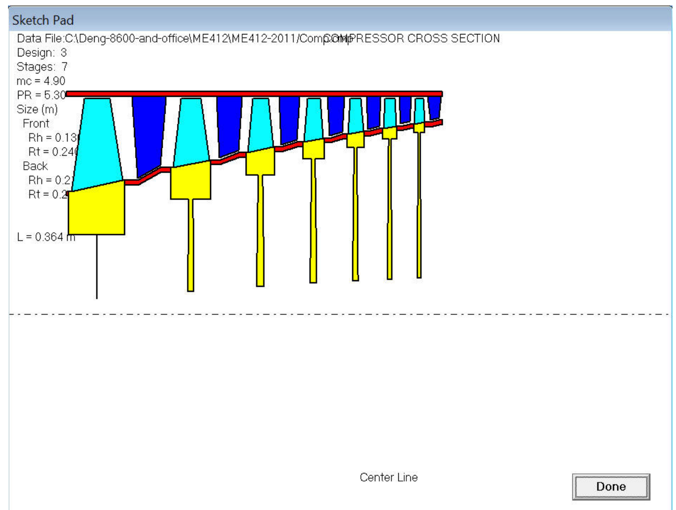


Figure 6. Sketch Pad Window from COMPR Showing the Cross-Sectional Area of the Compressor from Stages 1 to 7

7. Check that the cross-sectional area is complete. Close the Sketch Pad window. On the front window, click Blade Profiles. The Blade Description window will open. In the Blade Description window, specify that you want to see the blade profile for Stage 1, as in Figure 7.

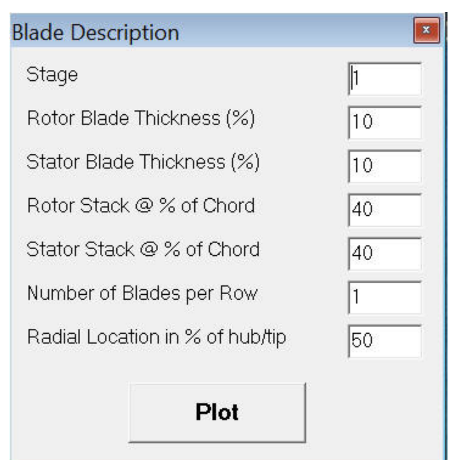


Figure 7. Blade Description Window for Selecting the Specific Stage and Viewing the Blade Profile for That Stage

8. Clicking the Plot button in the Blade Description window will open the Sketch Pad. The Sketch Pad gives two profiles, the one on the left is for the blade profile of the rotor and the right side is for the stator blade profile, as in Figure 8.

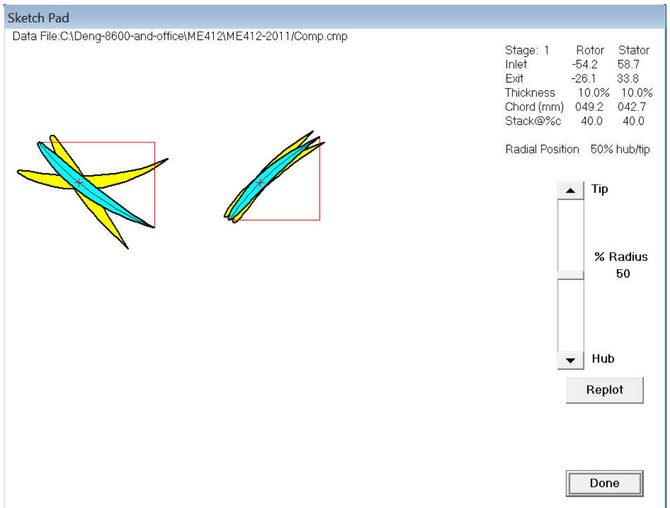


Figure 8. Sketch Pad Window from COMPR Showing the Rotor Blade Profile on the Left and the Stator Blade Profile on the Right

9. In the Sketch Pad window, three photos will be produced to develop a 3D model of the rotor blade. First, on the left side, slide the bar to the hub with % Radius reading 0, and click Replot. The blue image is the current viewing profile, as in Figure 9.

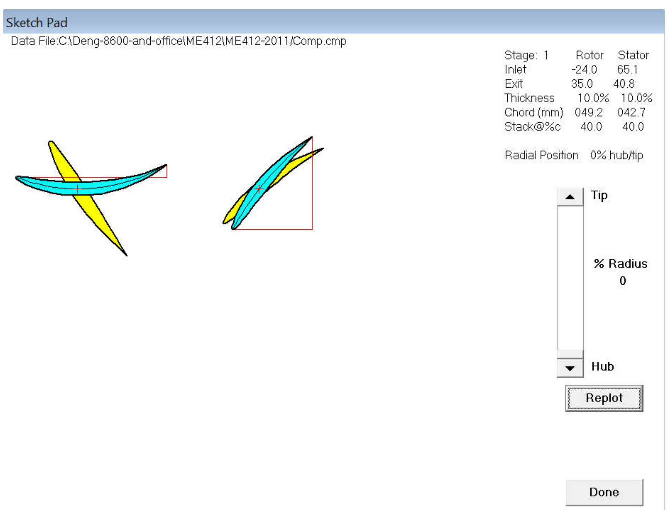
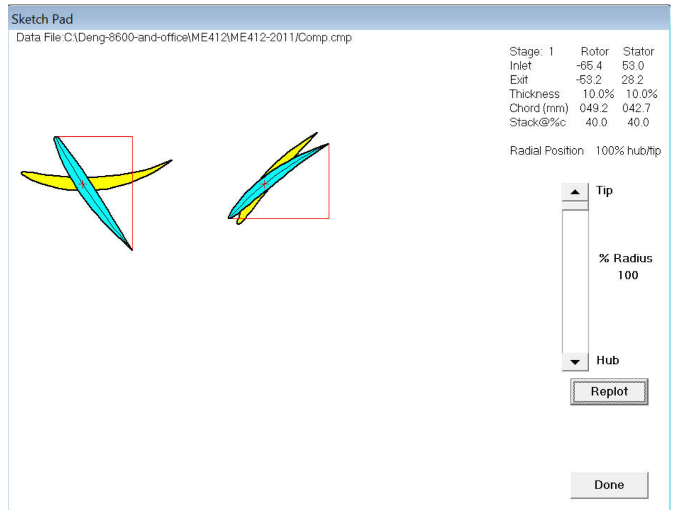
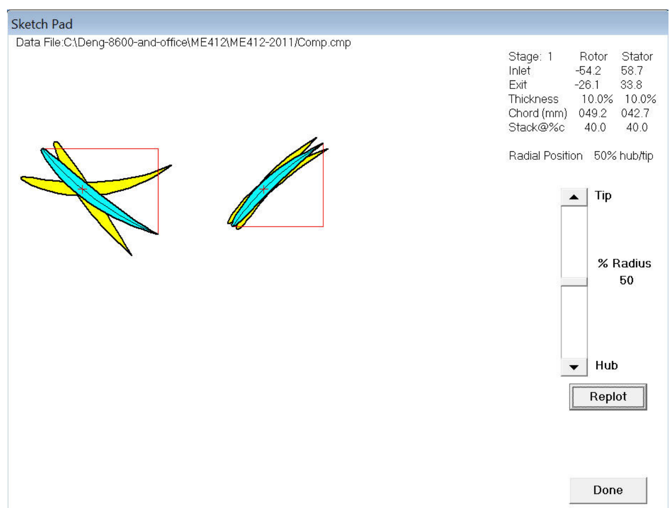


Figure 9. Blade Profile of the Hub Produced in COMPR

10. Once the Hub profile has been created, the mean and tip profiles will be created with the Mean profile at 50% and the Radius and Tip at 100%. Remember to click Replot after each change of the slide bar to produce the next desired profile, as in Figures 10(a) and 10(b). After this step, the blade profiles of the first-stage rotor were designed.



a) Tip Radius Position

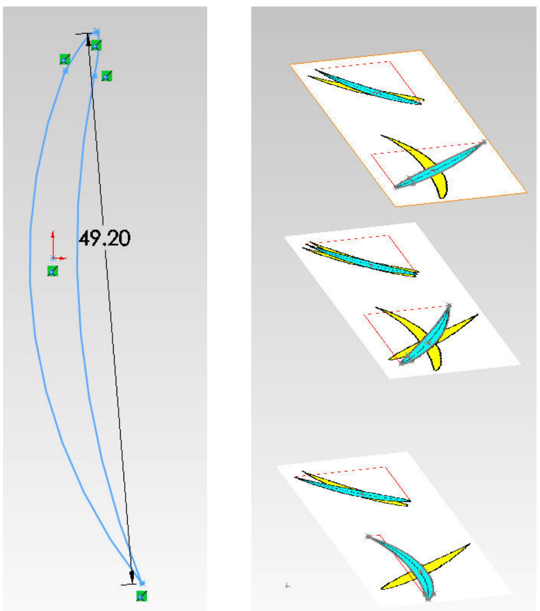


b) Mean Radius Location

Figure 10. Cross-Sectional Profiles of the Blade at Both the Tip and Mean Locations

<u>Step #3</u>: Generate a three-dimensional blade using SolidWorks. After saving each of the blade profiles, the images are to be imported into SolidWorks for a 3D modeling of the blades.

1. In a new part window in SolidWorks, select a top plane. In the menu select Tools → Sketch Tools → Insert Image. Select the Hub blade profile as the first image. Trace the profile using a combination of three -point arch and the spline commands. After the Hub has been sketched, repeat the steps but with images on new planes and the distance as shown in Figure 11 (a). Ensure that the chord length in SolidWorks is chord length given by the COMPR Program. After the trace sketches have been made, the images can be suppressed and the images will remain visible, as in Figure 11(b).



a) **b)**

Figure 11. 3D Iso-Views in SolidWorks
a) The Chord Length of the Blade Profile
b) The Hub, Mean, and Tip on Different Planes

2. From the Iso-view, select Loft as the feature to be created. In the Loft feature, right click and select the region selection, as in Figure 12.

3. Select the first sketch from the Hub sketch plane. Select the Mean profile next, followed by the Tip profile, as in Figure 13.

4. A preview of the Loft will begin to take shape, as in Figure 14.

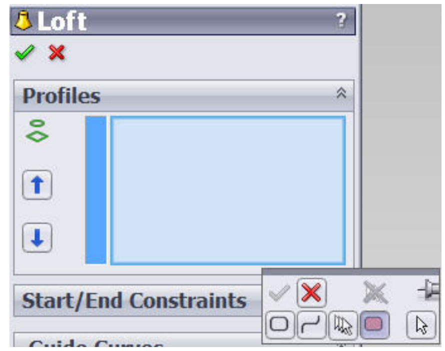


Figure 12. The Loft Feature in SolidWorks with the Pink Box for Selecting the Loft Region

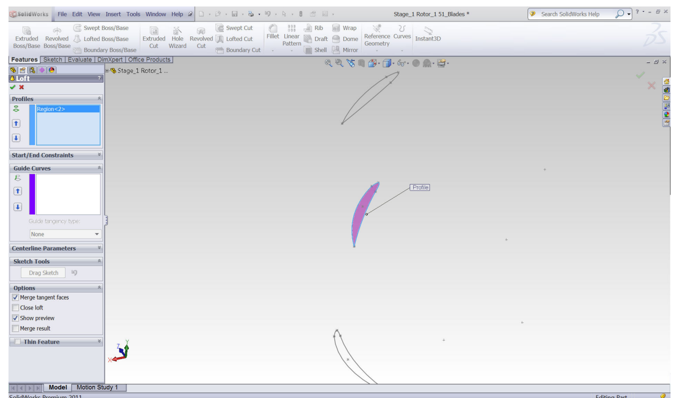


Figure 13. Loft Feature Using the Region Selection with all Three Profiles Selected

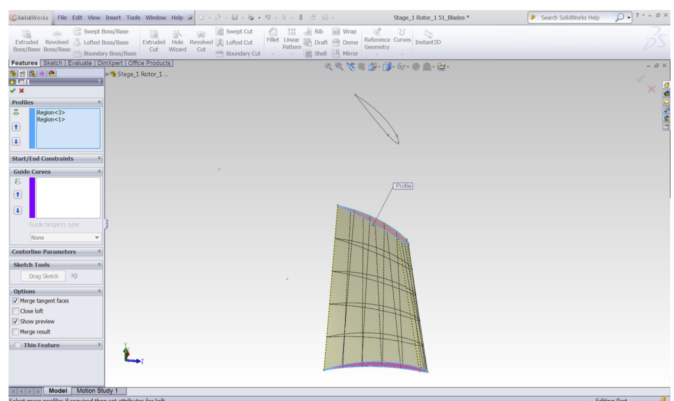


Figure 14. The Loft Beginning to Take Shape

5. After the Tip region is added into the Loft preview, the student should select the connecting lines to be at a common location on the profiles. For this blade model, the trailing edges of the blade profiles were chosen, as in Figure 15. Arrangement of the blade on the first stage rotor is shown in Figure 16.

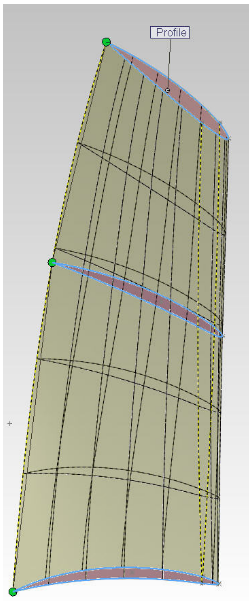
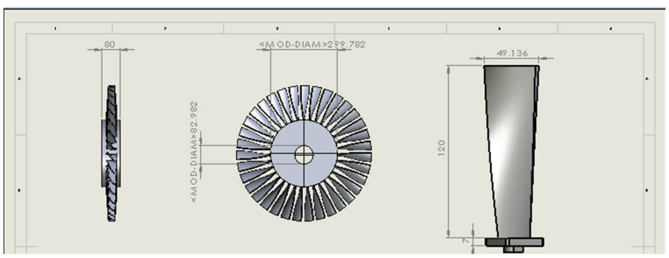
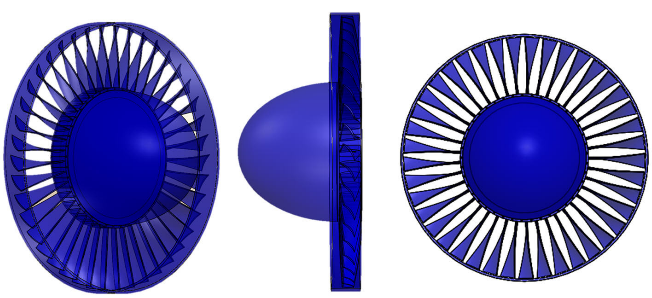


Figure 15. Preview of Complete Blade with the Common Location of the Trailing Edge on all Blade Profiles



a)

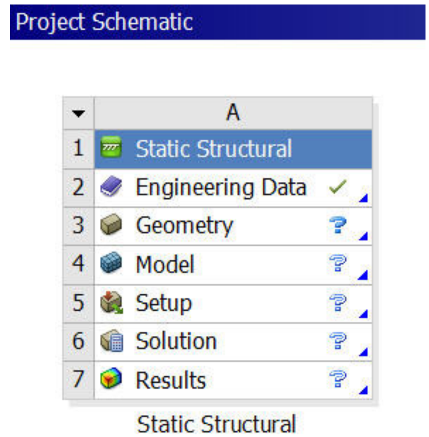


b)

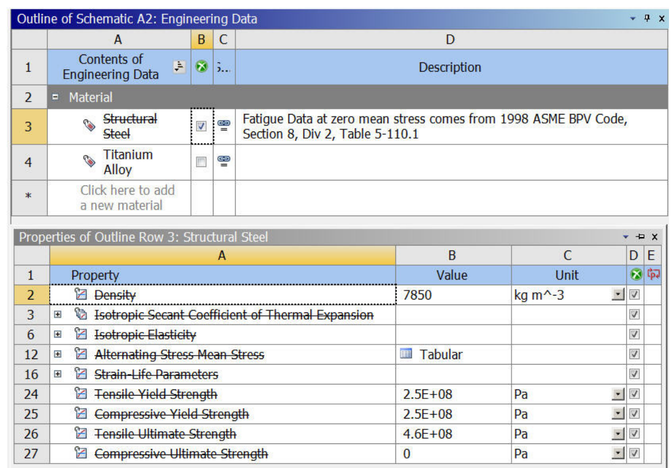
Figure 16. Arrangement of the First-Stage Blade on the First-Stage Rotor

Step #4: Perform an ANSYS/structural analysis. After completing the design of the rotor, save the model as an .igs file; this will allow the user to import the file directly into ANSYS.

1. Start ANSYS Workbench → Toolbox → Static Structural → Drag Static Structural to Project Schematic window, as in Figure 17(a). Right click on Engineering Data. Under the material group, right click on Structural Steel → Engineering Data Sources. Under Data Source → General Material → Select Titanium Alloy as shown in Figure 17(b).



a) ANSYS Static Structural Analysis Window



b) Material Selection

Figure 17. ANSYS Project Schematic Window

2. Right click on the Geometry column → Import Geometry → Browse → locate your saved CAD file → Double click on Model. File will import into ANSYS Mechanical analysis module.

3. Under the Model submenu → Generate Mesh, a finite element analysis mesh was generated, as in Figure 18, for the first-stage rotor with designed blades.

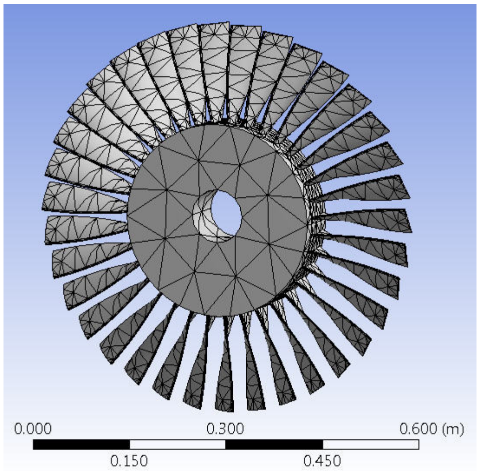
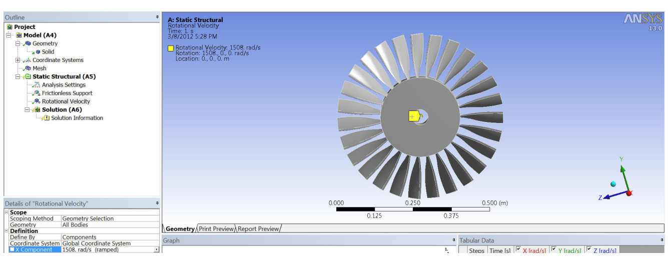
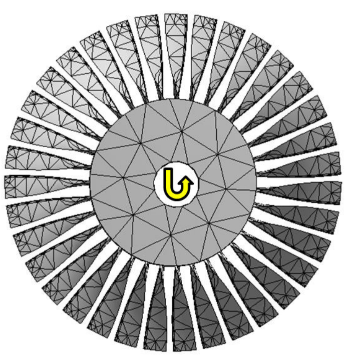


Figure 18. Finite Element Analysis Mesh for the First-Stage Rotor with Designed Blades

4. Right click again on the Static Structural in the Outline and choose insert. Insert a rotational velocity. Under definition change, define change Define by to components. In the “Z” direction change it from zero to 1508 rev/sec (students in this design used -1508 rev/sec to get the correct rotational. Specify Boundary Condition → Static Structural → Frictionless Support → Rotational Velocity (1508 rad/s), as in Figures 19(a) and 19(b).



a) Screen Shot of Boundary Condition Specification



b) Direction of Compressor Disk Rotation

Figure 19. Stress Analysis Boundary Conditions

5. Solving stress of the rotor blades using Solution→ Maximum Principal Stress. Results are shown in Figure 20.

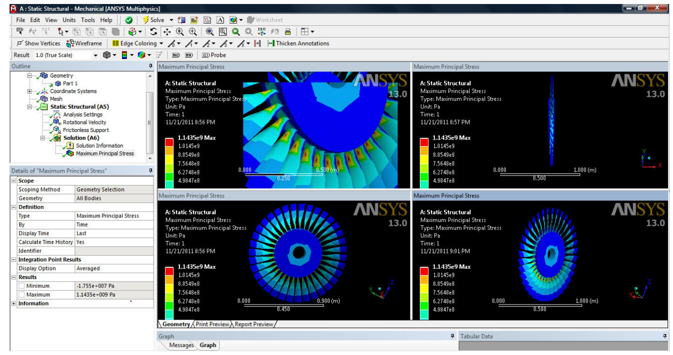


Figure 20. Maximum Principal Stress Solution for the First-Stage Rotor Blades

6. Obtain solutions for the total deformation of the first-stage rotor blades using Solution → Total Deformation, as shown in Figure 21.

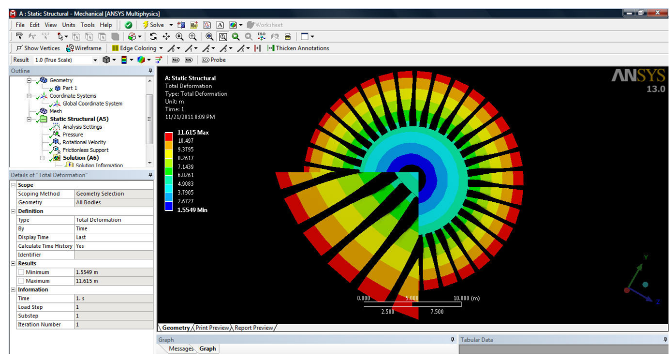


Figure 21. Total Deformation Solution for the First-Stage Rotor Blades

7. The comparison the Maximum Principal Stress to Titanium’s ultimate tensile strength showed that the maximum stress exceeded the material allowed stress limit if the rotational speed was 1508 rev/s. Therefore, the first-round design point rotational velocity was too high and resulted in the material failing at that rotational velocity. A few tries indicated that reducing the rotational velocity to 1370 rev/sec and modifying the design and analysis parameters, lowered the Maximum Principal Stress below the ultimate tensile strength. This allowed for the material to be within operational parameters for flight.

Conclusion

This study demonstrated the design of a first-stage axial-flow compressor blade using solid modeling through a classroom project. Step-by-step instructions using performance prediction tools PERF, COMPR, SolidWorks and ANSYS described the design of the first-stage axial-flow compressor blades. This sample project description provided a fast and easy access template for engine performance analysis and blade design using solid modeling and analysis efficiently. Use of this template will significantly reduce the time spent on learning how to use design tools to conduct solid modeling and analysis.

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Biographies

BREON WILLIAM is a Senior Mechanical Engineering Student of Mechanical Engineering at Alabama A&M University. Mr. William is a NSF STEM Scholarship recipient.

BRANDON HOWARD is a Senior Mechanical Engineering Student of Mechanical Engineering at Alabama A&M University. Mr. Howard is a NSF STEM Scholarship recipient.

XIAOQING QIAN is a Professor of Mechanical Engineering at Alabama A&M University. Dr. Qian can be reached at xiaoqing.qian@aamu.edu

Z.T. DENG is a Professor of Mechanical Engineering at Alabama A&M University. Dr. Deng can be reached at zhengtao.deng@aamu.edu