International Journal of Engineering Science Invention (IJESI)
ISSN (Online): 2319 – 6734, ISSN (Print): 2319 – 6726
www.ijesi.org ||Volume 8 Issue 05 Series. I || May 2019 || PP 49-57

Computer Aided Design and Analysis on Variable Geometry Turbocharger

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Abstract :*A turbocharger is a turbine that is used to compress air into a combustor. In which way, it can increase the volume of intake air of an internal combustion engine so that the volumetric efficiency is increased as well. A turbocharger takes advantage of exhaust gases to drive the exhaust turbine which connects with a compressor which is used to compress the intake air. A main problem that exists for a traditional turbocharger is turbo lag which happens when drivers accelerate in a low engine speed, because there are not enough exhaust gases outputted to drive the exhaust turbine. In this paper, a variable geometry turbocharger will be designed based on PRO/E in purpose of reducing the impact of turbo lag. A variable geometry turbocharger can change the geometry of the turbine housing when the engine accelerates, so that the turbo's aspect ratio can be maintained in its optimum. Also, from the area of engineering design, the design concepts of the turbine model will be stated. In order to help readers to build up basic concepts about variable geometry turbochargers, a complete turbocharger system will be introduced in this paper as well. What is more, a finite element analysis about the model will be developed in order to verify the reasonableness of the designed model.*

***Keywords** -Variable geometry, Turbocharger, Turbo lag, Mechanical engineering, Pro/E model*

Date of Submission: 25-04-2019 Date of acceptance: 05-05-2019

I. Introduction

Turbocharger is a main topic when people talk about high performance cars, and large diesel engines are usually equipped with turbocharges. It can significantly increase the horsepower of an engine without significantly increasing its weight by equipping a turbocharger on engines. Turbocharging has a hundred-year history. Tracing back to the late 20th century after the internal combustion engine was invented, Germans had had similar ideas to create a system to increase the engine power and reduce the fuel consumption. In 1905, the Swiss engineer and inventor Alfred Büchi registered the patent of the first turbocharger which is an axial booster driven by kinetic energy of the exhaust. Turbocharger was initially used in aviation industry, in order to increase the speed of aircrafts, the military applied turbochargers on aircrafts tentatively during World War I and it was put in large-scale production during World War II. In the 1960s, the exhaust turbocharger was firstly equipped in Chevrolet civilian cars which took advantage of the company Garrett which mainly produces aircraft turbochargers and solved the difficulties in turbochargers field, but Chevrolet failed because of the unreliability of exhaust turbochargers. On the other hand, the developing of exhaust turbocharger with engineering vehicles was relative successful. In the 50s, a compact exhaust turbocharger was produced and widely used on diesel trucks. Until 70s, the exhaust turbocharger was started use on civilian diesel cars widely, such as Mercedes-Benz 300SD. And in the 70s, a lot of classic cars were produced with exhaust turbochargers, such as 1973 BMW2002 Turbo, 1974 Porsche911 Turbo and Saab900. Nowadays, the exhaust turbocharger is not only used for increasing engine power, but also increasing fuel efficiency and reduce exhaust emissions. What is more, a turbocharger system enhances the dynamic response of the engine and in increase the limiting torque curve and torque back-up. The car with traditional exhaust turbocharger, however, has the problem of turbo lag because a traditional exhaust turbocharger cannot fulfill different working situations. In order to improve the performance of turbochargers, engineers developed variable geometry turbochargers and one of the first production cars to use these turbos was the Japanese 1988 Honda Legend which also used an integrated water-cooled intercooler installed on its 2.0L V6 engine. Figure 1 shows aturbocharger that is installed in a gasoline engine.

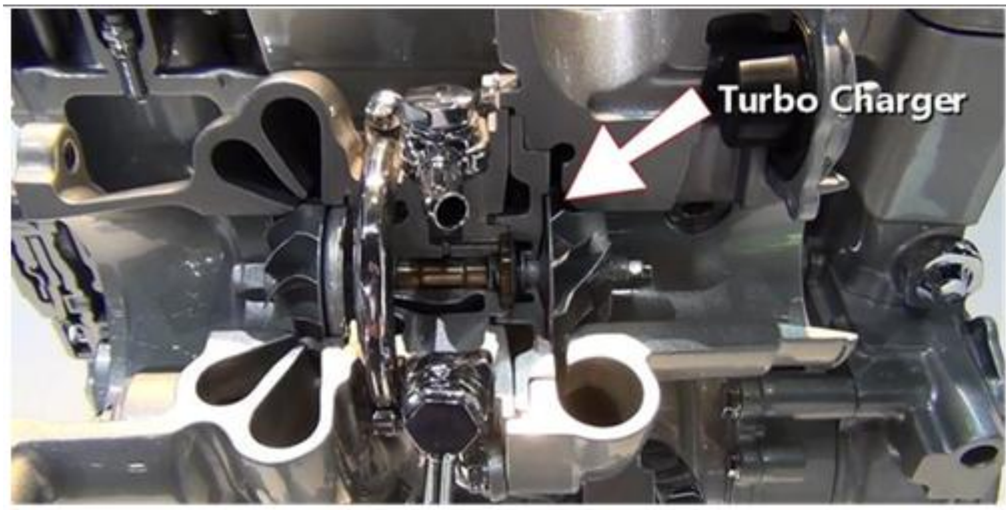

Fig.1 Turbocharger

II. TURBO SYSTEMS

A turbocharger system shows in Figure 2 mainly consists of a turbine and a compressor. The turbine is made up of a turbine impeller and a turbine housing. The inlet of the turbine is connected to the outlet of the engine so that it can gather the exhaust gas from the engine after the combustion of the mixture of fresh air and gasoline. The outlet of the turbine is connected to the exhaust vent of the car so that the exhaust gas can be emitted out of the engine. The compressor also mainly consists of two parts, the compressor impeller and the compressor housing. The outlet of the compressor is attached to the inlet of the engine and the inlet of the compressor is connected to the air between which there is an air filter. The turbine and the compressor are linked together through a shaft which makes the impeller of the turbine and the compressor to rotate simultaneously. In another word, the turbine is driven by the exhaust gas which is from the combustion in combustor and the compressor is driven by the turbine. In this way, there will be more air-gasoline mixture enter the combustor of the engine so that the fuel efficiency and horsepower will be increased.

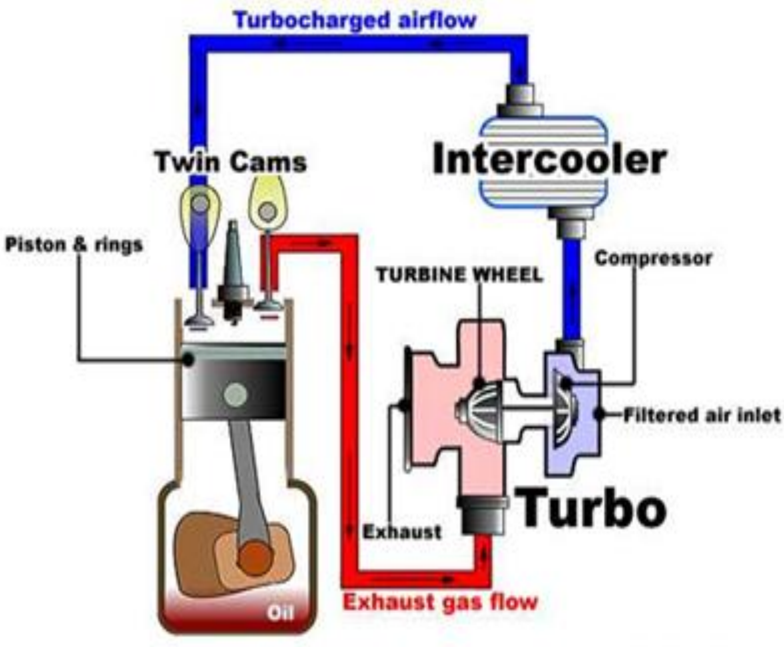

Fig.2 Turbocharger System

As for a variable geometry turbocharger, the turbine impeller is surrounded by a swing blade unit shows in Figure 3. In which way, when the exhaust gas is not enough to drive the turbine impeller, usually cause turbo lag, the swing blade changes its angle so that the pressure inside the turbine house is increased and the pressure drop is increased which will provide more power to drive the turbine impeller. As long as the car is sped up and the engine speed is in a relative high situation, there is more exhaust gas come to the turbine, in this situation, the swing blade is opening with a relative great angle which keeps the back pressure away and maintains a smooth air flow inside the turbine.

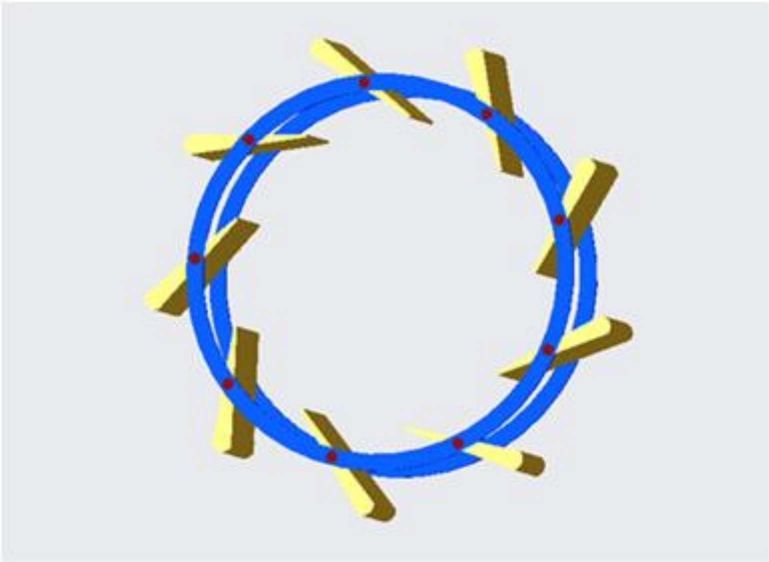

Fig.3 Swing Blade Unit

III. CHARACTERISTICS OF MODERN TURBOCHARGER

Nowadays, it is pretty common for people to see that a car is equipped with a turbocharger, usually, there is a suffix ‘T’ at the end of the symbol of engine displacement to refer that the car is equipped with a turbocharger, for example 2019 Audi Q7 3.0T. There are lists of main characteristics for modern turbocharger cars. First of all, turbochargers tend to be small-scale. Compare with traditional engine, turbochargers provide a significant chance for manufacturers to produce relative small-size engine in a certain situation that is preserving a stable engine power because turbocharger allows engine to gain a great improvement of power, almost improve 100 percent, while the weight and volume of the engine just increase a little bit. Second of all, turbocharger makes the car to be more energy-saving. The main principle of a turbo system is to make use of exhaust gas to drive the compressor in purpose of boost intake air to increase fuel efficiency. Alternately, the horsepower of an engine with 1.8L engine displacement when equipped with a turbocharger is equivalent to a naturally aspirated engine with 2.4L engine displacement. Thirdly, environmentally friendly. Generally, turbocharger makes the car to be more energy-saving, in other words, turbocharger-equipped engine need less energy compare with naturally aspirated engine if in an exactly same situation. In this situation, the former discharges relative less amount of harmful gas and CO_2, which means environmentally friendly. Usually, for a diesel engine, turbocharger decreases the emission of NO_x up to 80 percent and particulate matter up to 90 percent.

IV. PROBLEMS OF TRADITIONAL TURBOCHARGERS

As I mentioned in the introduction section, the first series cars that equipped with turbocharger did not have a good performance. Unfortunately, the traditional turbocharger, nowadays, also has problems. Above all, turbo lag. As we all know that the connection between the engine and turbocharger is pneumatic rather than mechanical, so there is a reaction period and it is much more obvious when in a low engine speed. Secondly, the performance of turbochargers is not that notable with a low engine speed. Because of the low engine speed, there is relative less amount of exhaust gas which leads to a low angular velocity of the turbine impeller and then leading to a low angular velocity of compressor impeller which is driven by the turbine impeller. In this case, a relative low pressure will be generated in the compressor housing and it is hard to provide enough intake air to the engine. Therefore, in a relative low engine speed, the performance of the turbocharger is not that significant. What is more, turbocharger might shorten the engine’s life. After boosting by using a turbocharger, the pressure and temperature of the engine tend to be higher compare with naturally aspirated engines, so that it will have a negative influence for the life of an engine that equipped with a turbocharger.

V. Variable Geometry Turbochargers

For the purpose of solving these problems that I mentioned upon paragraph, mechanical engineers developed a new type of turbocharger which is with a variable blade installed inside the turbine housing. In this way, the inside geometry of the turbine housing can be literally changed. At least, the variable geometry turbocharger can reduce the influence of turbo lag and improve the performance of the turbocharger when the engine speed is low. As for the principle of a variable geometry turbocharger, I have mentioned upon in the turbo systems section. Here the superiorities of variable geometry turbocharger will be presented. Gasoline engines equipped with variable geometry turbochargers performed much better than traditional turbocharged engines. The most important part of the variable geometry turbocharger is the housing geometry adjusting part, alternatively variable blade. These blades can be rotated to nearly closed position when the engine speed is low and it cannot generate enough exhaust gas to drive the turbine impeller. In which way, the pressure at the inlet of the engine will be increased and there will be more intake gas be charged into the engine. Finally, the efficiency of a variable geometry turbocharger equipped engine is much higher than a traditional turbocharger equipped engine no matter in which range of engine speed. Correspondingly, no matter in which range of engine speed, the fuel efficiency of the former engine is much high than the latter one.

VI. PRO/ENGINEER BASED MODEL

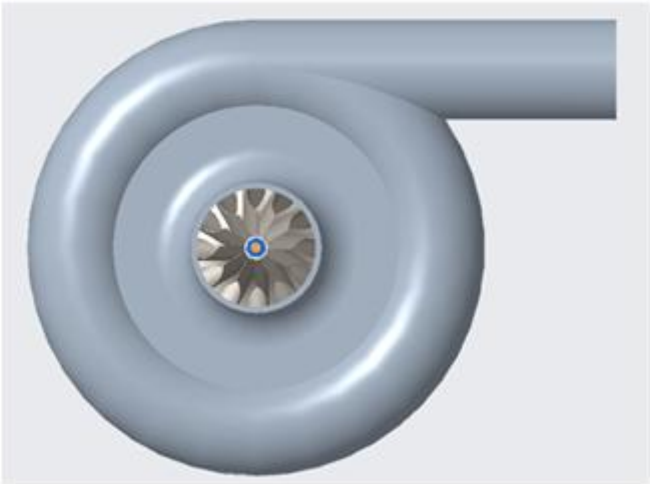

Fig. 4 3-D Model

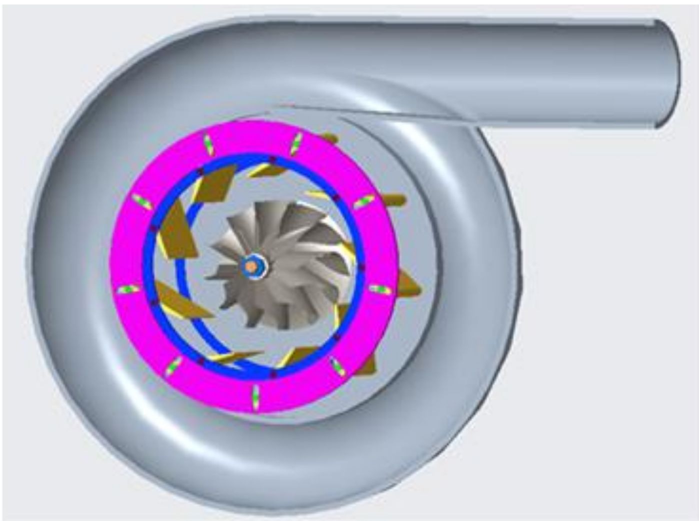

Fig.5 Cut Section

The assembly 3-D model of a variable geometry turbocharger was sketched by Pro/EINGEER and it will be showed in Figure 4 for the whole model and Figure 5 for the cut section. The model of variable geometry turbocharger mainly consists of five parts which are a turbine housing, a turbine impeller, a main shaft, a variable blade and a slot plate.

Figure 6 shows the variable unit with the slot plate. In this design, I set up the variable unit as an assembly in which way, the manufactures produce the whole unit as one part and in the future, if the variable unit is needed to be repaired, the only thing need to do for a mechanical person is to replace the whole unit. The main principle of my design is to reduce the manufacturing budget and make the maintenance much easier because turbocharger is relatively easy to have mechanical problems. In the model, the horizontal vent of the turbine housing is the inlet of the turbocharger which is also connected to the outlet of the engine. The vertical vent of the turbine housing is the outlet of the turbocharger which is connected to the exhaust vent of the car, in other words, it is connected to the environmental air. The plate with color of purple is the slot plate which will be controlled by a linkage so that it can change the angle of the variable blade via rotating. Those parts with color of yellow are the blades. The turbine housing is designed in two symmetrical parts which are screwed together so that when do maintenance, mechanical person just need to disassemble the turbine housing and replace the variable unit.

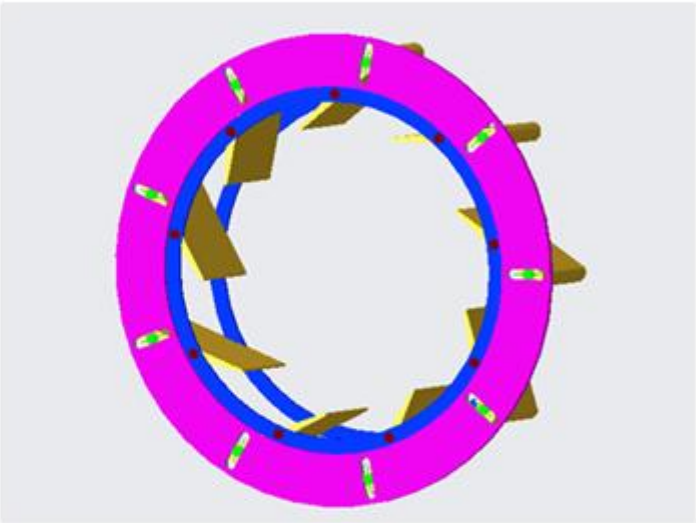

Fig.6 Variable Unit with Slot Plate

VII. MATHEMATICAL METHODOLOGY

Generally speaking, the working principle of the exhaust turbine is to translate the movement of the exhaust gas to the rotation of the turbine impeller. As for the variable unit that is installed in the exhaust turbine, the working principle can be simplified to be a moveable vane that is used to change the cross-sectional area between the turbine housing and the turbine impeller. If we treat the working principle of the exhaust turbine in this way, it could be simplified like that the angler velocity of the turbine impeller is directly proportional to the velocity of the exhaust gas that flow through the impeller blade. Then, if we consider that the volumetric flow rate of the exhaust gas that emitted by the engine is constant in certain engine speed, then the velocity of the exhaust gas is inversely proportional to the cross-sectional area. In this situation, when the variable vane is opened in a relative smaller angle, the cross-sectional area is smaller, then the velocity of the exhaust gas that pass through the impeller is greater which leads a greater angler velocity of the exhaust impeller. Ultimately, the angler velocity of the compressor impeller is greater and it will deliver more air to the engine. Therefore, in this calculation section, I prefer to assume that the exhaust turbine is a pipe with a rotational blade inside and there is air flow with a constant volumetric flow rate pass through the pipe. The ultimate goal is to analyze the relation of the cross-sectional area with respect to the velocity of the flow. Then I generate the following method,

$$Q = v \cdot A$$

Where,
Q is the volumetric flow rate
v is the velocity of the flow
A is the cross-sectional area
We need the velocity of the flow, so

$$v = \frac{Q}{A}$$

It is obviously to see that when ‘A’ is smaller, velocity ‘v’ tends to be greater, so that the angler velocity of the turbine impeller is greater.

VIII. FE BASED AIR FLOW ANALYSIS

Regarding to the air flow inside the exhaust turbine housing, we need to do a lot of analyses to make sure that the variable vane unit does not have negative influence to the engine. At least we need to ensure that the air flow inside the turbine housing is fluency and to monitor the pressure drop between the inlet of the exhaust turbine and the outlet of the exhaust turbine. Also, we need to make sure that the variable vane unit does real work to change the cross-sectional area of the turbine housing. So, in this section, I will present a FE based air flow analysis inside the exhaust turbine housing and I will show two different situations with different variable vane angle, 30° and fully open. For the volumetric flow rate, I keep that as constant in two different situations and we will see the difference of the pressure drop between two different situations.

8.1 Meshed Model

Figure 7 shows the meshed model. It is generated by FloEFD, the range of the mesh is set in level 6.

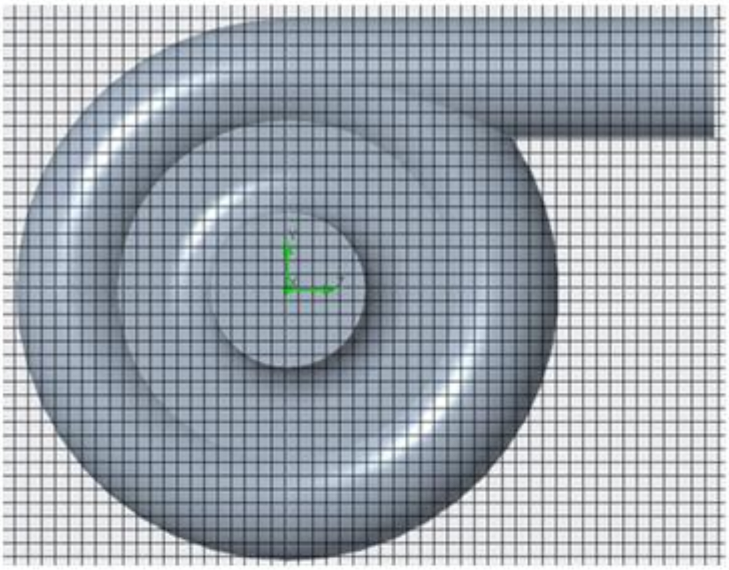

Fig.7 Mesh of the Model

8.2 Flow Analysis with 30° Opened

8.2.1 Streamlines Inside Turbine Housing

Regarding to the boundary conditions, I set the horizontal vent to be the inlet of the exhaust turbine and the vertical vent to be the outlet. When I did the analysis, I put two lids to cover these two vents. Also, I set a rotating region surrounding the turbine impeller. Because in different working conditions, the engine emits different amount of exhaust gas and it is vary between different engines with different displacement, so I just assume that the volumetric flow rate of the exhaust gas is $0.6m^3$ per second. Figure 8 shows the streamlines of the flow with respect to the pressure, it is obviously to see that there is not any vortex inside the turbine housing.

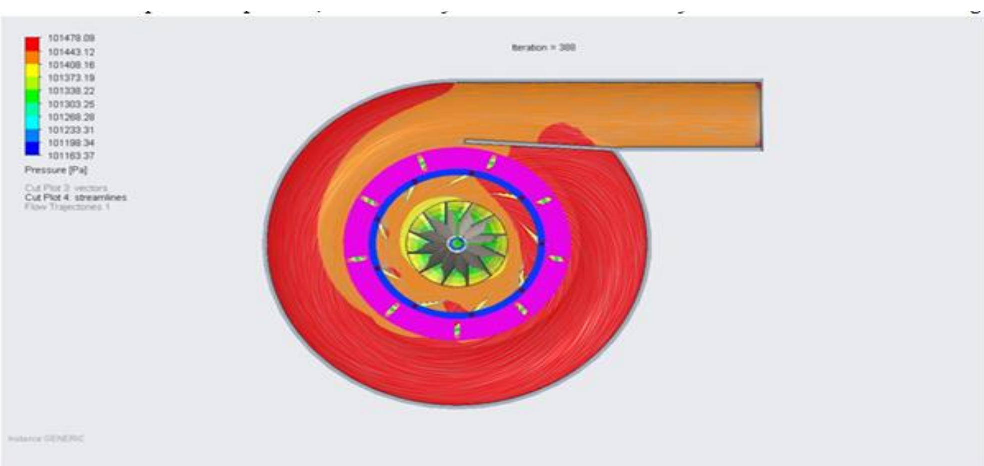

Fig.8 Streamlines with Pressure

8.2.2 Pressure Inside Turbine Housing

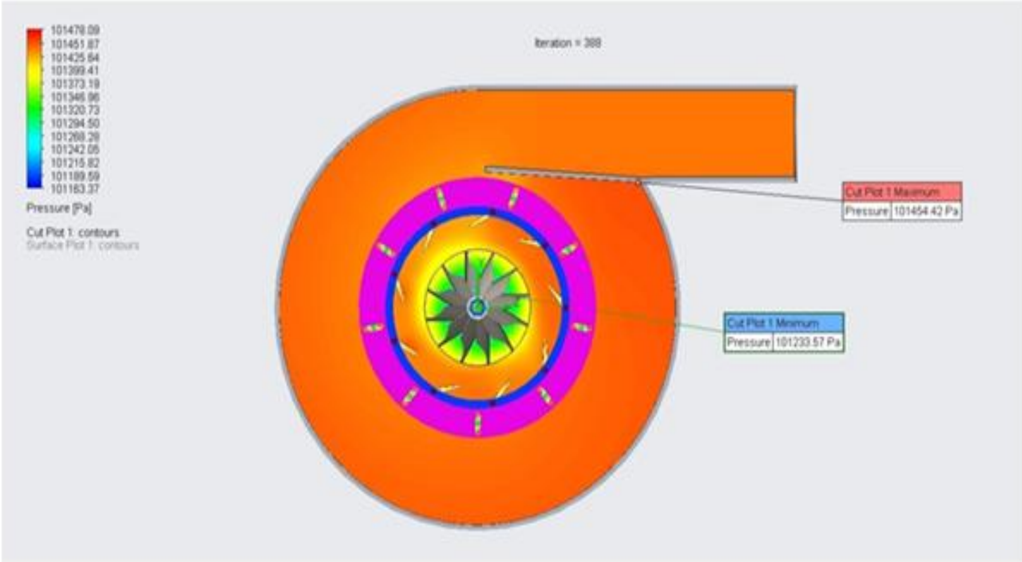

Fig.9 Pressure

From Figure 9 we can find the maximum and minimum pressure inside the exhaust turbine housing which are 101454.42 Pa and 101233.57 Pa, respectively. Then the difference between the maximum and minimum pressure is 220.85 Pa and later we see the difference between this situation and the fully opened situation.

8.3 Flow Analysis with Fully Opened

8.3.1 Streamlines Inside Turbine Housing

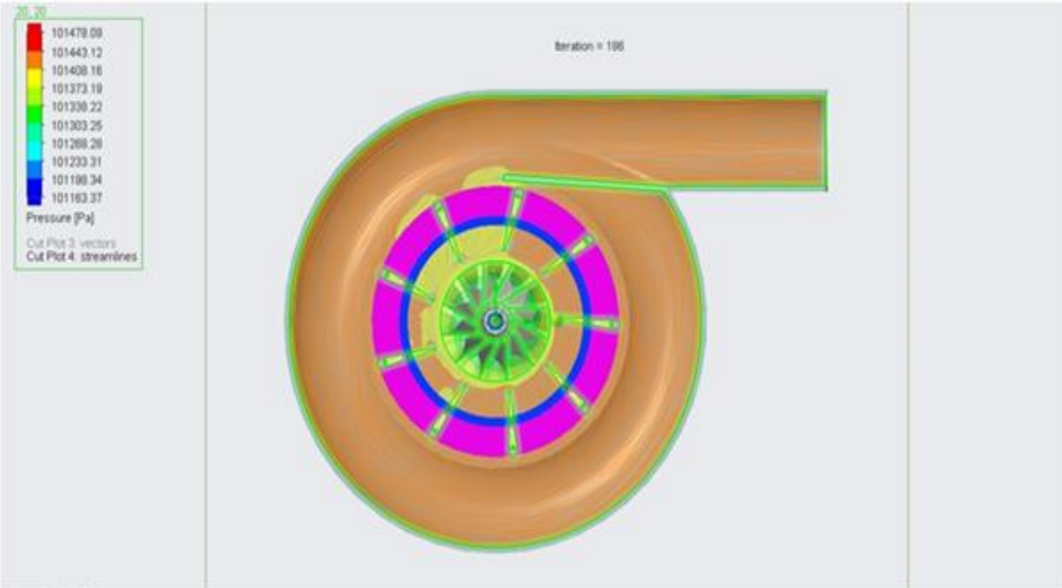

Fig.10 Streamlines

From figure 10, there is not any vortex inside the turbine housing as well when the variable vanes unit is fully opened based on the streamlines with respect to the pressure inside turbine housing.

8.3.2 Pressure Inside Turbine Housing

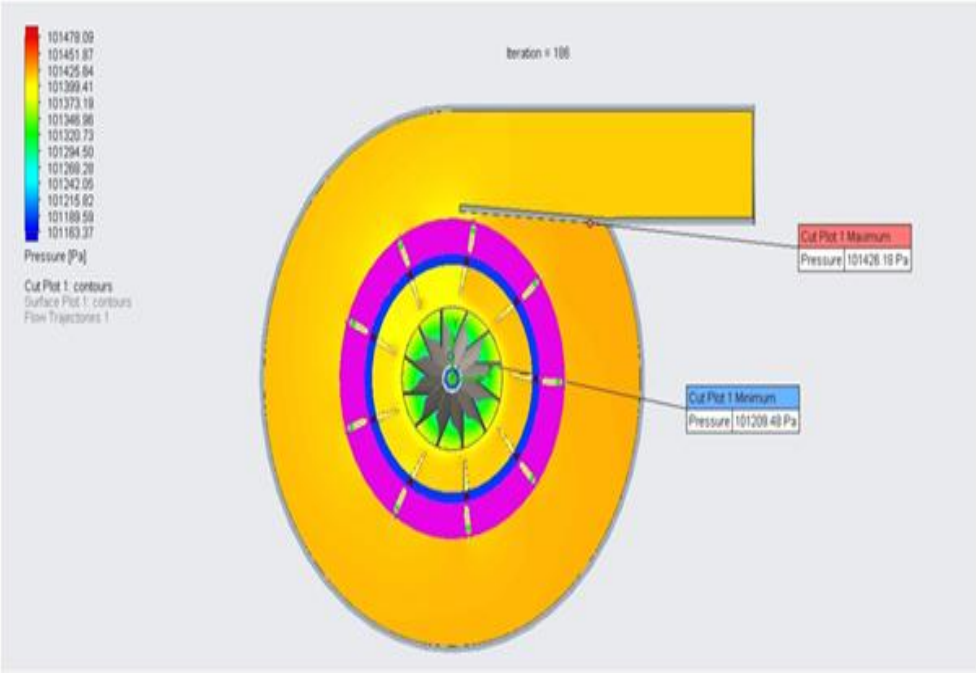

Fig.11 Pressure

In this situation with fully opened variable vanes, the pressure is relative lower than the previous one because I preset a constant volumetric flow rate and the variable vanes are fully opened which means the cross-sectional area is greater than the previous one with 30-degree angle. The following Figure 11 shows the pressure inside the turbine housing that with fully opened variable vanes. Alternatively, if the volumetric flow rate of the exhaust gas is greater or in other words the engine speed is greater, the pressure will also be greater than it in this situation. As we can see here in this figure for the pressure with fully opened variable vanes, the maximum is 101426.18 Pa and the minimum is 101209.48 Pa and the difference is 216.7 Pa which is smaller than the previous one with a 30-degree angle which is because of the change of the geometry inside the turbine housing.

IX. CONCLUSION

Variable geometry turbocharger is an amazing device to increase the horsepower of the engine and decrease the influence of turbo lag. In this paper, a variable geometry turbocharger is designed by using the software of Pro/ENGINEER. In order to help people to know the story of turbochargers, the basic history is mentioned, also in purpose of helping readers to get basic knowledge about turbochargers, the main working principle of turbochargers is presented in this paper. Furthermore, the flow analysis based on FloEFD proved that the variable vanes unit is a great device to change the geometry inside turbine housing. Finally, a new structure about the variable vanes unit is designed in this paper which will help mechanical person to do maintenance easily and it can reduce manufactures' budget.

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Tian (Richard) Zhao" Computer Aided Design and Analysis on Variable Geometry Turbocharger" International Journal ofEngineering Science Invention (IJESI), Vol. 08, No. 05, 2019, PP49-57