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DESIGN AND DEVELOPMENT OF A HIGH-PERFORMANCE CENTRIFUGAL COMPRESSOR/TURBOCHARGER

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Abstract

Computational Fluid Dynamic of Centrifugal Compressor

In this paper, fluid analysis of compressor wheel, turbine wheel and volute are presented. Paper focuses on the different construction with variation of shroud and hub of the compressor wheel and turbine wheel. It also includes study of volutes, the flow inside and different A/R ratio. The complete analysis helps to optimize the geometry of impeller, turbine and volute as well which will help to vary the parameters and constraints for the required output.

Key Words

Mass Flow Rate – MFR, Volumetric Efficiency, Pressure Ratio. Density Ratio, Ambient Temperature, Ambient Pressure, Flow Inlet angle, Rake angle, Shroud, Hub, Mach Number, Sub-sonic, Boost pressure, Compression Ratio, Displacement, Blade Tip Velocity, Turbocharger, Supercharger

1. Introduction

Motorcycles are categories according to the job they are capable of doing. From commuting to racing. Mostly all bikes use combustion engine, to be specific Naturally Aspirated Engine. They are well used between those limits, i.e., the dependency of air intake from atmosphere. A middleweight bike is a category of motorcycle where the engine capacity is from 600cc to 750cc. Depending on the engine layout variations and emissions, the output power of these engine can be from 70bhp to 150bhp. Power can be changes by varying the AFR (Air Fuel Ratio), Timing, Lift, Intake and Exhaust manifolds, Type of fuel, Rev range, ignition timing, compression ratio etc.

Motorcycle manufacturers increase the capacity of engine to increase the power output of the engine. Due to this, not only the efficiency of the motorcycle reduces but reliable factor also gets affected. More fuel consumption leads less motorcycle efficiency.

The main aim of every manufacturer is to extract maximum power from that engine to serve the purpose for which the motorcycle is designed for. The reasons of power loss can be from heat and mechanical loss to less thermal efficiency. To maximize the efficiency of the engine, manufacturer varies the parameters.

A four-stroke engine works in four strokes, 1) Intake 2) Compression 3) Combustion 4) Exhaust. During compression, the Air Fuel mixture is compressed, and the air is taken from the atmosphere. When the air gets denser, it gets cold and the amount of oxygen in it is high, therefore if we increase the air pressure at the intake stroke, the thermal efficiency of the engine will increase and there will be less eat loss. This will lead to increase the efficiency of the engine.

During combustion stroke, not all the fuel is burned. The reason is there is not enough oxygen to help combust the fuel during the second stroke. So, if the air is rich in oxygen, it will help to combust more fuel and increase the thermal efficiency.

In motorcycles, there is rarely any manufacture who use a compressor to increase. Those liter-class(1000cc) motorcycle which uses a compressor, gives output power up to 300+ bhp.

The basic idea of using a compressor at engine intake is to increase the oxygen content in the air fuel mixture to combust and increase thermal efficiency by increasing the intake air pressure.

There are mainly two types of compressors, Turbocharger and supercharger. In many cases manufacturers use variation of these two compressors in such a way that they can be used to increase the peak power or to widen the power band. That is done by changing the geometry of the impeller blades and vanes dynamically or by changing the A/R ratio of the turbocharger. A/R ratio is the aspect ratio of the Volute. Where A is the area of the inlet of the volute and R is the distance between the centroid of that area to the volute center.

2. DESIGN CASE

The purpose of the compressor is to increase the peak power of a 600cc middle-weight motorcycle. The motorcycle chosen is 2007 Honda CBR600RR. The following are the specs of 2007 Honda CBR600RR: Power: 116.93 bhp@13000RPM

Torque:64Nm @11000RPM

Compression Ratio: 12:1

Engine Type: Inline 4

Power to weight ratio: 0.45 (HP/Kg)

Displacement: 599 cc

The main aim is to increase the peak power at 13000 RPM. After several iterations, a best case was taken into consideration which would give a peak power of 198bhp at 13000RPM with 95% Volumetric efficiency.

The ambient conditions were taken as follows:

Air density: 1225 Kg/m^3

Temperature: 302.5 K

Using the above conditions, further calculations were done and geometries were made.

Turbocharger provides 75% to 80% stage efficiency and around 82%-to-85%-wheel peak efficiency. Most of the total pressure loss takes place in diffuser and volute which significantly affects the overall stage efficiency. CFD analysis was done to each geometry iteration to maximize the efficiency. Isentropic efficiency was the also taken into consideration since it also affects the overall efficiency.

3. Impeller

Impeller is a component which directs the air taken from the atmosphere to the volute. There are many of constraints which can be change to achieve the desired output of the impeller. The impeller which was designed for this purpose has a high trim since it majorly affects the mass flow of the compressor. Present design has a trim of 63.

The tip flow angle is recommended to keep between 60 degree to 75 degree since the tip flow angle progression affects the width of Exducer. The tip flow angle was set such that the relative velocity ratio was between the limits, from 0.65 to 0.9. At relative velocity ratio of 0.9, the blade tip width was 3.143mm and meridional velocity gradient of 1.1. The rake angle was set 12.5 degree.

A pressure ratio of 2.0203 and Angular velocity of 135000RPM was design point attribute as well

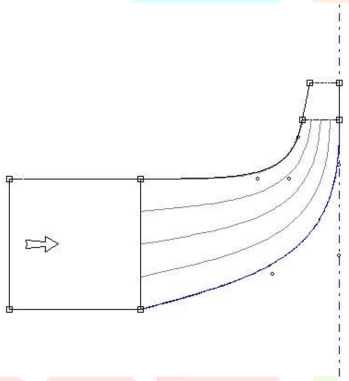


Fig 1. **Meridional plot for COMPRESSOR wheel**

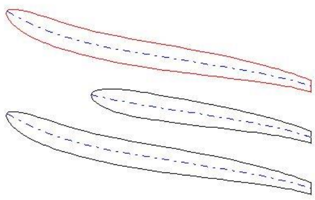


Fig 2. COMPRESSOR wheel Blade to Blade view

With 95% Polytropic efficiency, following values were achieved with the:

Flow coefficient: 0.16

Work factor: 0.61

Choke ratio: 0.998

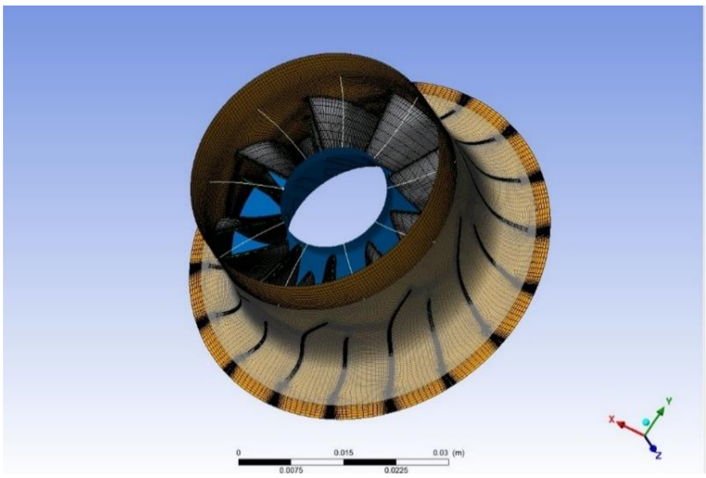
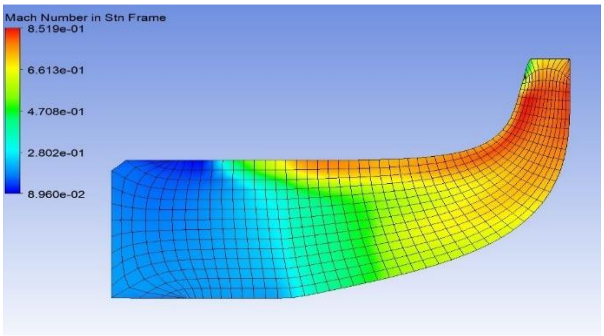


Fig 3. Meshed Impeller

Some exact values couldn't be achieved hence limits were set for those constraints. After considering Friction loss, recirculation loss and clearance loss, shock loss majorly affects the overall efficiency of the compressor. When the velocity of air is greater than the speed of sound, the Mach number exceeds 1, which generate shock waves, which causes shock loss.



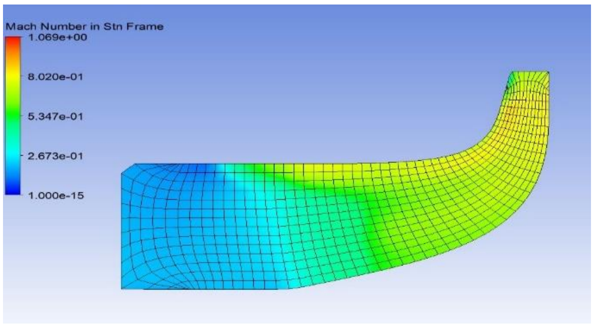


Fig 4. Meridional Mach Number in Stn Frame Global (left) and Local (Right)

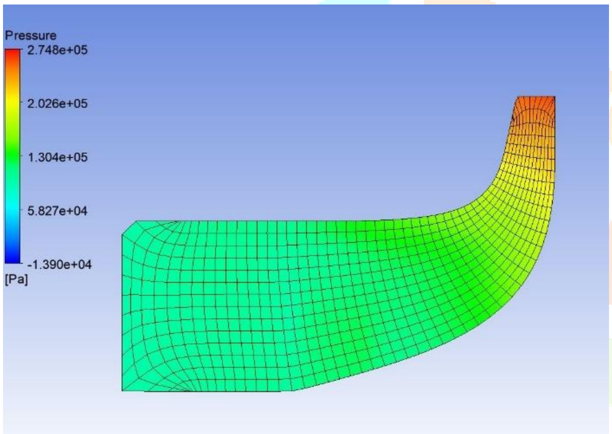


Fig 6 Meridional Pressure Contour

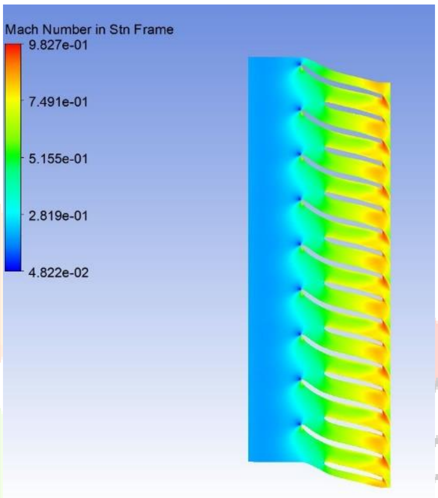


Fig 7. Blade-to-Blade Mach Number in Stn Frame

These constraints should also satisfy the structural integrity of the impeller, Increasing the blade tip angle not only affects the adiabatic efficiency but the stress intensity as well.

A complete analysis with the volute is done. The shape of the volute inlet also matters, since the vortices generated in the volute exit can change the pressure value about 5%. Therefore, various iterations were done. With diffuser at the extreme side and tangential to the surface was concluded as a acceptable design since it has uniform distribution of pressure at the volute outlet. Fig 9 shows the flow and velocity lines at in the volute.

The vortices which are generated causes flow separation due to which the pressure distribution is uneven. This causes non-uniform pressure distribution inside the intake runner of the engine which reduces the efficiency of the compressor. The vortices generated inside can be minimized by also taking aerodynamic parameters into consideration.

This Volute has A/R ratio of 0.45. Larger volute aspect ratio Implies that those volutes are capable of transferring more mass flow of air. This could result in achieving more peak power but losing the powerband i.e., compromising power at low RPM. At high RPM, the compressor gets spooled up and provides enough air to engine to achieve that peak power.

Fig 8. Intake Volute

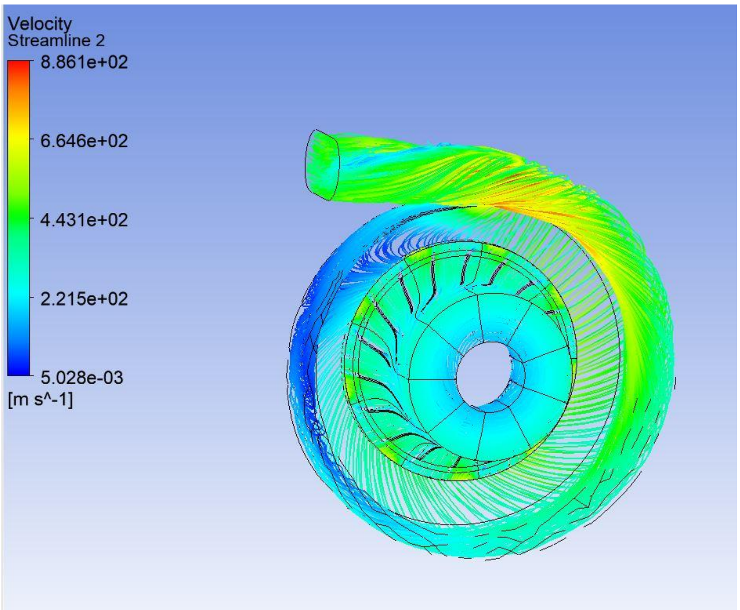


Fig 9. Compressor velocity lines

4. TURBINE

The is a component which spins due to the exhaust gases coming from the exhaust manifold. The temperature of turbine can get up to 700 degrees due to hot gases and increased thermal efficiency. The turbine and impeller are coupled with a shaft. As the velocity of air from the exhaust gases increases at higher RPM the compressor gets spooled up and thus the engine delivers power

There is no diffuser needed as the mass flow and velocity of gases are high. The pressure at the exhaust can be more than 10 times the inlet pressure depending on the compression ratio, AFR, valve lift etc.

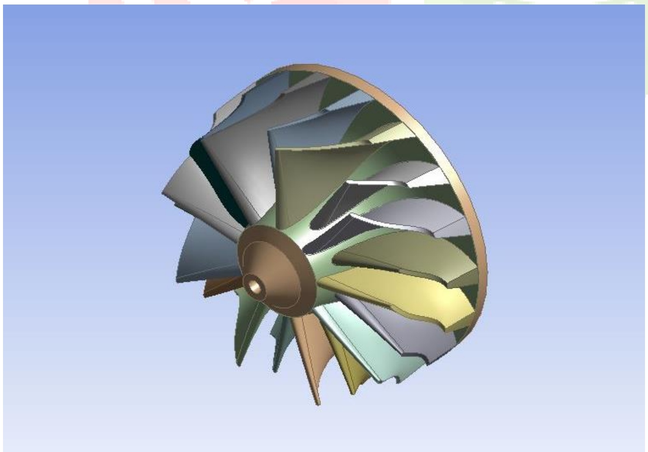


Fig 10. Turbine CAD

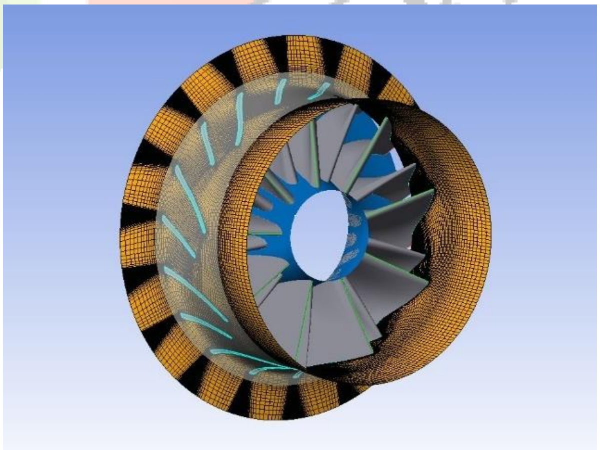


Fig 11. Meshed Turbine

As the air enters the volte first and then the turbine, the width of the tip must be larger. If the width is not enough to let pass the air, the air will get push back in the manifold which would result back

pressure in the manifold. If there is too much back pressure, the engine can blow off. Turbine design with low back pressure and high structural integrity were one of the primary aspects.

With 90% polytropic efficiency and low angle progression at trailing edge, following values were achieved:

Relative velocity ratio > 0.75

Mach number < 1

Backsweep angle >35

Choke ratio < 1

FOS of turbine blade > 2.3

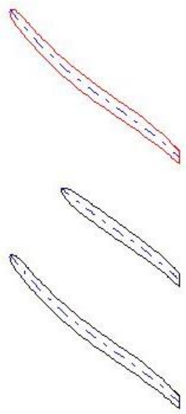


Fig 12. TURBINE wheel Blade to Blade view

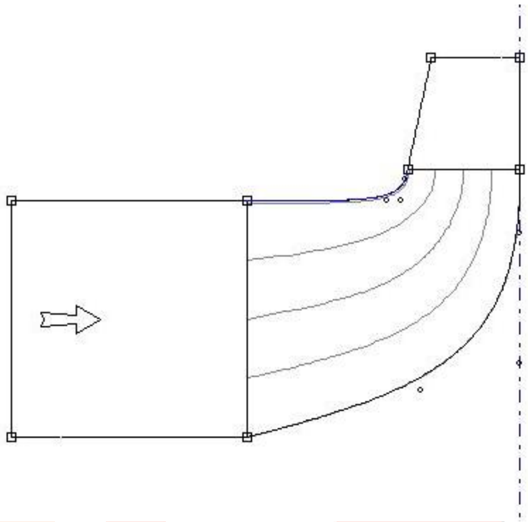


Fig 13. Meridional plot for TURBINE wheel

As the temperature of a material increases, the properties of that material also change. Ductile material expands when they are operated at high temperature which Is called thermal expansion, so the bonds of that material become weak. Due to thermal expansion the part will not be withstand the stress causing failure.

Hence, the turbine was designed with high FOS.

Fig 14. Exhaust Volute CAD

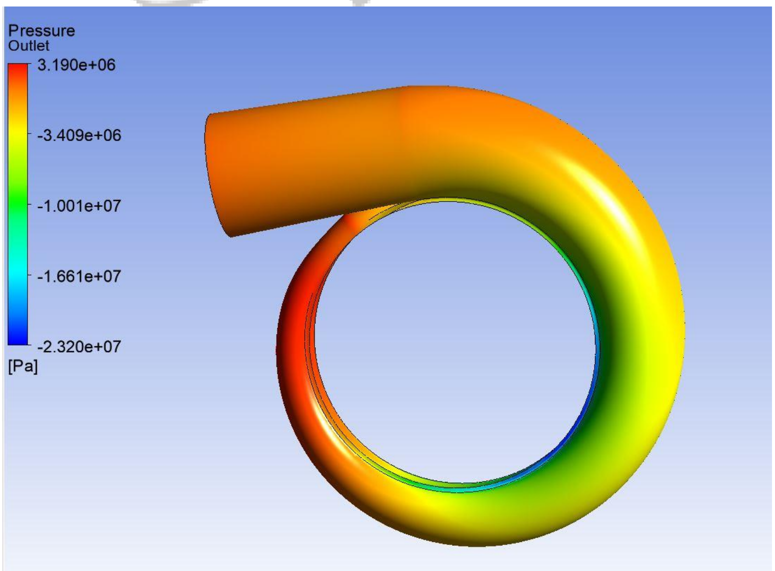


Fig 15. Exhaust Volute Pressure Contour

After combustion the pressure at the exhaust manifold is increased and the mass flow rate is increased as well due to the density of exhaust gas, the volute needs to be big enough allowing more air to flow inside the volute reducing the back pressure. Due to this a higher A/R ratio of the volute was considered. The ratio is higher than the compressor volute. The exhaust volute has A/R ratio of 0.57 and β angle of 14 degrees Diffuser is not needed as the design aim focus more on reducing back pressure and increasing mass flow rate at the turbine.

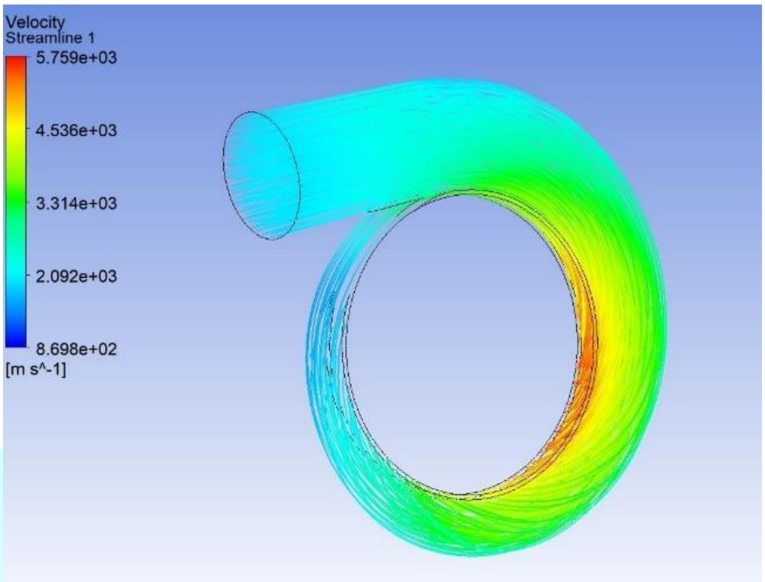


Fig 16. Exhaust Volute Velocity

As showed in Fig 16. there is no flow separation hence no vortices are generated. This reduces recirculation losses as well increasing overall efficiency.

5. CONCLUSION

The design is intended to achieve improved performance of the engine as compared to the stock Naturally Aspirated Engine.

From the CFD simulations we understood how the relative inlet flow angle of impeller affected the mass flow rate and the Mach number. To reduce the tip velocity primary parameters such as relative velocity ratio and meridional velocity gradient were not compromised. As the trim was increased the choke ratio was also increased. For Turbine wheel, it is better to have larger tip width to allow larger mass flow rate. As the temperature of the turbine.

The volute CFD simulation showed the weak areas and the flow separation regions. This helped us understood how the placement of diffuser and the shape of the volute inlet and outlet matters for fluids.

Since the above iterations were mainly focused to increase the peak power, we can do similar iterations to increase the powerband by changing constraints and parameters.

We achieved the desired theoretical overall efficiency of engine after using the above turbocharger after considering all the losses which affects the turbocharger during its working.

From the iterations performed in we can conclude that the designed turbocharger is capable enough to support the engine to deliver the desired peak power.

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