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Redesigning of the diesel engine turbocharger compressor wheel to improve the low-cycle fatigue life

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ABSTRACT
The compressor wheel of a turbocharger is one of the highly stressed components in automotive engines. The compressor wheel undergoes variations in rotational speed, depending on vehicle operating conditions. These variations cause cyclic mechanical load in the wheel which results in fatigue stress. The continuous operation with fatigue stress results in fatigue fracture and failure. The fatigue is classified as low-cycle fatigue and high-ycle fatigue based on the number of load cycles to failure and type of fracture growth. The present work is focused on the analysis of the compressor wheel that includes measurement of load–time histories in terms of turbocharger speed for different vehicle duty cycles, finite element analysis simulation of stress distribution in the compressor wheel for given load conditions, prediction of fatigue life of the compressor wheel using cumulative damage accumulation theory and the various possibilities for improving the compressor wheel fatigue life.

KEYWORDS
Low-cycle fatigue; high-cycle fatigue; finite element analysis

1. Introduction

The maximum power output that can be delivered by a diesel engine is limited by the amount of fuel that can be burned efficiently inside the combustion chamber. This is limited by the amount of air entrained into the combustion chamber in each cycle. If the air is compressed to high density than atmosphere more amount of air can be introduced into the cylinder and more amount of fuel can be burnt (Baines 2005). This enables the increased power output from an engine without modifying any fixed dimensions of the engine. This is done by a super charger or a turbocharger. Since the super charger absorbs the effective power from the engine with respect to the speed, it is considered as less efficient than the turbocharger and not used in regular diesel engine applications. Turbocharger is a mechanical device which provides high-density airflow to the engine (Christmann et al. 2010).

The turbocharger converts the energy contained in the exhaust gas of the internal combustion engine into positive pressure within the intake manifold, which forces more air into the engine. It uses the engine's exhaust gases to power a turbine, which drives a compressor, and pushes more air into the engine (Greuter and Zima 2012). This allows the engine to produce more power without any increase in size. A turbocharger consists of three major components, the turbine, the compressor and the housing to support turbine, and compressor wheels (Hertzberg 1996). Figure 1 shows the construction of the compressor wheel of the turbocharger.

2. Experimental set-up

In the fatigue life analysis, the time-dependent speed profile of the turbocharger speed needs to be collected for different vehicle running conditions in different regions. For the turbocharger speed measurement, the the experimental set-up as shown in Figure 2 is used.

2.1. Turbocharger selection for analysis

For fatigue life analysis, the following type of of turbocharger is selected which fails frequently in field. The selected turbocharger compressor wheel has premature failure in field applications particularly in city driving conditions (Japikse 2010). Failure of the compressor wheel occurs in the vehicle endurance period in between 100,000 km to 1, and 80,000 km.The engine and vehicle details of turbocharger application are listed

- Compressor wheel: 63 mm (Exducer) × 43 mm (Inducer).
- Vehicle: mid-range city bus application.
- Capacity: 35 seats.
- Engine cylinders: 4 numbers.
- Engine Power: 88 kW @ 2400 rpm.
- Torque: 425 N m @ 1400–2000 rpm.

2.2. Turbocharger speed measurement

The duty cycle or load profile of the vehicle is recorded in terms of turbocharger speed.

For the measurement of rotor speed, a speed sensor is placed into the compressor housing of the turbocharger. It does this by detecting contactless and directly the individual vanes of the aluminium compressor wheel the sensors are made of a simple coil with a ferrite core. If a compressor wheel's vanes are brought in front of the coils, the inductance changes, this change

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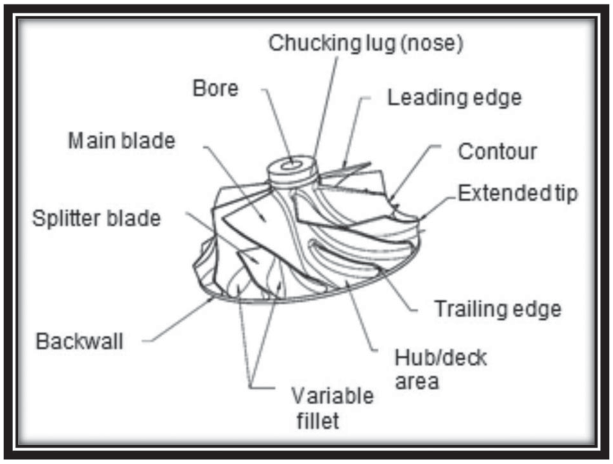

Figure 1. Typical elements of the compressor wheel.

of inductance is measured by a time-to-digital converter, and the measured data are processed by a digital signal processor which finally emits a signal proportional to the rotational speed. The system is capable of speed measurement up to 400,000 rpm. The minimum speed is 200 rpm as shown in Figure 3.

2.3. Data logger

The input from the speed sensor is fed into a data logger which will record the speed of the turbocharger with respect to time. The recording is made with the frequency of 10 Hz, i.e. 10 reading per second. The signal condition box provides an analogue signal to the data logger. The data logger observes the analogue signal voltage and converts into turbo rotational rpm. The value is logged against time and provides output into the text file for further analysis through a computer.

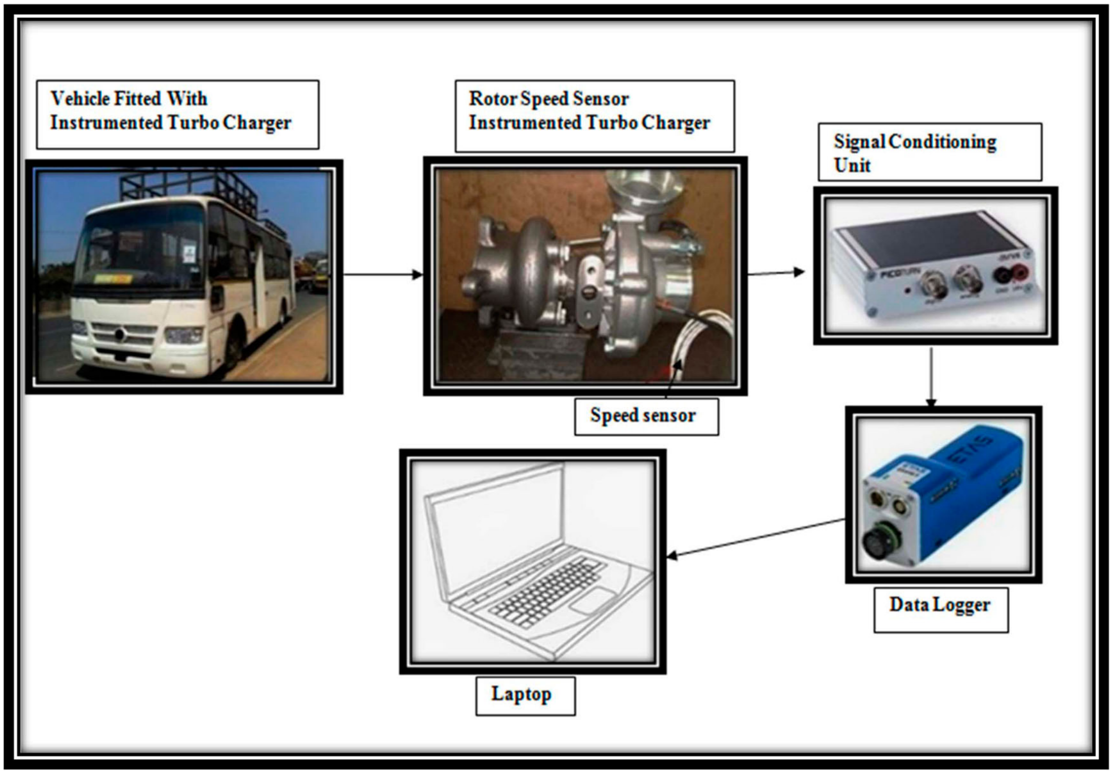

Figure 2. Experimental set-up layout.

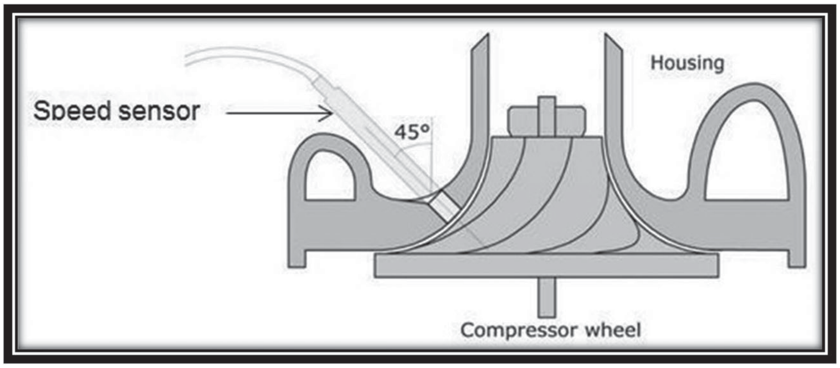

Figure 3. Speed sensor position in the compressor.

Table 1. Duty cycle measurement regions.

Sl. no.	Cycle	Distance (km)	Time (h)
1	City cycle 1	60	3.5
2	City cycle 2	70	4.5
3	Highway cycle	245	5.5

2.4. Measurement regions

The measurement of the vehicle duty cycle is carried out in three different routes which include two city cycles and one highway cycle (Ohri and Shoghi 2012). The city cycle data were measured during high traffic hours to induce more fluctuations in vehicle and engine rpm. The measurement was carried out in two different city routes to produce two different time-dependent load patterns. Measurements were also carried out in the highway also to analyse the load pattern in highway drive. Table 1 provides the details of test routes. The total vehicle run distances are limited based on the driving route. The city cycle route is selected based on regular running of a passenger carrying bus which comes across regular stops and goes on for boarding and alighting of passenger and stops at frequent traffic signals. The highway cycle is selected based on the route which covers two major cities which have wider roads and less traffic conditions. The duty measurement regions, distance travelled and time taken for a particular drive cycle are shown in Table 1.

2.5. Measurement data

The important parameter for fatigue life calculation is turbo rotor speed with respect to time.

The variation of turbocharger rotor speed with respect to time is measured for various drive cycles. Figure 4 shows turbo rotor speed vs. time for city vehicle duty city cycle 1. Figure 5 shows turbo rotor speed vs. time for city vehicle duty city

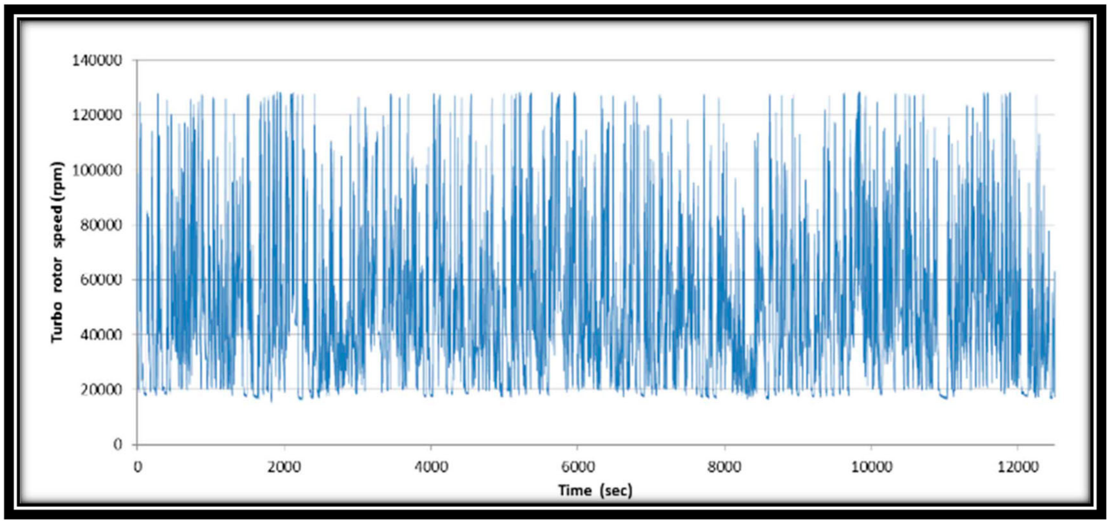

Figure 4. Turbo rotor speed vs. time for city vehicle duty cycle 1.

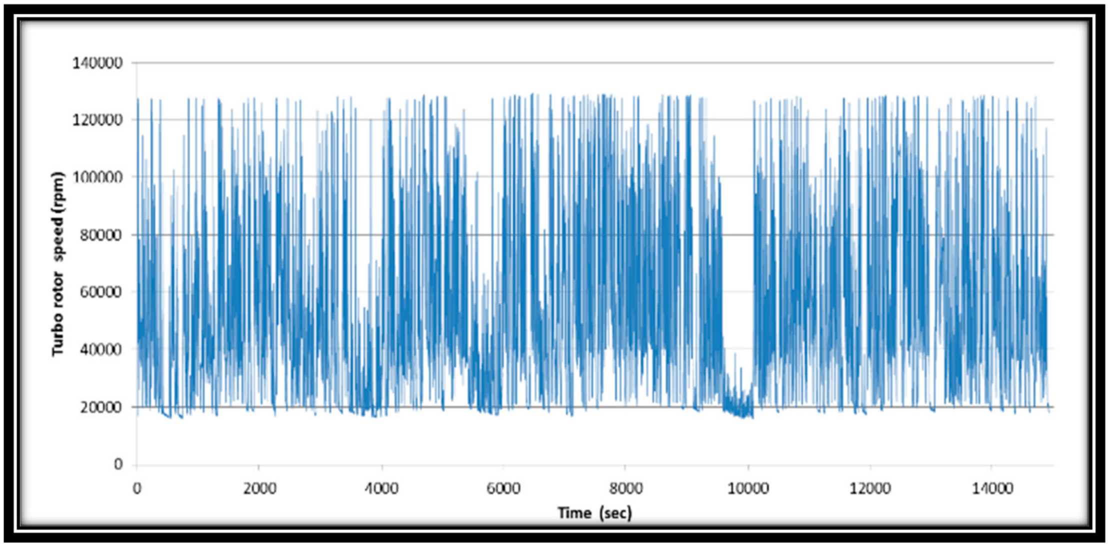

Figure 5. Turbo rotor speed vs. time for city vehicle duty cycle 2.

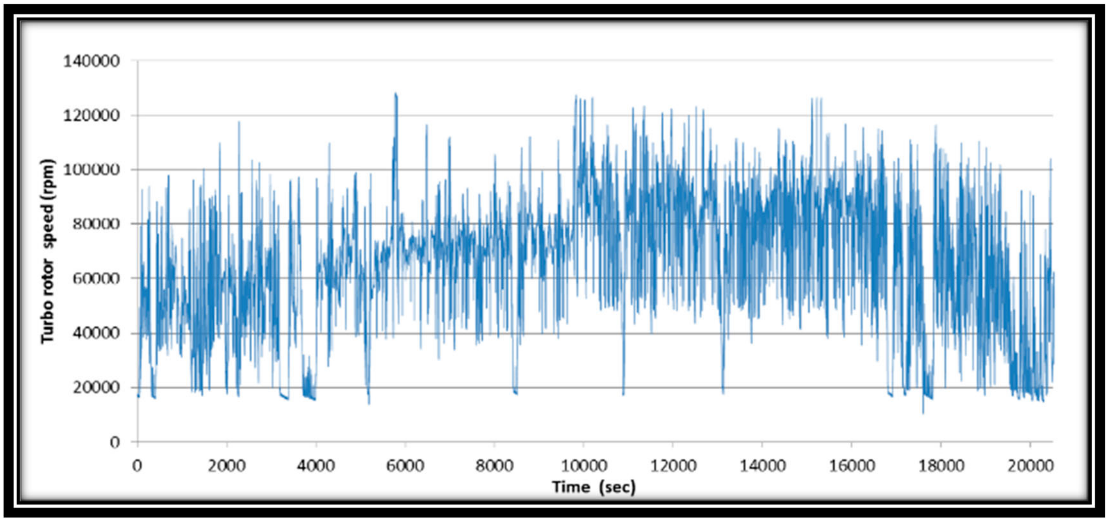

Figure 6. Turbo rotor speed vs. time for highway vehicle duty cycle.

cycle 2. Figure 6 shows turbo rotor speed vs. time for city vehicle duty highway cycle. The variation in the turbocharger speed with respect to time is responsible for the fatigue failure.

2.6. *Measurement data analysis*

From the graphs, it is evident that the city cycle 1 data are having more fluctuations of turbocharger speed with respect to time. This is reflected in the city duty cycle data 2 also. This is mainly due to traffic conditions, frequent stop and travelling conditions and driving environment in the city routes. However, in the highway cycle the fluctuations are less compared to city driving conditions (Zheng and Zeng-quan 2013). This is understandable that less traffic congestions and wider roads make the vehicle operation in the cruise speed mode. So, the vehicle speed and engine speed fluctuations are very less thereby less fluctuation in turbo speed. This creates less cyclic load to the compressor wheel and fewer possibilities to fatigue fracture and failure.

3. Existing compressor wheel

The compressor wheel is basically designed in pro engineer under the engineering guidelines. The current compressor wheel has 63 mm (Exducer) × 45 mm (Inducer) without the super back design. The existing compressor model is shown in Figure 7. Inducer and Exducer ratio is called as the compressor wheel trim, the compressor performance is modified by varying the trim design and with this we can achieve various pressure ratio and volume flow rate of air to the engine.

The existing design compressor wheel is selected for one of the engine application by the turbocharger matching procedure. In the process of the validation period most of the compressor wheel failed during the vehicle testing.

3.1. *Fatigue life of the existing compressor wheel*

By using the MATLAB program, fatigue life of the compressor wheel is calculated for vehicle running in city cycle 1, city cycle 2 and highway cycle. The values are tabulated in Table 2.

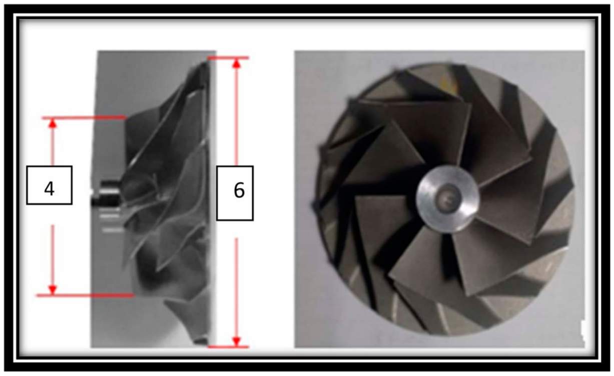

Figure 7. Compressor wheel without modification.

Table 2. Fatigue life of compressor wheel without modification.

Sl. no	Duty cycle	Wheel material	Compressor wheel life (km)
1	City cycle 1	Cast aluminium	181,342
2	City cycle 2	Cast aluminium	172,520
3	Highway cycle	Cast aluminium	438,580

From Table 2 it is obvious that the life of the compressor wheel is below the expected life of 200,000 km. This is the reason behind the failure of the compressor wheel in the earlier

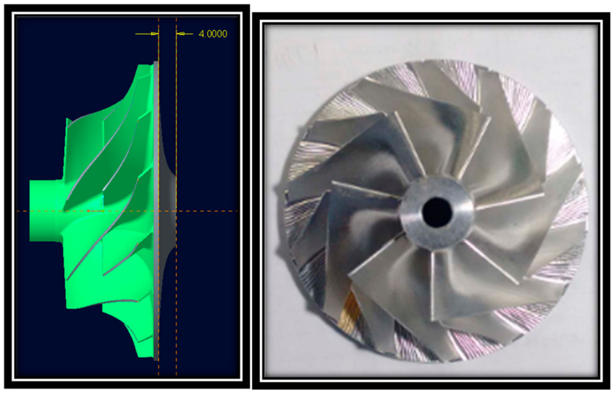

Figure 8. CAD model and the fabricated new compressor wheel.

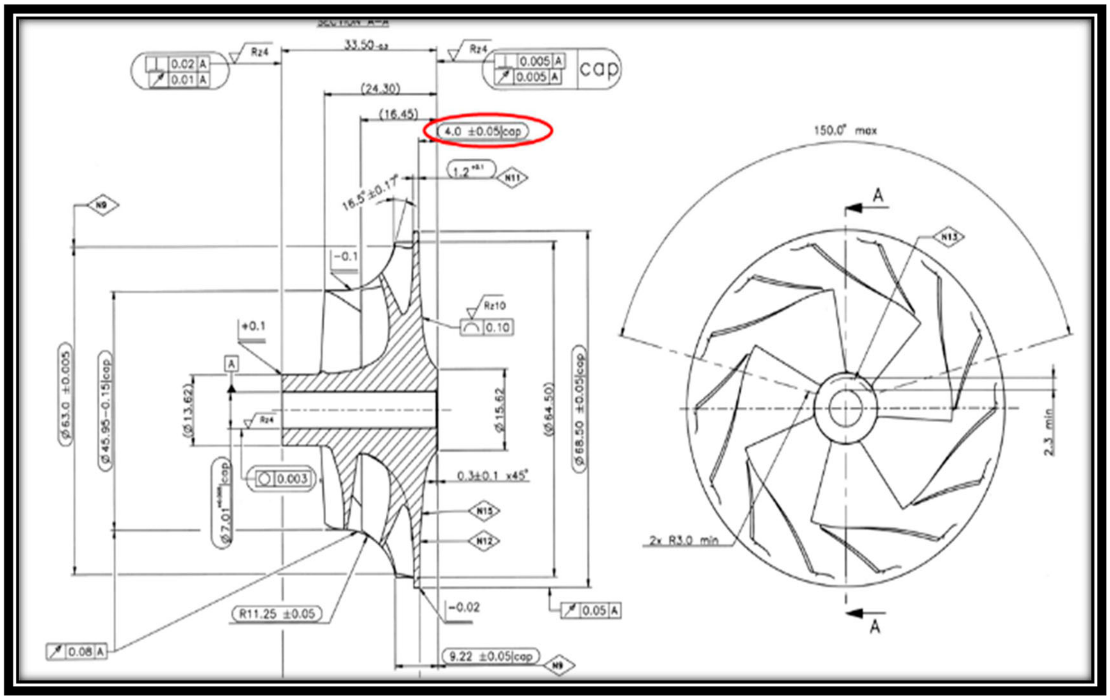

Figure 9. CAD diagram of the modified compressor wheel.

stage itself in field applications. Though the highway cycle has enough limit of fatigue life, the city cycle has fewer margins. Therefore, the vehicle running under the traffic city condition is highly prone to the failure even though speed of the engine or turbocharger is well below the yield stress points. So, necessary improvement action is needed to be implemented to control the failures.

4. Design of new compressor

The factors controlling the fatigue life of the compressor wheel are material property, load cycle and manufacturing process as shown in Figure 8.

The manufacturing process has less influence on the fatigue life compared with other two factors. The load cycle factor cannot be modified as it depends on the vehicle operation and the driving environment. By changing the material properties, the fatigue life can be improved. The new compressor wheel is designed by adding material to the back of compressor wheel. The new modified compressor wheel is shown in Figure 9.

4.1. Fatigue life of the new compressor wheel

The new modified compressor wheels are tested for measurement of the fatigue life. For the modified compressor wheel, the fatigue life calculation is carried for the three-duty cycle as given in Table 1. The measured fatigue life is shown in Table 3. As expected the reduced stress in the compressor wheel improves the fatigue life for the given different duty cycles. The reduction stress is around 100 MPa, the improvement in the fatigue is life is around double the times.

So, it is evident that the small change in the stress of the compressor wheel leads to a significant change in the fatigue life of the compressor wheel. As per the new improved wheel model, the component is manufactured by small modification in the machining of the basic compressor wheel.

Table 3. Fatigue life of modified compressor wheel.

Sl. no.	Duty cycle	Material	Compressor wheel life (km)
1	City cycle 1	Cast aluminium	405,900
2	City cycle 2	Cast aluminium	386,800
3	Highway cycle	Cast aluminium	837,600

5. Conclusion

To improve the fatigue life, design modification is carried out to reduce stress in the compressor wheel bore area without affecting the pressure and airflow characteristics. The fatigue life of the new compressor wheel shows an increase in fatigue life about two times compared to the basic compressor wheel. This is well within the required reliability requirement period. The reliability of the turbocharger is increased with the new compressor wheel even in stringent driving and traffic conditions without affecting performance requirements.

Disclosure statement

No potential conflict of interest was reported by the authors.

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