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Design and Performance Analysis on E-Tronic Turbocharger to eliminate Turbo Lag

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ABSTRACT

A turbocharger is a turbine which compresses and forces air into a combustion chamber of internal combustion engine which in turn increases the volumetric efficiency of a naturally aspirated engine. It uses exhaust gases to spool up the exhaust turbine and a compressor is coupled with the exhaust turbine which compresses the intake air which in turn lets higher fuel to burn efficiently in a smaller displacement engine, thus producing higher power. The electric turbocharger works like a normal turbocharger which spools up and compresses air into the engine. But instead of connecting the compressor directly to the exhaust turbine, the exhaust turbine is connected to a high current alternator and runs a high-speed motor at the intake compressor. This reduces the spooling time of a turbocharger eliminating turbo lag which is in conventional turbocharger. The present work is focussed on design and performance analysis on E-tronic turbocharger to eliminate turbo lag.

KEYWORDS: Turbo lag, BLDC Motor, Naturally aspirated Engine, Turbo Spool up, E-Tronic

1. Introduction

An electronic turbo charger uses a high speed exhaust turbine generator and a high speed electric supercharger which runs at 100,000 RPM max and generate electricity which runs the turbine at the required RPM variable through throttle eliminating the spool up time which is backed up by a set of super capacitors. The supercapacitors are charged through the exhaust turbine generator. This is used to run the intake air compressor at the required moment. The total charge required to run the intake compressor for a certain period at higher boost pressure is provided through the supercapacitors when at the required time. For operation under normal load conditions the exhaust turbine is directly coupled to the intake compressor through a solenoid clutch. The normal lag in turbo is eliminated completely by use of the electrically assisted system. Thus, producing more power on demand. The modes are programmed into the engines ECU which controls the turbo timing and pressure, through a set of sensors such as Crank position sensor, Manifold Absolute Pressure Sensor, Exhaust O_2 Sensor. This also eliminate the need of variable geometry turbo (VGT) [1-2]. The need for waste gate mechanism is eliminated due to variable compressor speeds which can be controlled through the manifold absolute pressure sensor. Which quickly reduces the speed of compressor at full throttle conditions, which synchronises the engine's RPM to the required boost pressure. As conventional turbochargers are couple together in a single shaft for power delivery this uses a clutch in between which makes the thermally isolated from the heat of the exhaust turbine. This uses ball bearings and a thrust bearing instead of normal bush bearings lowering the friction losses and in turn lowers the time for attaining the required RPM thus lowering the lag [3].

The E turbo was first conceptualized by Aristech. Ltd. As hybrid turbo technology which has a same system by default but the system doesn't use a clutch for decoupling the exhaust turbine for a higher boost at required time period instead it uses a fully electronically controlled system for the boost pressure control at the given load and RPM. The usage of fully electronic system increases the overall cost of system and it increases the maintenance of the motor [4].

As a recent upgrade VALEO and Audi Gmbh. Joint designed an electric turbo for new RS and R series cars which uses both normal turbocharger and electrical boost turbo for lag elimination which the electric turbo acts as a supercharger for a given time period, which provided higher boost pressure for on demand times. Although this uses the electrical assist for a limited time period the power is delivered from normal battery of the vehicle. This makes the battery system strain a lot and changing the voltage standards from 12v DC to 48v DC making the standard car equipment incompatible in today's standards [5].

1.1 System Model

To make turbocharged downsizing engines really attractive to the common, additional measures must be taken to support the turbocharger in transient operation. These should all pursue the same targets: increase the energy supply for the turbines in dynamic operation. The most effective means to positively influence the dynamic behaviour of turbocharged engines is to feed the system temporarily with auxiliary power. For more than ten years, the idea is pursued to support the charging process temporarily by the help of electric motors. The basic idea was to decouple the high-speed rotating parts responsible for the delayed response of the thermodynamic function and increase the number of revolutions primarily by the electric motor. Besides the pure electromotive support of the charging process, such an approach in principle offers the possibility to recuperate energy. Rather than directing the exhaust gas energy via the waste gate unused, by utilising a generator, electric energy can be produced and stored temporarily in an energy storage. In addition, these charging units should be able to be controlled more accurately as a constant speed monitoring takes place. Features such as an active post-cooling, avoid harmonics and over-speeding, pre-charging for the cold start to reduce emissions etc. represent other possible benefits. Many attempts to realise an electrically assisted hybrid turbocharger failed up to now because the used conventional electric motors have increased the moment of inertia of the rotor group to such an extent that an improvement of the response of the electrically assisted turbocharger could not be reached [6-7].

The approach is to use a conventional electrical system and a lag less turbo under an acceptable price compromise, not to implement an insane piece of technology which cost too much to implement and to maintain. Everything to be under manageable extent usage of simple system such as a turbo which regenerates the power required under seconds in normal riding conditions and provides a surge when power is required as a top priority. To make things compact and the pipe work easy the cooling mechanism is eliminated for the intake air as the intake compressor stays cool under maximum cycles, Because of the isolation of the turbines through a solenoid clutch in between.

1.2 System Working

The turbo charger coupled to the engine. Now the turbo shaft is modified to required diameter to fit the brushless motor to it. The brushless motor has the capability to run at variable RPM using PWM signals. The motor which is connected to the motor control unit controls the speed of the motor. And the MCU is connected to step supplier and battery. Then the MCU is directly connected to buffer. A buffer is a unity gain amplifier packaged in an integrated circuit. Its function is to provide sufficient drive capability to pass signals or data bits along to a succeeding stage. Both ends of brushless motor is connected to intake and exhaust turbine. The exhaust of the turbo is connected to the throttle valve to the engine. When the engine is operated and in the minimum rpm the brushless motor starts and run the turbo shaft. Accordance to the size of the turbocharger the motor may also vary. By this maximum boost pressure can be gained and turbo lag can be reduced.

The turbocharger which is connected to the four-stroke diesel engine. Now the turbo shaft is modified by required diameter to fit the brushless motor into it. The brushless motor has the capacity to run up to high rpm and operate at low rpm. The motor which is connected to the motor control valve where it controls the speed of the motor. And the MCV is connected to step supplier and battery. Then the MCV is directly connected to buffer [8]. A buffer is a unity gain amplifier packaged in an integrated circuit. Its function is to provide sufficient drive capability to pass signals or data bits along to a succeeding stage. Both ends of brushless motor is connected to intake and exhaust turbine. The exhaust of the turbo is connected to the throttle valve to the engine. When the engine is operated at minimum rpm the brushless motor starts and rotates around the turbo shaft. Accordance to the size of the turbocharger the motor may vary. By this maximum energy can be gained and turbo lag can be reduced [9].

ON DEMAND MODE: When the pedal is depressed the ECU senses the need for power and as the throttle valve opens the solenoid clutch disengages from the exhaust turbine and the ECU sends as surge of power to the intake compressor motor making higher boost pressure according to the power required, in mean time to compensate the air the MAP sensor senses the increase in air pressure and provides higher fuel increasing the Fuel to the amount of air. Thus, extracting more power from the engine at a required time period. As the capacitors discharge rapidly the ECU senses the voltage drop and charges it through the generator coupled on exhaust turbine. This is shown in figure 1.

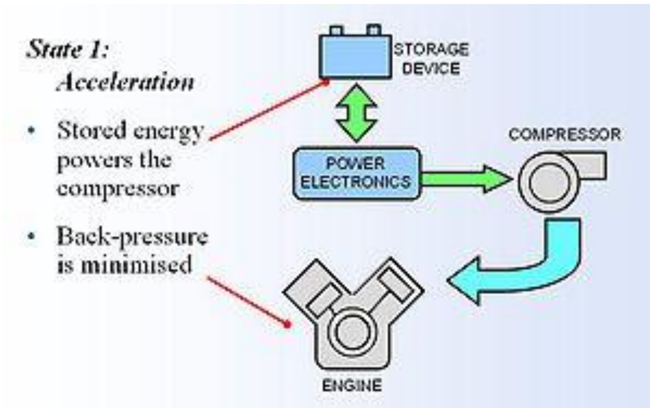

Fig. 1. Acceleration phase schematics.

NORMAL MODE: At normal operating times the solenoid clutch engages the intake turbine shaft with it making them run at the tuned RPM for providing a standard boost pressure for normal riding modes. Although in this mode also the Capacitors gets charged whenever the ECU senses a drop-in voltage in the capacitors. This normal mode is shown in figure 2.

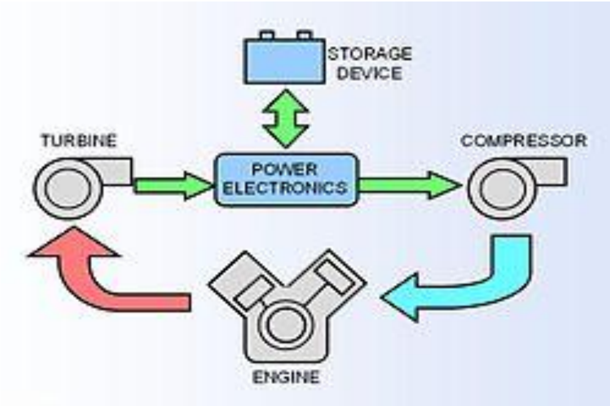

Fig. 2. Normal cruise phase schematics.

CHARGING MODE: When engine runs at lower loads there is less need of the turbo to provide higher boosts. The exhaust energy is use to charge the rest of the electricals of the vehicles this provides extra room for electrical upgrades and lower wear and tear of battery. The higher voltage is converted using a step down converter to be fed to the car battery. This charging mode is shown in figure 3.

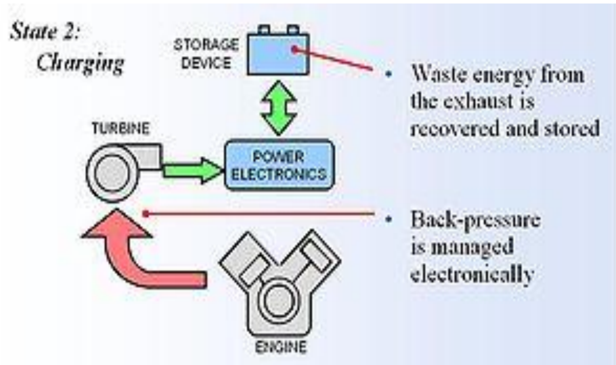

Fig. 3. Charging phase schematics.

2. Problems and Solutions

The common problem with turbocharger is its turbo lag, which occurs when the demand for an increase in power and the turbocharger providing intake pressure and thus increase in power, this happens due to the time taken for build-up of exhaust pressure.

SOLUTION: This occurs due to the time taken for pressure build up, this is eliminated completely by using high speed motor in intake compressor. That provides instant boost pressure when power is required through constant monitoring of the power and load characteristics of engine through closed loop monitoring system.

Conventional turbochargers use pressurized oil for lubricating the bush bearings and thrust bearings which is prone to leakage on high temperatures or when the oil loses its viscosity. This causes the oil to enter the intake side of the turbo causing oil leaks and thus causing white smoke in exhaust.

SOLUTION: Electronic turbochargers uses a thrust bearing at the turbine side, needle bearings for motor, ball bearings and thrust bearings on the intake compressor side. This uses sealed bearings thus eliminating the need of lubrication on intake side of the compressor preventing oil leaks. Although the exhaust side requires oil but at lower pressure unlike normal bush bearings.

Higher pressure on the intake side will lead to over revving of the engine causing engine damage and will damage the compressor itself.

SOLUTION: Electronic supercharger uses MAP sensor for monitoring the manifold pressure and regulating it by varying the motor RPM thus eliminating the need for a waste gate or blow off valve. This method is more advanced than Variable Geometry Turbo which FIAT and other leading manufacturers use [10].

Full time usage of motor will cause higher wear and tear of the motor to prevent this a solenoid clutch is used for coupling and decoupling the turbine from the compressor at the required time periods. This is controlled through the inbuilt ECU of the engine.

4. Analytical Calculations.

The following test is conducted in Mitsubishi K3C diesel engine. [11]

Table 1. Mitsubishi K3C diesel engine Specifications

Specifications:

Model	k3c
Type	3 cylinder,4 stroke,over head valve. Inline, diesel engine
Combustion Chamber	swirl chamber type
Bore X Stroke	70 mm(2. 75 in)x78 mm(3. 07 in)
Displacement (swept Volume)	900 cu. Cm(54. 9. Cu. In)
Compression Ration:	11:01:00 PM
Max. Torque	5. 2 kg. M / 1900 rpm
Output / Rated	18. 5 hp / 2700 rpm(is : 10,000)
S. F. C. (specific Fuel Consumption)	230 gm/hp-hr
Cooling System	water-cooled radiator, forced water circulation by centrifugal pump
Governor System	mechanical centrifugal type
Dry Weight	125 kgs
Starting System	starter motor 12 volts - 1. 6 k w.
Fuel System	
Fuel	high speed diesel oil (h. S. D.)
Fuel Tank Capacity	18 liters
Nozzle	pintle type
Lubricating System	
Capacity of Oil Sump	3. 0 liters
Type of Lubricating System	forced feed trochoid pump
Air Cleaner	3 stage oil bath type
Lighting System	
Lighting	12 volts,35 watts
Alternator	12 volts, 40 amps
Glow Plug	12 volts quick heat type

With the following tests we implement normal turbocharger to see the engine output. The test results show a power gain from 18.5 to 22hp @2700RPM and a torque increase from 55Nm to 62Nm@2000RPM.

Although the power and torque figures increased by using forced induction system. The engine now loses the crisp throttle response and linearity in power delivery the given 22hp at a particular RPM. This makes the low end power to struggle and makes the engine stall. To actually overcome the above said issue now we implement E-Tronic Turbocharger where the electronic assist BLDC motors support the turbo to actually provide the necessary boost pressure making the engine to produce a more usable power curve and torque ensuring the engine provides the necessary output for its required applications.

4.1 Design Calculations

Turbo map = 2.66 pounds per minute air flow

Actual airflow (Wa) = 590 CFM or 16.50 lb/m

Target HP= 22.5@2700RPM

A/F = 14:1 one part of fuel to 14 parts of air

Manifold absolute pressure to meet the target horsepower

Map_{req} = Wa x R x (460+Tm) / VE x N/2 x Vd

Where:

Map_{req} = manifold absolute pressure required

Wa = Actual air flow (lb/min)

R = gas const. = 639.6

Tm = intake manifold temperature = 50 C or 130 F

N = Engine RPM = 2700

VE = volumetric efficiency say 90%

Vd = engine displacement (Ci) 0.9*61=54.9Ci

MAP_{req} = 34.5psia

To get atmospheric pressure to set gauge 34.5-14.7 = 19.6psig

P2c=MAP▲ P loss

P2c = 34.5+2 = 36.5psia

To correct inlet conditions and to eliminate restrictions such as air filter, Intercooler and waste gates piping.

Ptc = P_{amb} – P loss

Ptc = 13.7 psia

Pi c = 36.5/13.7 = 2.7

The value when compared with the turbo map provides the turbo map at different RPMs.

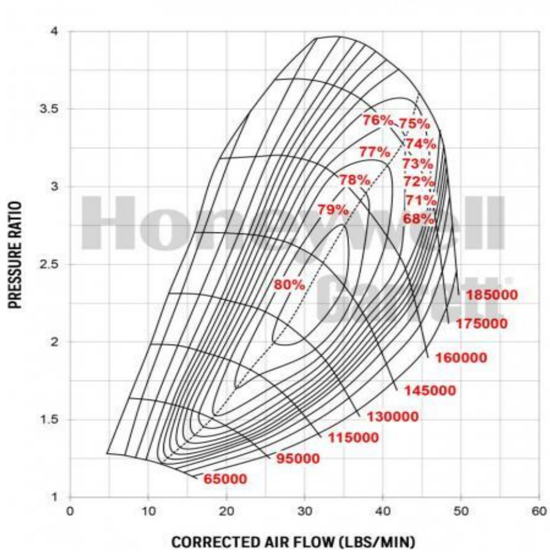

Fig.4 Turbo Pressure vs flow chart from the manufacturer (Honeywell Garett) [8]

The turbo efficiency for the given turbine speeds reduce at lower RPM causing the lag to make engine sluggish. To correct this issue the BLDC motor will provide 20Kw of power to turbo by assisting the turbo to be running at a much higher boost pressure to eliminate the turbo lag.

This can be electronically mapped in the ECU so that the Map sensor provides the necessary data for a closed loop monitoring system. The CANBUS data is used to closely vary the BLDC motors RPM such the motor precisely varies the pressure without the need of waste gate system The turbo pressure vs flow chart from manufacturer is shown in figure 4.

5. Thermal Analysis

Many heat transfer applications like nozzle, engine block, piping system involves thermal analysis. For each load step, both load and temperature are specified. So, when the excess temperature acting on the blade where more deformation takes place. In this, turbine blade is undergone thermal analysis by changing the material as titanium alloy which has the good ductility and high strength and this is shown in figure 5-6.

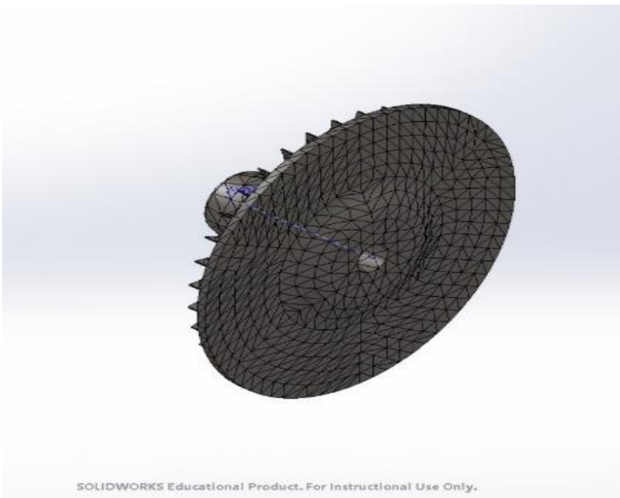

Fig.5. Exhaust Turbine Meshed

Treated as,	**Volumetric Properties**
Solid body	Mass:50.1108 Kg Volume:0.0103964 m^3 Density:4820 Kg/m^3 Weight:491.086 N
Analysis type	Thermal
Mesh type Entities	Solid mesh 218 faces
Solver type	FFE plus
Material name	Ti-3Al-8V-6Cr-4Mo-4Zr (SS)
Model type	Linear Elastic Isotropic
Thermal conductivity Temperature	6.2 W/(m.K) 300*C
Specific heat Mass density	515 J/(kg.K) 4820 kg/m^3
Solution type	Steady State

Table.2 Material Properties

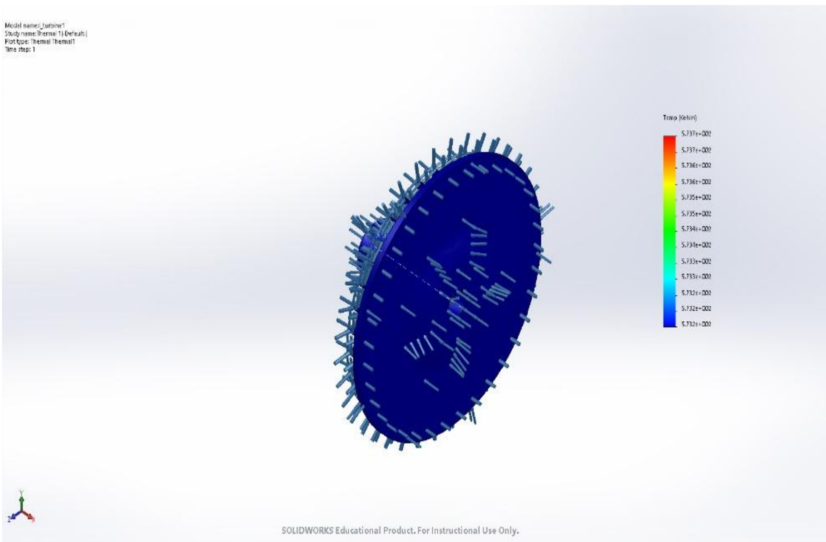

Fig.6. Exhaust Turbine Under Thermal Stress

6. Static Load Analysis

In this the turbine wheel material is changed to AISI type stainless steel. The stainless steel has the high tensile strength and compression ratio. When the heavy load is applied on the material only minimum deformation takes place. Here, the load analysis is made on the intake turbine wheel because, the intake side which allow the compressed air to pass in. So, the static load analysis is carried out to predict the strength of the AISI steel material and this is shown in figure 7-10.

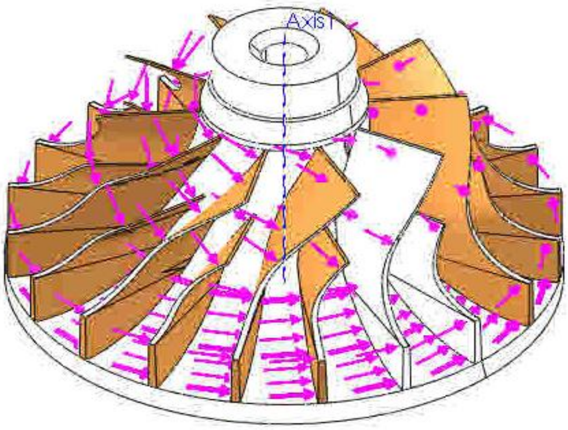

Fig.7 Intake Turbine Under High Flow and Pressure

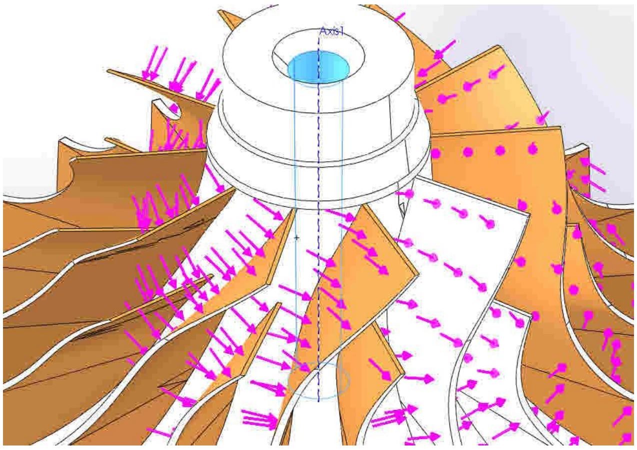

Fig.8 Detailed View of Intake Turbine Under High Flow and Pressure.

Table.3 Material Properties of the Intake Turbine

Treated As	Volumetric Properties
Solid Body	Mass:70.8678 kg Volume:0.00882867 m^3 Density:8027 kg/m^3 Weight:694.504 N

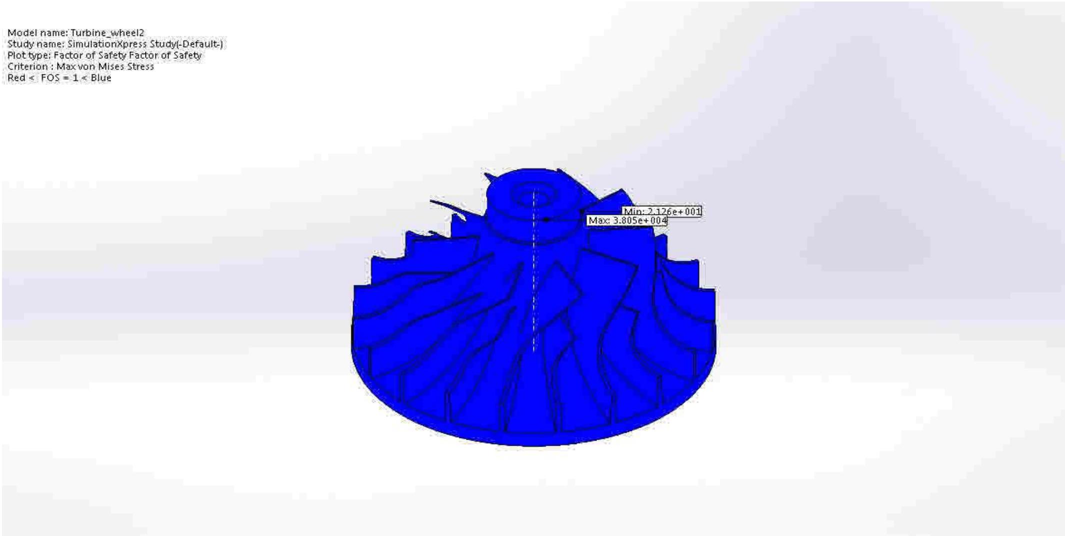

Fig. 9. Factor of Safety for Intake Turbine (Allowable limit)

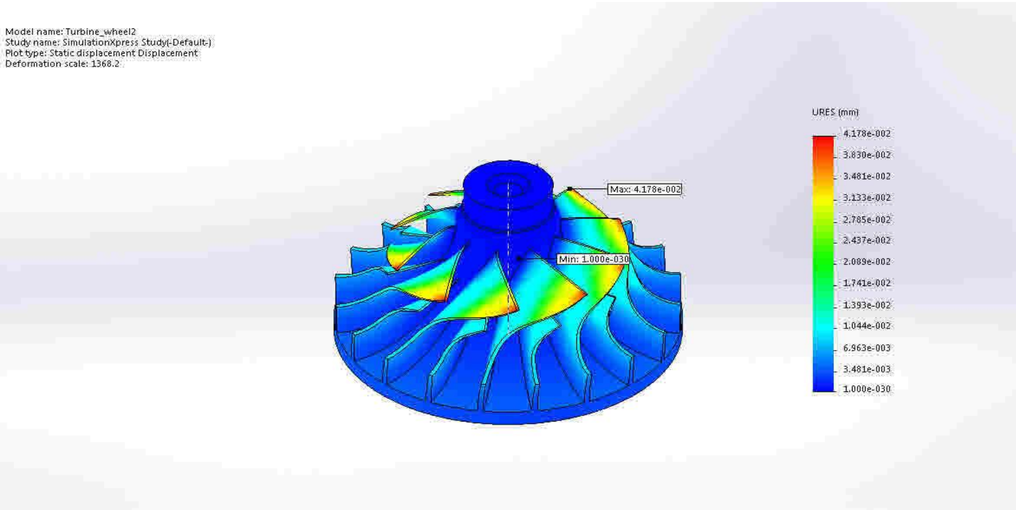

Fig.10. Stress on Intake Turbine Wheel

8. Comparative Test Results

The system thus reduces the response time which causes the lag to occur which reduces the usable narrow power band of diesel engine. This system provides a linear power band transition and stronger midrange torque, thus reducing the fuel consumption by 10-12% yielding better efficiency, a power gain of 15% and torque is boosted up to 35% at 2700 RPM with the same engine capacity.

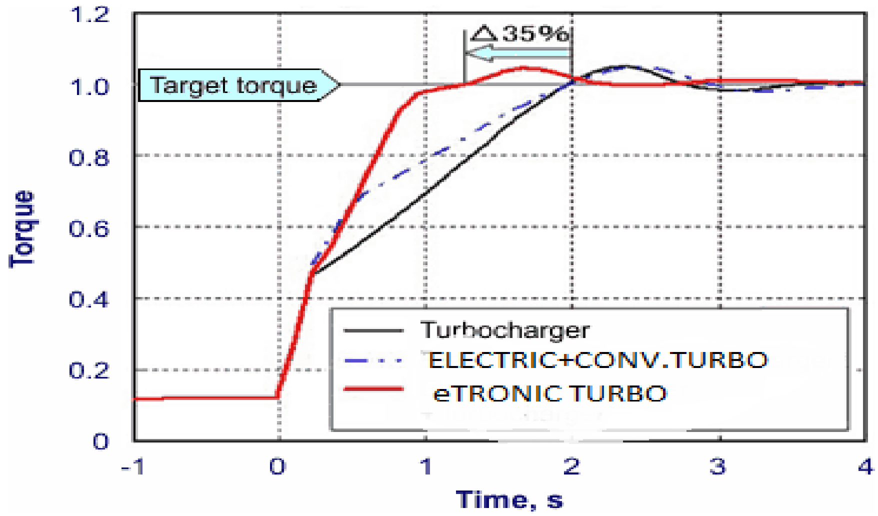

Fig.11. Turbo Spool Up Response Time

This power gain comes at 1.4seconds after throttle actuation vs the conventional turbo offering peak power at good 1.8 seconds late. Thus, conventional turbo's peak torque at 3.2 seconds and E-Tronic turbo at 1.4 seconds. So, boosting the engine power and torque much quicker than conventional turbo and providing ample power and crisp throttle transitions without compromise in reliability on the longer run. The comparative results of three different methods turbo spool up response time is shown in figure 11.

9. Conclusion

- The stated system reduces 10-12% fuel consumption, provides 15% move power on the same engine and a 35% increase in torque. And the main advantage is that it offers a tractable power and torque curve with a linear power delivery.
- This method helps in downsizing of engines which a more powerful thus making a regular consumer vehicle more efficient yet powerful enough for a performance run.
- This method will be a step up in the diesel vehicles providing better performance for the given engine size, eliminating turbo lag. This system provides higher output for the same fuel consumption as a conventional turbo but providing the throttle response of a naturally aspirated engine and at the same fuel consumption of a conventional turbo. Downsizing the engine makes a lighter diesel vehicle as of gasoline vehicles.

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