EML 4905 Senior Design Project

A B.S. THESIS
PREPARED IN PARTIAL FULFILLMENT OF THE
REQUIREMENT FOR THE DEGREE OF
BACHELOR OF SCIENCE
IN
MECHANICAL ENGINEERING

Radial Compressor Optimization
25% Final Report

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March 8, 2014

Ethics Statement and Signatures

The work submitted in this B.S. thesis is solely prepared by a team consisting of Xavier Medina, Fernando Lopez, and Gianfranco Pisani, and it is original. Excerpts from others' work have been clearly identified, their work acknowledged within the text and listed in the list of references. All of the engineering drawings, computer programs, formulations, design work, prototype development and testing reported in this document are also original and prepared by the same team of students.

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Abstract

In an effort to reduce fuel consumption and remain completive in an automotive industry that continues to increase regulations for environmental protection there has been an increase in popularity of turbochargers. Due to this increase in demand, there is now a greater need for a centrifugal compressor that provides a wide and stable operating range that delivers a low cost. The analysis of the phenomena that occurs within a centrifugal compressor is extremely challenging and presents three-dimensional unsteady flow with the addition of thermal flow and expansion. Based on experimental and numerical simulation analysis, this team will develop a design optimization process for a centrifugal compressor that has an optimum operating range while increasing the overall efficiency of the compressor.

1 Introduction

1.1 Problem Statement

The Radial Compressor Optimization project's goal is to increase the pressure ratio and to reduce overall production cost by optimizing the housing and compressor wheel. The blades will be designed and optimized using special software that is comparable to the current market standards. The modifications in the compressor wheel are expected to increase the maximum efficiency of the system by at least 5% while also improving the efficiency in the important regions of its operating range, such as near the surge region and the choke region. Each turbocharger needs to be paired with an engine that will compliment the mass flow rate and pressure ratio that is produced; therefore as a base model size for this compressor, it shall compliment a 2.0L engine with a power output of 200hp (149 kW). This type of engine was chosen due to the current trend of car manufacturers' downsizing their engine sizes and displacements in the majority of their product line.

1.2 Motivation

The motivation for studying a radial compressor is mainly due to the increase in price in fossil fuels and a growth of interest in the area of efficiency in the car industry. Centrifugal compressors are currently downplayed heavily in the car industry due to the lack of power that they produce in the race industry. Approaching the optimization of our radial compressor through our senior design project will show that there is an interest and that there are practical applications for this type of technology. The team has selected this project for the opportunity to apply advanced concepts and techniques that have been presented during our pursuit of a bachelor's degree such as thermal and fluid mechanics.

2 Literature Survey

Centrifugal compressors are a result of complex phenomena at play that manages to achieve a pressure rise while adding kinetic energy to a continuous flow of fluid through either a rotor or an impeller. This kinetic energy is then converted to an increase in potential energy by means of a diffuser that slows down the flow of fluid creating static pressure at the outlet. The inlet to a centrifugal compressor is typically a cylindrical pipe that may have features such as vanes to help rotate the flow, as well as pressure and temperature measuring devices. These features add what is known as, prewhirl, to the fluid making it possible to reduce the Mach number at the inlet. The relative Mach number at the inlet will be given by:

$$M_1 = \frac{V_1}{\sqrt{\gamma R T_1}}$$

where,

T_1 is the static temperature at the inlet.
V_1 is the Velocity at inlet
γ is the specific weight of the fluid
R is the gas constant (R=8.314 J/mol x K)

The Mach number is important at the inlet because shockwaves can occur on the curved part of the impeller from the air that is breaking away as shown below in Figure 1.

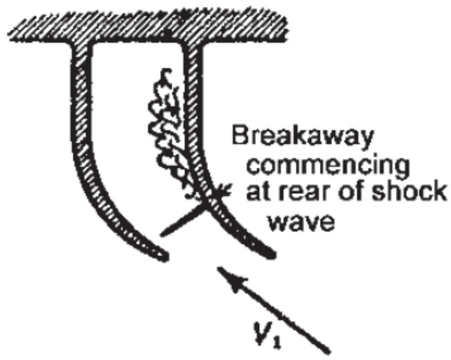


Figure 1. Breakaway commencing at the aft edge of the shock wave

As the relative velocity reaches the speed of sound, this separation causes huge pressure losses and drastically affects the efficiency of the compressor. A disadvantage that arises when using prewhirl is that the work capacity is reduced since a whirl component has already been added to the fluid before entering the impeller.

Once the fluid has entered the impeller, it enters the only rotating aerodynamic part in a centrifugal compressor. It is the most critical component, and provides all of the kinetic energy that will be added to the gas as well as being responsible for up to 70% of the static pressure rise in the system. A well-designed impeller will result in a well-designed compressor because they have been calculated to achieve efficiencies in excess of 96%. [[impellers – the heart]] There are two categories for impellers: shrouded (Figure 2) or unshrouded (Figure 3), and their blades can be either two-dimensional (Figure 4) or three-dimensional (Figure 3).

Figure 2. Shrouded Impeller.

Figure 3. Unshrouded impeller. These impellers also tend to have complex 3-D shaped blades.

Figure 4. Two-dimensional impeller blades.

Each different design has its own advantages and disadvantages. Unshrouded (open) impellers can operate at much higher rotational speeds, equating to higher pressure ratios. Shrouded (closed) impellers deliver pressure ratios of 3:1 or less, while open impellers can reach pressure ratios upwards of 10:1. impellers – the heart]] While that may be an advantage, open impellers also tend to be less efficient due to losses associated with tip leakage flow which does not occur in closed impellers. Tip leakage flow is the flow of fluid the leaks over the rotating blades and flows in-between the blades and the housing causing losses in pressure. Different factors are taken into consideration when selecting the type of impeller to be used in a compressor, one of them being the impeller flow coefficient, φ.

$$\varphi = \frac{Q}{N \times {D_2}^3}$$

Where:

Q is the impeller flow capacity
N is the operating speed
D_2 is the exit diameter

The impeller flow coefficient relies on the flow range that the compressor will be dealing with. Impellers that have low flow coefficients are described by long, narrow passages, while impellers with high flow coefficients have wider passages in order to adjust for the higher flow rates. For this study, the mass flow rate of a typical engine for a typical American driver will be used as the base line for the compressor's size. The composition of gas to be compressed as well as the ranges of pressures and temperatures of the gas as it enters the compressor must also be specified for a certain application.

From a design point, there are certain zones within the operating range of the compressor that are more important than others shown below in Figure 5. A turbocharger operates within the green zone when a vehicle is in idle and while accelerating from a standing start, making this region very important during city driving. This region is also critical in terms of eliminating turbo lag, which dictates the peak torque point of the engine and the amount of emissions produced. The red zone in Figure 5 has to do with supplying the engine with high volumes of air that is needed in driving at higher speeds.

In this region, the stress subjected to the impeller is at its highest. The deciding factor related to the performance in the red zone is the compressor's ability to meet the additional demands of high-altitude driving since it is this variable that causes the impeller to reach its highest speed.

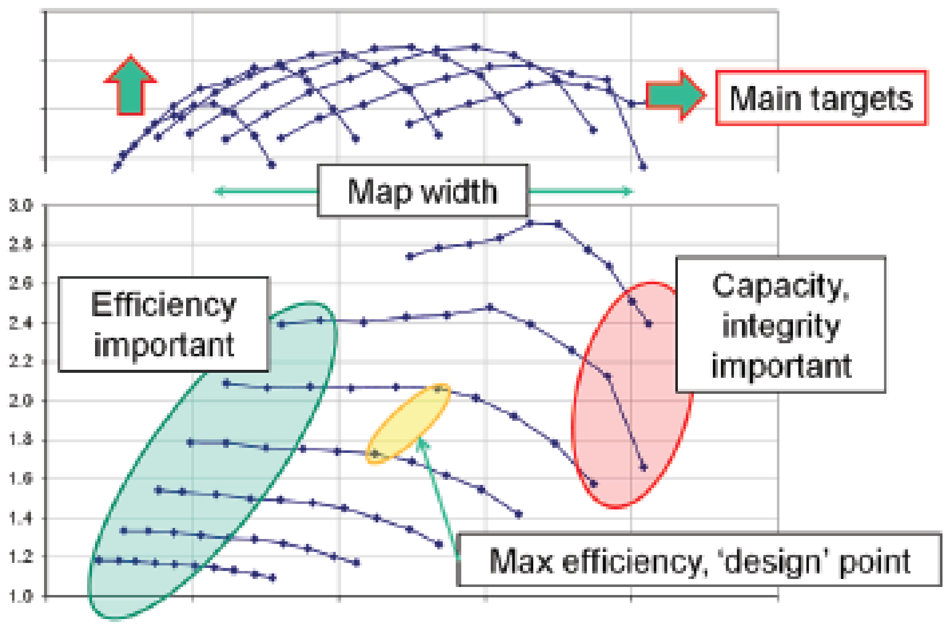


Figure 5. Zones on compressor map of turbocharger that are most important from design/research and development standpoints.

The configuration of these blades play a major role in the efficiency and the pressure rise that is seen when the fluid is exiting the impeller. Once the fluid has passed the inducer, it goes through the exducer, which converts all of the kinetic energy of the fluid into pressure by slowing down its velocity. At the very tip of the exducer the velocity of the fluid is at it's fastest which leads to the Mach number to be in excess of unity. These high Mach numbers can cause shockwaves, which propagate downstream causing cyclic loading of the impeller. This loading can lead to early fatigue failure if the frequency is of the same order as one of the natural frequencies of the impeller vanes.

Once the fluid has passed the diffuser it is received by a collector, which also can take several forms. If it is a large chamber, it is called a Plenum, but when it is collected into an object that looks similar to a snail shell it is termed as a volute or scroll. The collector's purpose is to gather the flow that has been discharged from the diffuser and deliver it towards a downstream pipe that could also contain valves and instrumentation that gauge the performance of the compressor.

3 Conceptual Design

Current turbocharger and supercharger companies use designs that tend to be simple and cheap to produce. The performance of their product is largely overlooked when it comes to commercial vehicles due to the greater importance of decreasing cost. These lower price options use simply designed wheels, poor quality manufacturing processes and low cost materials. The designs that are used tend to have 7 or even 5 impeller blades, which reduces the overall performance of their products. On the other hand, high performance companies use high quality materials, with high tolerances in the manufacturing processes, with improved wheel designs.

The purpose of this project is to bridge the divide between the better performing high quality compressors, and the more economically viable compressors. Using the same high quality manufacturing processes while maintaining performance and durability will be the top priorities for this project. In the process of creating this centrifugal compressor, the cost of manufacturing will become the main challenge in creating this product in order to make it appealing for commercial use. Achieving these goals will result in more fuel-efficient cars producing the same power with less fuel.

4 Proposed Design

4.1 Major Components

The design related to the compressor blade impeller is practically completed using SolidWorks Modeling. It will consist of an aluminum wheel with 10 blades as shown in Figure 6, and 10 smaller vanes in between each main blade, these smaller blades are not shown, but the final design will include them. These smaller blades are considered a second family in the main compressor, giving the principal compressor blades the name of primary family.

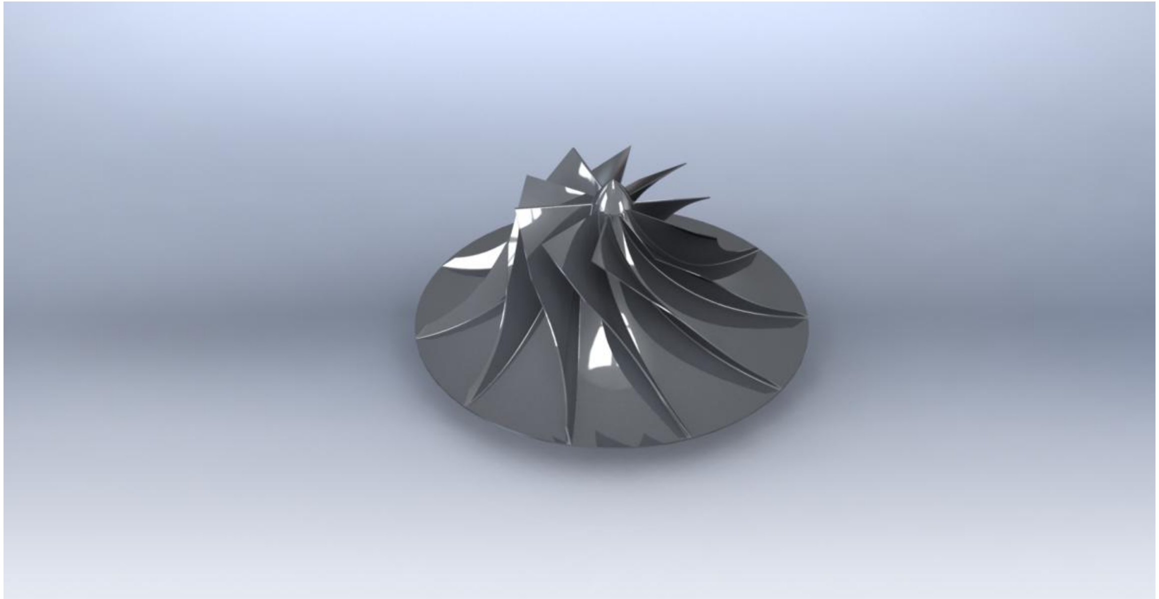


Figure 6. Proposed Design

Regarding the compressor housing, the initial design is still in development since it must work together with the compressor wheel and will soon be ready for its final concept.

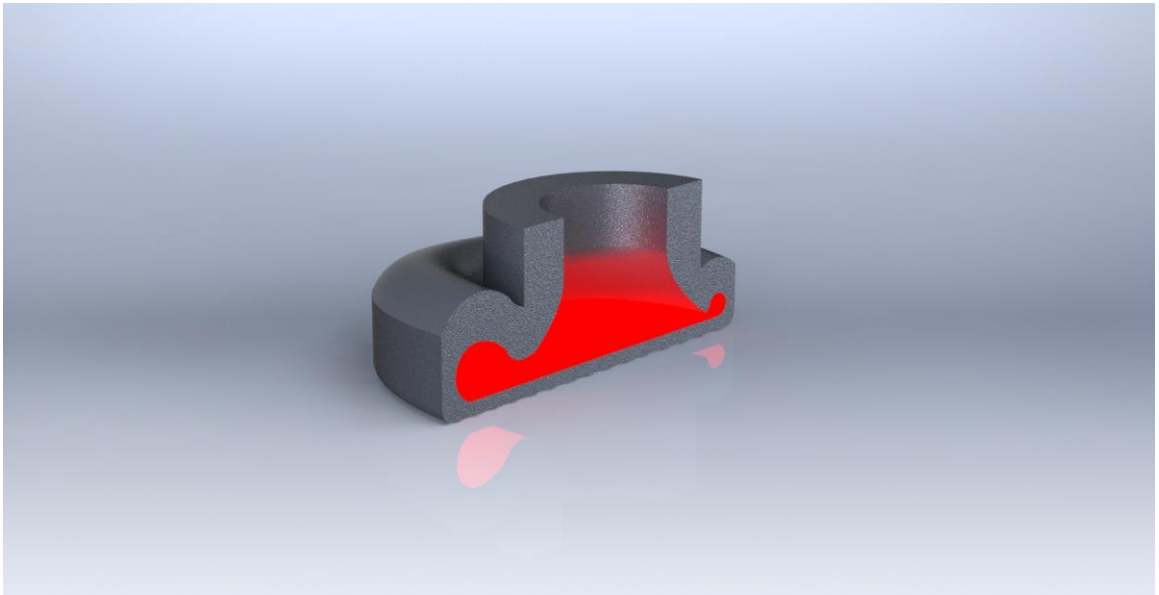


Figure 7. Cut away view of Initial compressor housing design

Figure 8. Assembly of compressor wheel and housing

4.2 Structural Design

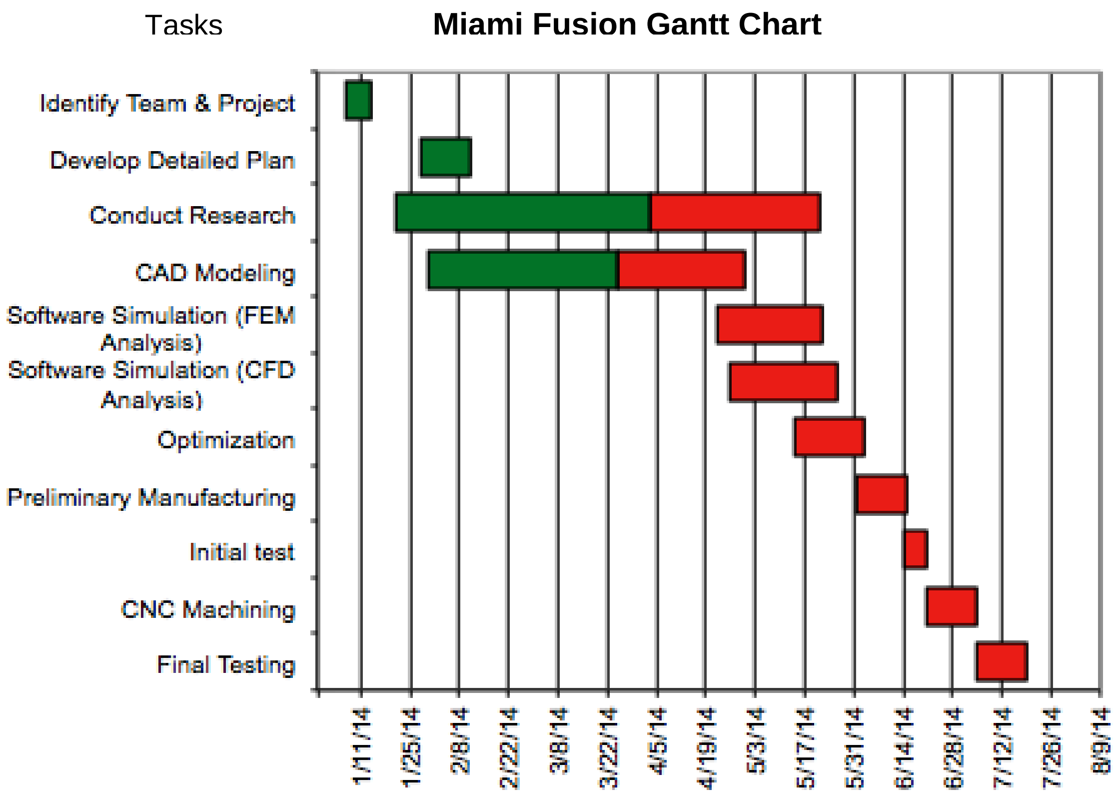
For the wheel blades, we used a rectangular profile extruded following a twisted line in order to achieve the angle required to be able to create airflow in and specific direction. For the optimization, different designs will be used to let the algorithm learn and be able to improve the design on the right direction, this will only be achieved by iterations, these iterations will be small changes in between each design in order to test different flow patterns.

The housing will be kept as a constant since changing only one part will show improvements, since iterations on both parts could result in deficient flow.

The iterations process will alter: the primary blades family and the secondary, the primary will create the major air flow component, and the secondary will give that extra improvement, in order to achieve maximum efficiency.

5 Logistical Analysis

5.1 Timeline



5.2 Cost Analysis

In the cost analysis, every expense will be reported and added to a final amount, three categories which would best sum up and take into account the amount of work and cost necessary are as follows:

Material

Design

Manufacturing

Materials

For the design of the compressor wheel, aluminum 7000 or 2000 series. The price of a cylindrical billet for the manufacturing of the wheel will be around 120$.

The housing will be made of iron, for initial design, and simplicity, this compressor housing will have to be created using a sand mold to pour liquid metal and form the compressor housing.

Design

All the design will be made on Solid Works, and later tested on Ansys, with flow simulations, all these simulation and process will take about 100 hours.

Manufacturing

For the compressor wheel, it will be formed from an aluminum billet, as previously stated, and will require a CNC machine to be able to create all the features, and hand crafted details such as polishing and cleaning. The CNC cost will be 70$ per hour of machine time.

The compressor housing manufacturing will require molten iron and a sand mold with all the features.

6 Prototype Analysis

6.1 Prototype System Description

The prototype will consist of the components that have been outlined that will be optimized. The compressor wheel will be made into a prototype that will be machined. The compressor housing will either be machined, welded, or possibly bought so that it can later be fitted into an actual car for real world application and testing.

6.2 Plans for Tests on Prototype

Once a prototype is designed and machined next step is to put it through benchmark tests. First tests will include manual rotation to see if the system actually spin nicely and has proper clearances with the housing. After those first tests are done, next step of testing will be to apply it into a real world application and testing. Fitting will be done on an operational car and take it through the paces of regular everyday driving. Performance will be measured and analyzed through the real world testing of the prototype.

7 Conclusions

The motivation is the biggest driving force for the passion of optimizing the compressor. Being able to optimize this technology to make it more optimal for everyday use is something that can produce a big demand. Fuel economy is a rising problem that more and more people are becoming aware of. Society is becoming more aware of being environmentally friendly and this technology could provide a different option that allows expanding into a field to create more efficient engines. Improving compressors is a big step on the fuel consumption field, since it will make an already efficient system even more efficient, this technology will for sure impact todays markets, and making a change is big possibility and with the proper study and development.

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