Design and analysis of assembly of Piston, Connecting rod and Crankshaft

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Abstract

The present aim of the project is to study the effect of the materials being used for the Piston, Connecting rod and Crankshaft assembly for an engine of a four wheeler vehicle. The material selected for the piston is Cast Iron, Manganese steel for the connecting rod and High Carbon Steel for the crankshaft. The engine speed was desired to be increased. The effect of the materials used for the assembly and its behavior was required to be studied. The parts piston, connecting rod and crankshaft are designed using theoretical calculations. The designed parts are modeled and assembled in 3D modeling software Pro/Engineer. The meshing is done in Hypermesh. The Finite Element Analysis is done in Ansys. The FE Analysis involves structural and analysis of the assembly. The parts of the assembly should be rigid. And, when they are connected together, they should perform as a mechanism. This requires calculation of the forces acting on the components and the dynamic stresses. As the assembly will be working under high temperatures, thermal analysis also has to be done. From the results, it is observed that a change in the piston material will allow the engine to operate at the new high speed.

Keywords: Engine displacement, Piston skirt, Under square, Crank web, HyperMesh, Ansys.

1. Introduction

The assembly of the piston, connecting rod and crankshaft in an engine behaves like a mechanism during the working of the engine. The weight of the Cast Iron piston is preventing the engine to operate at a higher speed. The dimensions of the engine piston, connecting rod and crankshaft are calculated theoretically. Both structural analysis and dynamic analysis are to be done for the assembly. As the piston and the other components of the assembly work under high temperatures, thermal analysis is also done.

The piston, rings, and wrist pin

The piston makes the crankshaft to turn by utilizing the energy supplied to it by the combustion of the fuel. It is cylindrical in shape and reciprocates inside the cylinder. Pistons are provided with grooves near the top and provide an air tight fit. The pistons do not allow the high pressure mixture from the combustion chambers into the crankcase. The piston has four strokes in total, two upside and two down. During the intake stroke, the piston moves down and the cylinder is filled with air fuel mixture. The upward stroke compresses the mixture and as it reaches near the top position, the ignition of the fuel causes the piston to move downwards, the third stroke. During the fourth stroke, the piston moves upward and pushes the burnt gases to the exhaust system. The piston operates under high pressure and high temperature.

The top portion of the piston is called as Crown. It’s bottom is called as skirt. The diameter of the piston crown is less than the skirt. There are grooves at the top for oil ring and compression rings. The oil groove is wider and deep than the compression ring. The oil ring scraps the excess oil and returns back and prevents the oil reaching the combustion chamber. Lands are the spaces between the grooves. In the design of pistons, the weight of the piston is an important factor.

The top surface of the piston called as “Crown” is provided many shapes viz. convex, concave, and flat to control the combustion. Some pistons are provided with a narrow groove above the top ring to reduce the heat reaching the top ring.

The wrist pin connects the connecting rod at the bottom of the piston, wherein the pin connects by passing through the side of the piston.

Piston stroke

The piston stroke displacement is determined by the axis of the crank throws from the axis of the crankshaft.
Increasing the stroke increases the low-speed torque of the engine. This increases the reciprocating vibration and limits the high speed capability of the engine. If the stroke is longer than the cylinder bore diameter is called as "Under square" or long-stroke.

Materials for the Piston

Cast Iron, Aluminum Alloy and Cast Steel etc. are the common materials used for piston. These pistons have greater strength and resistance to wear. In Aluminum Alloy pistons piston slap results due to insufficient piston clearance. A vertical slot is cut to overcome the defect. To increase the life of grooves and to reduce the wear, a ferrous metal rings are inserted in the grooves of high speed engines.

Connecting rod

The connecting rod links the piston and the crankshaft. It has a hole at the upper end (small end) and is connected to the piston by the wrist pin. The lower end, also called as Big end, is attached to the crankshaft. The small end is press fit and can swivel in the piston. The Connecting rods are usually made of alloy steel, Titanium and sometimes with aluminum. They are not rigidly fixed at either end, so that the angle between the connecting rod and the piston can change as the rod moves up and down and rotates around the crankshaft. The big end is connected to the bearing journal on the crank throw. The connecting rod is under a lot of stress with every rotation. High factor of safety is provided as the failure of the connecting rod is very likely under such heavy stresses. Attention has to be paid to eliminate the stress risers in the connecting rod during production. Also, the bolts should be tightened with proper torque.

Wearing of engine is due to the sideward force exerted on the piston which results into wearing of the cylinder into an oval cross section.

For a given engine block, the sum of the length of connecting rod plus the piston stroke is a fixed number. This is determined by the fixed distance between the crankshaft axis and the top of the cylinder block where the cylinder head fastens. Thus, for a given cylinder block longer stroke, giving greater engine displacement and power, requires a shorter connecting rod (or a piston with smaller compression height), resulting in accelerated cylinder wear.

Materials used for Connecting Rod

Steel has good strength, durability and has less cost. But, it has high density which creates excessive stresses on the crankshaft. This requires a heavier crankshaft for carrying the loads. This causes to limit the maximum RPM of the engine. It also reduces the acceleration or declaration rates of engine speed. Light alloy metals such as aluminum and titanium are used to overcome these problems.

Crankshaft

The turning motion to the wheels is provided by the crankshaft, which converts the reciprocating motion of the pistons into a rotary motion. The crankshaft is usually either alloy steel or cast iron. Crankshafts are connected to the pistons by the connecting-rods. The crank shaft has crank throws which are offset from the crank. The big end of the connecting rod is attached to it. The crank shaft is connected to a flywheel to reduce the torsion vibrations.

2. Design calculations

Pressure calculations

Specifications of the engine

<table>
<thead>
<tr>
<th>Table 1 Engine specs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type : air cooled 4-stroke SOHC</td>
</tr>
<tr>
<td>Bore x stroke (mm) = 79.5 x 80.5 mm</td>
</tr>
<tr>
<td>Displacement - 1598 Cm3</td>
</tr>
<tr>
<td>Maximum power = 77 @5250rpm</td>
</tr>
<tr>
<td>Maximum torque = 153 @3800 rpm</td>
</tr>
<tr>
<td>Compression ratio = 9.35/1</td>
</tr>
<tr>
<td>Density of petrol = 0.0000073722 kg/mm3</td>
</tr>
<tr>
<td>Temperature = 60°F</td>
</tr>
</tbody>
</table>

Density of petrol \( C_\text{H}_18 = 737.22 \text{ kg/m}^3 \) at 60°F

\[\text{Density of petrol} = \frac{0.00000073722 \times 159800}{0.1178kg} = 0.1178kg\]

Molecular cut for petrol 114.2285 g/mole

\[\text{PV} = mRT\]

\[P = \frac{(0.1178 \times 8.3143 \times 288.555)}{(0.11422 \times 0.0001598)}\]

\[P = 12287695.65 \text{ J/m}^3 = N/m^2\]

Gas pressure, \( P = 12.287 \text{ N/mm}^2\)

Mean effective pressure, \( P_m = 2 \pi (T_{\infty} / V_a)\]

\[= 153 \times 2 \times 3.14 / 1598 = 1.202\]

Indicated power \( IP = \frac{P_m \times 1 \times A \times n}{60}\]

\[= (2 \times 3.14 \times 5250 \times 153) / (4 \times 60) = 84073.5 \text{ kw}\]

Brake power \( BP = (2 \pi N T) / 60\]

\[= (2 \times 3.14 \times 5250 \times 153) / (4 \times 60) = 84073.5 \text{ kw}\]

Mechanical efficiency, \( \eta_P = BP / IP = 84073.5 / 128018.57 = 0.656 = 65.6\%\)

Piston

Material: Cast Iron

Temperature at the center of piston head

\(T_c = 260^\circ C \text{ to } 290^\circ C\)

Temperature at the edge of piston head

\[\text{Table 1} \]
Te = 185°C to 215°C

Maximum gas pressure \( p = 12.287 \text{mm}^2 \)

Bore or outside diameter of piston = 79.5mm

**Fig. 1** Piston nomenclature

1. **Thickness of piston head**
   
   \[
   Th = \sqrt{(3pD^2 / 16 \times \text{tensile stress})}
   \]
   
   Tensile stress = 50 to 90Mpa
   
   \( Th = 15.57\text{mm} \) (or)
   
   Considering heat transfer
   
   \[
   Th = h / (12.56 \times k (t_c - t_e))
   \]
   
   Heat conductivity force = 174.75w/m°C
   
   \( t_c-t_e = 75°C \)
   
   \[
   H = C \times HCV \times m \text{BP (in KW)}
   \]
   
   C = constant = 0.05
   
   \[
   HCV = 47 \times 10^3 \text{KJ/kg for petrol}
   \]
   
   \[
   m = \text{mass of fuel for brake power per second}
   \]
   
   \[
   BP = \text{brake power}
   \]
   
   \[
   \text{H} = C \times HCV \times (m/BP)
   \]
   
   \[
   C = 0.05 \times 47 \times 10^3 \times 0.11 = 258.5
   \]
   
   \[
   Th = h / (12.56 \times k (t_c - t_e))
   \]
   
   \[
   = 258.5 / (12.56 \times 174.75 \times 75) = 0.00157\text{m}
   \]

   **Thickness of piston head, \( Th = 15.57\text{mm} \)**

2. **Piston rings**
   
   Radial thickness \( t_1 \)
   
   \[
   = D \times (\sqrt{3p_w} / \text{tensile stress})
   \]
   
   \[
   p_w = \text{pressure of the gas on the cylinder wall} = 0.042N/mm^2
   \]
   
   Tensile stress = allowable bending (tensile stress) for cast iron rings = 110Mpa
   
   \[
   t_1 = 2.69\text{mm}
   \]
   
   Axial thickness \( t_2 = D / 10n_r = 79.5 / 10 \times 3 \) \( [n_r = \text{no of rings} = 3] \)
   
   \[
   t_2 = 2.65\text{mm}
   \]
   
   Width of the top land \( b_1 = 1.2t_h = 1.2 \times 15.57 = 18.684\text{mm} \)

   Width of other land (i.e.) distance between ring grooves, \( b_2 = t_2 = 2.6\text{mm} \)

   The gap between the free ends of the ring = 3.5t to 4t = 7.72mm

3. **Piston barrel**
   
   Maximum gas load on the piston
   
   \[
   P = p \times \pi D^2 / 4 = (12.287 \times \pi \times 79.5^2) / 4
   \]
   
   \[
   P = 60960.67\text{N}
   \]
   
   Maximum side thrust on the cylinder
   
   \[
   R = p / 10 = 6096.06\text{N}
   \]
   
   R = bearing pressure \times \text{bearing area of the piston skirt}
   
   \[
   R = p_b \times D \times l
   \]
   
   \[
   l = \text{length of the piston skirt in mm} = 45.6\text{mm}
   \]
   
   Bearing pressure \( p_b = 1.5\text{N/mm}^2 \)
   
   Total length of the piston
   
   \[
   L = \text{length of the skirt + length of ring section + top land}
   \]
   
   \[
   L = 45.6 + 2.6 + 18.65 = 66.9\text{mm}
   \]

4. **Piston skirt**
   
   Center of piston pin should be 0.02D to 0.04D above the center of skirt = 0.04D = 3.18mm
   
   Tensile strength = 710 to 910Mpa
   
   Length of the pin in the connecting rod bushing, \( l_1 = 0.45D = 35.775\text{mm} \)
   
   Load on the piston due to gas pressure = 60960.67N
   
   \[
   p = p_b \times d_0 \times l_1
   \]
   
   \[
   l_1 = 35.775\text{mm};
   \]
   
   \[
   p_b = 50 - 100\text{Mpa for bronze}, p_b = 100\text{Mpa}
   \]
   
   \[
   d_0 = 17.04\text{mm}
   \]
   
   Inner diameter of piston pin, \( d_i = 0.6d_0 = 10.22\text{mm} \)
   
   Maximum bending moment at the center of pin
   
   \[
   M = (P.D) / 8 = (60960.67 \times 79.5) / 8
   \]
M = 605796.658s N-mm

Z = π/32 [(d₀)⁴ - (d₁)⁴]/d₀ = 4445.0689

Allowable bending stress \( \sigma_b = M/Z = 139.02 \)

This is less than the allowable value 140mpa for heat treated alloy steel

The mean diameter of the piston bosses = 1.5d₀ + 1.5 x 17.04 = 25.56mm

**Design calculations of connecting rod**

1. **Dimensions of cross section of connecting rod**

   Thickness of flange & web of the section = t
   Width of section B = 4t
   Height of section H = 5t
   Area of section A = 2(4t×t) + 3t×t
   Height of section H = 5t
   Width of section B = 4t
   Thickness of flange & web of the section = t

   On solving,
   \[ 5993.856t^2 + 23849.3166 = 172 \times 11t^2 \]
   \[ 5993.856t^2 - 749198.1551t^2 = 162418497.747714 = 0 \]

   On solving, \( t = 23.32 \)mm

   Width of section, B = 4t = 93.28mm
   Height of section, H = 5t = 116.6mm
   Area A = 11t² = 5982.64mm²
   Height at the big end (crank end) = H₂ = 1.1H to 1.25H
   H₂ = 128.26mm
   Height at the small end (piston end) = 0.9H
   H₁ = 104.94mm

2. **Dimensions of crank pin**

   Load on the crank pin = projected area × bearing pressure, \( F_L = d_c \times l_c \times p_{bc} \)
   \( l_c = 1.25 \)dₐ to 1.5dₐ
   \( F_L = 1.5 \)dₐ² × pₐ
   \( p_{bc} = \) allowable bearing press. at the crank pin bearing
   \( p_{bc} = 12.5N/mm² \)
   \( F_L = (\pi D²/4) \times P = 60960.67 \)
   \( 60960.67 = 1.5 \)dₐ² × 12.5
   \( d_a² = 3251.2357 = 57.01 \)mm
   \( l_c = 1.5d_c = 85.515 \)mm

3. **Piston pin (gudgeon pin (or) wrist pin)**

   \( d_c = \) outside dia of the piston pin
   \( l_b = \) length of the piston pin in the bush of the small end of the connecting rod in mm
   \( l_b = 0.45D = 0.45 \times 79.5 = 35.775 \)mm
   Load on the piston due to gas pressure
   \( P = 62017.45 \) N
   \( P_{max} = (\pi D²/4) \times P = 60960.67 \)
   \( P_{max} = 60960.67 = 77.28 \) N/mm²
   \( d_a = 22.05 \)mm
   \( d_o = 0.6d_o = 13.23 \)mm
   \( l_b = \) length between the supports \( l_b = (l_1 + D)/2 = 57.635 \)mm

**Crankshaft**

\( D = \) piston diameter or cylinder bore = 79.5 mm
\( P = \) maximum intensity of pressure on the piston = 12.287 N/mm²
\( F_p = \) thrust in the connecting rod will be equal to the gas load on the piston
\[ F_p = (\pi D²/4) \times P = 60960.67 \]
\( F_p = 60960.67 = 77.28 \times d_c \times 35.77 \)
\( d_c = 22.05 \)mm
\( d_o = 0.6d_o = 13.23 \)mm

Due to the piston gas load \( (F_p) \) acting horizontally, there will be two horizontal reactions \( H_1 \) & \( H_2 \) at bearings 1 & 2 respectively.

Considering the crankpin as simply supported beam i.e., \( H_1 = H_2 \)
\( b = \) distance between the bearings 1 & 2 is equal to twice the piston diameter
\( b = 2 \times 79.5 = 159 \)mm
\( b_1 = b_2 = b/2 = 79.5 \)mm

1. **Design of left hand crank web**

   Thickness of the crank web
   \( t = 0.4d_c = 0.6d_c = 0.22D = 0.32D \)
   \( t = 0.65d_c + 6.35 = 0.32 \times 79.5 \)
   \( t = 25.44 \)mm [from 0.32D]
Width of the crank web
\[ w = 1.125d_s + 12.5 = 1.125 \times 57.01 + 12.5 = 76.63 \text{ mm} \]

Maximum bending moment on the crank web
\[ M = H_1(b_2 - l/2 - t/2) = 30462.97 (79.5 - 85.5/2 - 2445./2) = 732025.1691 \text{ N-mm} \]

Section modulus
\[ Z = \frac{1}{6} wt^2 = \frac{1}{6} \times 76.63 \times 25.44^2 = 8265.74 \text{ mm}^3 \]

Bending stress on crank web
\[ \Sigma_b = \frac{M}{Z} = \frac{732025.1691}{8265.74} = 88.56 \text{ N/mm}^2 \]

Compressive stress on the crank web
\[ \Sigma_c = \frac{H_1}{wt} = \frac{30462.97}{(6376. \times 25.44)} = 15.62 \text{ N/mm}^2 \]

Total stress of crank web
\[ \Sigma = \Sigma_b + \Sigma_c = 88.56 + 15.62 = 104.18 \text{ N/mm}^2 \]

Here total stress is less than the yield strength of carbon steel (560 N/mm²)
\[ d_s = \text{diameter of the shaft in mm} \]
\[ t = 0.4d_s \text{ to } 0.6d_s \]
\[ d_s = \frac{t}{0.6} = \frac{25.44}{0.6} = 42.4 \text{ mm} \]

3. Analysis procedure

a. 2D drawings

b. CAD

CAD is mainly used for detailed engineering of 3D models and/or 2D drawings of physical components. It is used throughout the engineering process from conceptual design and layout of products, through strength and dynamic analysis of assemblies to definition of manufacturing methods of components.

Introduction to pro/engineer - Pro/ENGINEER

Wildfire is the standard in 3D product design.
Design and analysis of assembly of Piston, Connecting rod and Crank shaft

4. Analysis of the piston, connecting rod and crankshaft assembly

a. Static analysis - Element Type – Solid 20 Node 95

Table 2 Properties of the materials

<table>
<thead>
<tr>
<th>Material</th>
<th>Young’s modulus (N/mm²)</th>
<th>Poisson’s ratio</th>
<th>Density (Kg / mm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cast Iron</td>
<td>75000</td>
<td>0.211</td>
<td>0.0000007</td>
</tr>
<tr>
<td>Manganese Steel</td>
<td>210000</td>
<td>0.29</td>
<td>0.0000008</td>
</tr>
<tr>
<td>High Carbon Steel</td>
<td>200000</td>
<td>0.295</td>
<td>0.000007872</td>
</tr>
</tbody>
</table>
Design and analysis of assembly of Piston, Connecting rod and Crank shaft

Fig. 11 Meshed model

Fig. 12 Displacement with Loads – Pressure on Areas – 12.26N/mm²

Fig. 13 Von Mises Stress

Fig. 14 Nodal temperatures

Fig. 15 Thermal gradient

Fig. 16 Thermal flux

b. Thermal analysis – Element Type – Solid 20Node 90

Table 3 Material’s thermal properties

<table>
<thead>
<tr>
<th>Material</th>
<th>Density (Kg / mm³)</th>
<th>Thermal conductivity (W/m k)</th>
<th>Specific heat (J / g °C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cast Iron</td>
<td>0.000007</td>
<td>53.0</td>
<td>0.506</td>
</tr>
<tr>
<td>Manganese Steel</td>
<td>0.000008</td>
<td>51.9</td>
<td>0.472</td>
</tr>
<tr>
<td>High Carbon Steel</td>
<td>0.00000787</td>
<td>52.0</td>
<td>0.669</td>
</tr>
</tbody>
</table>

c. Dynamic analysis - Element Type – Solid 20Node 95

Loads

Time Step – 10secs, Pressure – 12.26N/mm²
Time Step – 20secs, Pressure – 18.39N/mm²
Time Step – 30secs, Pressure – 30.65N/mm²

Fig. 17 Loads at different time and Pressures

Loads: Temperature on Areas – 973K
Convection: Film Coefficient – 0.000025W/m²K
Bulk Temperature – 570K
Fig. 18 Displacement

Fig. 19 Stress

Fig. 20 Strain

Results table

a. Table 4 Static analysis

<table>
<thead>
<tr>
<th>Piston – Cast Iron Connecting rod – Manganese Steel Crankshaft – High Carbon Steel</th>
<th>Displacement (mm)</th>
<th>Von Mises Stress (N/mm²)</th>
<th>Strain</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0.439956</td>
<td>709.594</td>
<td>0.011</td>
</tr>
</tbody>
</table>

c. Table 6 Dynamic analysis

<table>
<thead>
<tr>
<th>Piston – Cast Iron Connecting rod – Manganese Steel Crankshaft – High Carbon Steel</th>
<th>Displacement (mm)</th>
<th>Von Mises Stress (N/mm²)</th>
<th>Strain</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1.226</td>
<td>1538</td>
<td>0.013998</td>
</tr>
</tbody>
</table>

Conclusion

In this project, the main parts of the engine piston, connecting rod and crankshaft are designed using theoretical calculations for the given engine specifications. The designed parts are modeled and assembled in 3D modeling software Pro/Engineer. The materials used are Cast iron for piston, Manganese steel for the Connecting rod and High Carbon steel for crankshaft. To use the same piston assembly for higher speed engines, the material of the piston has to be changed.

References


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Arvind Dave1 Rana Manoj Mourya2 Dr. V. N Bartariya3, Buckling Analysis of Connecting Rod to the Shank Sectional Area Reduction of Variable Cross Section by using Finite Element Method.

