Performance Analysis of Variable Compression Ratio (VCR) of Diesel Engine by Thermal and Fatigue Analysis on Crankshaft

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Abstract - Internal combustion (IC) diesel engines are established as the main power source for the automobiles and marine vessels due to its superior efficiency over the other engines. The efficiency and life of IC diesel engines are one of the important criteria. An extensive work has been carried out to increase the efficiency of the engine, but only few works has been done in the area of service life of diesel engine. There are various methods to increase the life of engine, like Variable Compression Ratio (V.C.R), different materials of construction, fuel type and fuel quality. Hence, in the present work, an experimental analysis is carried out on Variable Compression Ratio (V.C.R.) diesel engine to measure the engine performance and to determine its optimal compression ratio at a constant speed of 1500rpm. The operational parameters like efficiencies and power adopted are determined at different compression ratios of 16.5, 17.0, 17.5, 18.0 and 18.5 at different loads. Kinematic and Dynamic stress analysis is performed on Piston, Connecting rod and Crankshaft to identify the thermal and structural stresses induced in the VCR engine followed by fatigue analysis to determine its life and factor of safety.

The experiment is validated through the simulation. The simulation consists of thermal, structural and the thermo-mechanical analysis. The thermal analysis provides the effect of temperature on the crankshaft, while the structural analysis determines the fatigue life of the crankshaft. Kinematic and dynamic analysis helps in providing the forces on the crankshaft, which are responsible to generate the stress. The forces can be found out by the use of free body diagrams. These forces will continue to change in its magnitude and direction. Hence crankshaft is subjected to the reversal of stresses. It will reduce the life of the engine.

The design of the V.C.R. was carried out at peak pressures and maximum temperatures are obtained through the experiment for different C.R. at different crank angles. For design, optimization and analysis, Solid works, and ANSYS software were used. Different materials were considered for the different components for the optimization and increase of life of the engine like AISI E4340 Forged steel, Aluminum alloy 7075-T6 etc. Total deformation and factor of safety at different crank angles for the two materials are analyzed. The fatigue analysis is carried out to know the factor of safety of the two materials.

The stress analysis was carried at critical angles of 365^0, 490^0, 540^0 and 590^0 with different loading conditions at a constant compression ratio of 16.5. The results obtained from the structural analysis shows that the stresses induced at the crank pin and bearing supports in the aluminum alloy (7075-T6) are lesser in comparison with AISI E4330 forged steel for different crank angles. For the above crank angles, structural analysis was done using ANSYS and the results show that the stresses and total deformation are more at crank pin than at bearing supports. The analytical and ANSYS results were compared for both the materials. It was found that the variation in the stress value for the Aluminium alloy is less than 1% and for the forged steel is less than 5%. The simulation performed is in very good agreement with the analytical results.

The fatigue analysis is conducted for 106 cycles at all critical angles for two materials of the crankshaft. The results shows that the minimum factor of safety these materials is found to be 4.24 for Aluminium alloy and 3.80 for Forged steel. The maximum factor of safety is found to be15.10 for Aluminium alloy and forged steel. The working life of the Al-alloy (17777 hrs.) is more than the forged steel (10233 hrs.), which can lead to lowering the overall cost of the engine. The comparative result shows that the aluminum alloy (7075-T6) exhibits better life than forged steel at 16.5 optimum compression ratio. Hence Al-alloy is the best choice for the material construction for the crankshaft.

Key Words: Variable Compression Ratio (V.C.R.), Solid works, and ANSYS software, Aluminium alloy, fatigue analysis.

1. INTRODUCTION

Crankshaft is a large component with a complex geometry in the engine. The crankshaft, connecting rod, and piston constitutes a four-bar slider-crank mechanism, which converts the reciprocating displacement of the piston to a rotary motion with a four-link mechanism. Since the rotation output is more practical and applicable for input to other devices, the concept design of an engine is that the output would be a rotation. In addition, the linear displacement of an engine is not smooth, as the displacement is caused by the combustion of fuel in the combustion chamber. Therefore, the displacement has sudden shocks and using this input for another device may cause damage to it. The concept of using crankshaft is to change these sudden displacements to a smooth rotatory output, which is the main input to many other devices such as generators, pumps, and compressors.

During the service life of a crankshaft, it is subjected to several cyclic bending and torsion loads induced by the pressure generated from the combustion process and the inertia of the components in relative motion. The magnitude of the force depends on many factors which consist of crank radius, connecting rod dimensions, the weight of the connecting rod, piston, piston rings, and pin. Combustion and inertia forces acting on the crankshaft cause two types of loading on the crankshaft structure: torsional load and bending load.

Mechanical failures of the crankshafts are caused by fatigue phenomena. For improvement of the fatigue resistance, they are mainly ascribed to both the residual stress field and the surface hardening. Surface treatments of mechanical components are usually applied for increasing the hardness and wear resistance without the modification of the mechanical characteristics of the bulk material, but recently it is demonstrated that they also increase the fatigue limit because of compressive residual stress induced at the surface and subsurface layers.

In the present work, an experiment is carried out on Variable Compression Ratio (V.C.R.) engine to measure the engine performance of an internal combustion (IC) Diesel engine and to determine its optimal compression ratio. Kinematic and Dynamic stress analysis is performed on Piston, Connecting rod and Crankshaft with various materials to identify the thermal and structural stresses induced in the IC engine followed by fatigue analysis to determine its life and factor of safety.

2. LITERATURE REVIEW

During the last decades, researchers and manufacturers invented several engine concepts that with variable compression ratio. Shaik et al. (2007), Nilsson (2007), Gupta (2012), Radonjic (2010), and Wos et al. (2012), proposed different classifications of the VCR field. Thus, in order to understand their classification and to check their completeness, it was decided to run a patent survey. More than 1000 patents from 1974 to 2014 were analyzed the trend for the VCR research. Since 2000, the number of filed patents has been increasing significantly, suggesting a growing interest from automotive sector. From 2013 to the present date, the numbers are still incomplete since some patent applications are under confidential status. Excluding from the survey all patents related to control, hydraulics and improvements of previous designs, a total of 127 different VCR engine designs (patent families) remained.

Crankshaft is an important component of internal combustion engine with complex geometry. Crankshaft experiences a large number of load cycle during its service life (Taylor and Ciepalowicz 1997). The sudden failure of crankshaft made researchers and academia to investigate the problem. Because of complicated loading and geometry problem, general method to predict fatigue life is still not evolved. Since crankshaft is subjected to several forces which vary in magnitude and direction (multiaxial) and connecting rod transmitting gas pressure from cylinder to crankpin, stresses acting in the crankshaft vary with respect to time (Montazersadgh and Fatemi, 2007) Most of the time crankshaft fails due to fatigue at fillet areas due to bending load. Fillet rolling can increase fatigue life [Park et.al.2001].

The work on the service life of IC engine with respect to the failure of different components was not touched upon in great details. The IC engine has different components as Cylinder head, Cylinder, Piston, Connecting Rod, Crankshaft etc. To increase the overall service life and performance of the engine, each component has to be analysed in detail. A Comprehensive examination of existing literature related some of the research gaps in the work reported on crank shaft of different compression ratios at different crank angles. The observations lead to formulation of the present research investigation as follows.

1. Most of the crankshafts that failed in fatigue were due to bending fatigue. The work on the service life of IC engine with respect to the failure of different components was not touched upon in great details.
2. From literature survey it is understood by this author that there is a lot of scope for studying the stress analysis with different compression ratios and at different crank angles.
3. Taking into these considerations, the author has embarked on studying the stress analysis of crank shaft with three compression ratios and at four crank angles.

3. EXPERIMENTAL ANALYSIS OF VCR ENGINE

Experimental tests were conducted on a Variable Compression Ratio (VCR) diesel engine at Engines Laboratory in the Department of Mechanical Engineering, Anil Neerukonda Institute of Technology and Science (ANITS) Autonomous, Visakhapatnam India.

VCR engine test rig can be used to determine the effect of compression Ratio (CR) on the performance and emissions of the engine. It can also be used to study the health i.e. life of the engine. However, the objective is to determine the optimum compression ratio for which the best performance with good life is possible. The test rig has one very important feature that the compression ratio can be varied in the steps of 0.5. Hence the optimum compression ratio can also be found out between the two CR integers like 16.0, 16.5, 17.0, 17.5, 18.0, 18.5 etc.

3.1. Experimental process

Experimentations were carried out on a single cylinder water cooled fourstroke variable compression ratio (VCR) diesel engine. Figure 3.1 represents the schematic diagram with different components present in it. The engine is tested at different compression ratios varying from 16 to 18.5 with an increment of 0.5 by maintaining fixed rpm of 1500. Eddy current dynamometer is used for loading purpose, parameters like cylinder peak pressures, brake thermal efficiency and brake specific fuel consumption were measured.

The performance results of 16.5, 17.5 and 18.5 compression ratio were chosen for the kinematic and dynamic analysis of piston and crank mechanism. The detail description of equipment's and their specifications were discussed in the following sections.

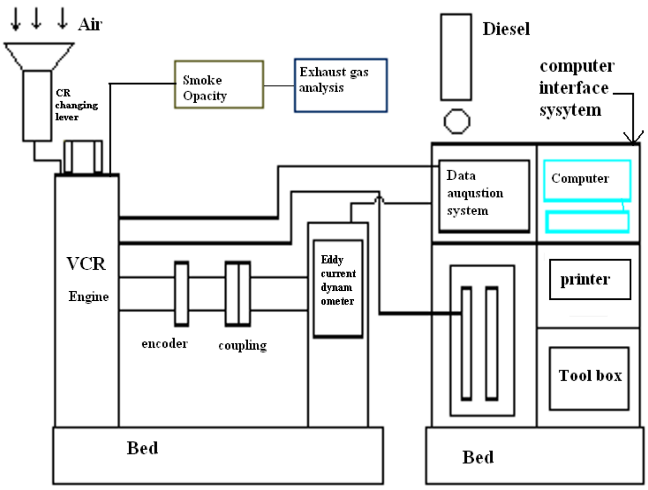


Figure 3.1 Schematic representation of the experimental test rig

Fig.ure 3.2. Experimental test rig

Table 3.1. Technical specifications of the VCR Engine

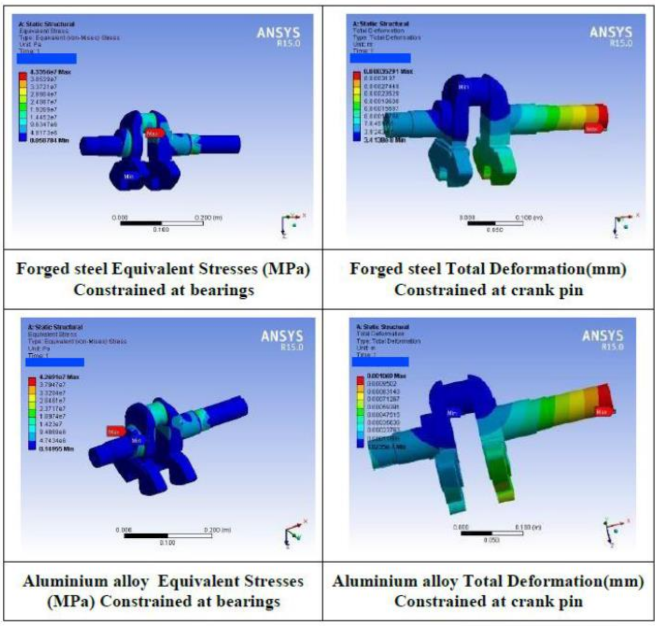
Sl. No.	Features	Specifications
1	Make	Kirloskar oil Engine
2	Type	Four strokes, Water Cooled Diesel
3	No. of cylinders	One
4	Combustion Principle	Compression ignition
5	Max speed	1500 rpm
6	Crank Radius	55mm
7	Connecting Rod length	300mm
8	Cylinder diameter	80mm
9	Stroke length	110mm
10	Compression ratio	Variable
11	Loading	Eddy current dynamometer
12	Maximum Load	23.86 N
13	Constant Speed	1500 rpm
14	Fuel rate (at 16.5C.R.)	1.46-2.06 kg/hr
15	Air rate	16.20-17.08 m^3/hr
16	Water Flow	40.80cc/sec

4. RESULT ANALYSIS

4.1. Thermal Analysis results for crankshaft at 365degrees crank angle

Steady state thermal analysis is considered before the structural analysis, in this analysis, boundary conditions (heat transfer coefficient, heat flux) are applied on the piston and we observe the maximum and minimum temperatures, and the total heat flux of piston. A steady-state thermal analysis may be either linear with constant material properties, or nonlinear with material properties that depend on temperature. The thermal properties of the most material do vary with temperature, so the analysis usually is nonlinear. 7075-T6 materials at critical angles of 365, 490, 540 and 590 by considering the (Rax, Ray) & (Rox, Roy) forces applied at crank pin and bearings supports. The structural results of Equivalent stresses and deformations obtained from ANSYS are shown in Table 4.1.

At different critical angles between 0 to 720 degrees with variation of force components over one complete engine cycle at the crankshaft speed 1500 rpm.



Forged steel Equivalent Stresses (MPa) Constrained at bearings | Forged steel Total Deformation(mm) Constrained at crank pin

Aluminium alloy Equivalent Stresses (MPa) Constrained at bearings | Aluminium alloy Total Deformation(mm) Constrained at crank pin

Figure 4.1 Crank angle 365 degrees Maximum values of Equivalent von-Mises stressesand Total Deformation

Table 4.1 Maximum values of Equivalent von-Mises stresses and Total Deformation

Sl. No.	Materials at Crank angle	Equivalent Stresses (MPa)		Total Deformation(mm)	
		Constrained at bearings	Constrained at crank pin	Constrained at bearings	Constrained at crank pin
1	Forged steel at 365	43.351	170.612	0.0160	0.351
2	Aluminium alloy at 365	42.692	166.733	0.0491	1.068
3	Forged steel at 490	38.021	52.303	0.007	0.084
4	Aluminium alloy at 490	37.152	51.532	0.021	0.256
5	Forged steel at 540	3.121	5.991	0.001	0.012
6	Aluminium alloy at 540	3.042	5.861	0.003	0.038
7	Forged steel at 590	34.532	52.712	0.006	0.086
8	Aluminium alloy at 590	34.621	51.832	0.021	0.262

From the table 4.1, it can be observed that stresses and total deformation are more at crank pin than at bearing supports. Minimum stresses are obtained at crank angle 540^0 and maximum stresses are obtained at crank angle 365^0, as shown in figure 4.1. The order of stresses is same for both the materials at all critical angles of rotation but the deformation is almost three times higher in Aluminium alloy when compared to forged steel.

Validation of Results (Al-Alloy) Stress validation at Crank Pin LocationSection modulus of Crank Pin = 16333 mm³
Distance of force for the bending moment = 18.5 mm

4.2. Thermo-Structural Analysis of Crankshaft

Thermo-Structural Analysis for different crank angles of the crankshaft is shown in the figure below. The body temperature is been imported from the results of the static thermal analysis as shown in the figure 4.2.

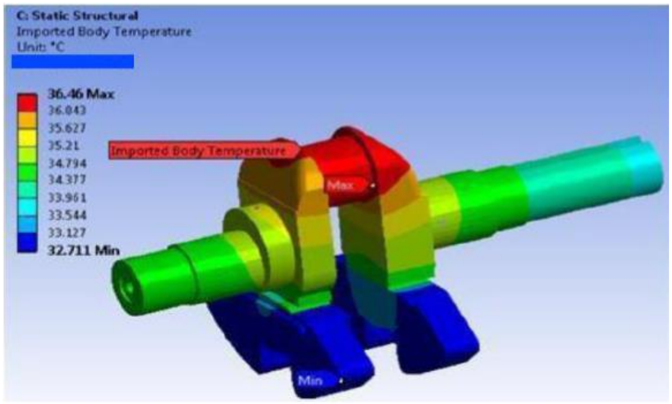


Figure 4.2 Imported Body Temperature from thermal analysis

After importing the thermal load, the static structural analysis is carried out forwhich the equivalent stress and total deformation are shown below in figure 4.3 a & b.

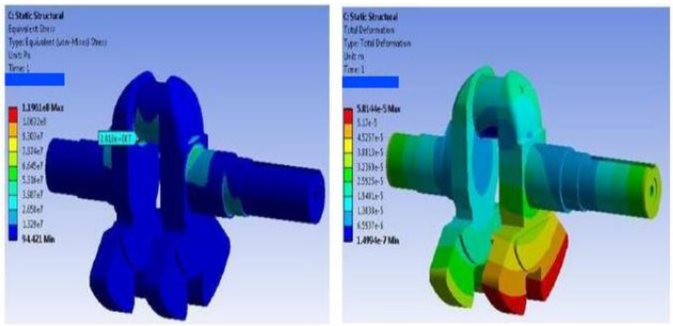


Figure 4.3 (a) and (b) Equivalent Stress and Total Deformation on the crankshaft

Thermo-Structural (365) degrees crank angle.
Von-Mises Stress at Crank Pin Location (Structural) = 28.26 Mpa
Von-Mises Stress at Crank Pin Location (Thermo-Structural) =30.37 Mpa
Increase in Stresses = 2.11Mpa

Hence the effect of temperature can be neglected for all other cases.

4.3. Fatigue Analysis on Al-Alloy and Forged Steel crankshaft

During the service life of a crankshaft, they are subjected to several cyclic bending and torsion loads induced by the pressure generated from the combustion process and the inertia of the components in relative motion. The magnitude of the force depends on many factors which consist of crank radius, connecting rod dimensions, the weight of the connecting rod, piston, piston rings, and pin Combustion and inertia forces acting on the crankshaft causes two types of loadings on the crankshaft structure, torsional load, and bending load. Mechanical failures of the crankshafts are caused by fatigue phenomena. For improvement of the fatigue resistance, they are mainly ascribed to both the residual stress field and the surface hardening. Design developments have always been an important issue in the crankshaft production industry. In order to manufacture a less expensive component with the minimum weight possible by proper fatigue strength and other functional requirements, these improvements result in lighter and smaller engines with better fuel efficiency and higher power output.

Fatigue analysis is carried out for Al-Alloy and Forged Steel with the rotational velocity of crankshaft 158 rad/s shown in figure 4.4.

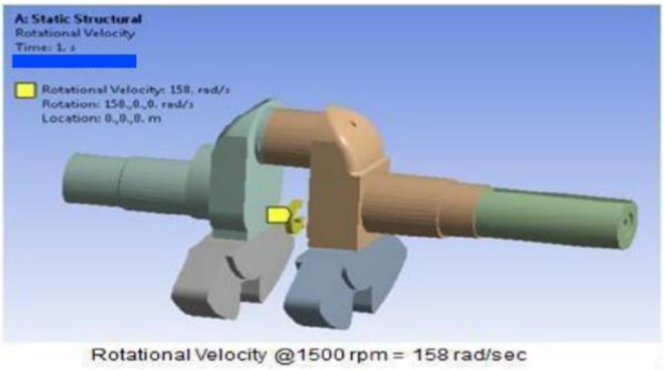


Figure. 4.4 Crank Shaft Boundary Conditions for Fatigue analysis.

Table 4.2 Factor of Safety values at different crank angles

Sl. No	Materials	Crank angle 365^0	Crankangle 490^0	Crank angle 540^0	Crankangle 590^0	Life at Crank angle 365 (hrs.)
1	Forged steel	3.807	12.416	15.1	12.332	10233
2	Aluminium alloy	5.153	4.265	15.1	4.243	17777

Hence in the present work, fatigue analysis is carried out at all critical angles for both the materials and the results of Factor of safety are shown in table 4.2. In this analysis consists of determining the factor of safety for a minimum assumed number of cycles of 10^6. As the maximum factor of safety is to be considered, a factor of safety of 15.1 has to be taken for both the materials are shown Appendix D and E .The aluminum alloy is a more suitable material with respect to the forged steel.The working life of the Al-alloy (17777 hrs.) is more than the forged steel (10233 hrs.).The temperature of the combustion chamber is having the less effect on the crankshaft.

The structural, thermal and fatigue analysis results are discussed. The maximum temperature achieved in the cylinder head does not affect the temperature profile of crankshaft. The thermo-structural analysis concludes that both the materials of the crankshaft are suitable.

But the working life of Al-Alloy is more than forged steel. Hence Al-alloy is the best choice for the material construction for the crankshaft.

5. CONCLUSIONS AND FUTURE SCOPE

Following conclusions were derived during the experimental study:

- Maximum pressure and temperatures were found at the different compression ratios during the combustion of the gases inside the IC engine cylinder . It is observed from the experimental data that there is an increase of brake thermal efficiency with CR. The maximum temperature occurs on the piston crown and minimum temperature at piston skirt for all compression ratios.
- Thermal analysis was performed to get the heat transfer from the connected components to the crankshaft. The connected components which can affect the crankshaft are cylinder head, cylinder, piston and connecting rod. The stresses developed from the temperature gradient is not significant due to the heat removal at the different stages.
- The results obtained from the structural analysis shows that the stresses induced at the crank pin and bearing supports in the aluminum alloy(7075-T6) are lesser in comparison with AISI E4340 forged steel for different crank angles.
- For the above crank angles, structural analysis was done using ANSYS and the results show that the stresses and total deformation are more at crank pin than bearing supports. Minimum stresses are obtained at a crank angle of 540^0 and

maximum stresses are obtained at a crank angle of 365^0.

- The order of stresses are same for both the materials at all critical angles of rotation, but the deformation is almost three times higher in Aluminium alloy when compared to the forged steel. Thus, Aluminium alloy(7075-T6) exhibits better results in comparison with AISI E4340 Forged steel.

- The analytical and ANSYS results were compared for both the materials. It was found that the variation in the stress value for the Aluminium alloy is less than 1% and for the forged steel, it is less than 5%. Hence it is verified that simulation performed is in very good agreement with the analytical results.

- The thermo-structural analysis concludes that both the materials of the crankshaft are suitable. But the working life of Al-Alloy is more than forged steel. The working life of the Al-alloy (17777 hrs.)and the forged steel (10233 hrs.), which can lead to lowering the overall cost of the engine.

- The fatigue analysis of two different materials is conducted for 10^6 cycles. This analysis carried out at all critical angles for both the materials and the results shows that the minimum factor of safety is found to be 4.24 for Aluminium alloy and 3.80 for Forged steel. The maximum factor of safety is found to be 15.1 for both the materials.

- The results conclude that Aluminum alloy (7075-T6) exhibits better results in comparison with AISIE4340 forged steel for the crankshaft. Hence Al-alloy is the best choice for the material construction for the Crankshaft.

5.1. FUTURE SCOPE OF THE WORK

There is lot of scope for production of crankshafts as per ASTM standards with new materials and manufacturing them as per the specifications, for operation of IC engines. Further analysis can be performed on the crankshaft in order to optimize the manufacturing cost. Further research can be implemented for different speeds of the engine. Simulation of IC engine with Computational Fluid Dynamic (CFD) analysis on VCR engine with Diesel and alternative fuels to enhance the overall performance and life of the engine can be carried out.

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