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Design of a Crankshaft Driven External Gear Type Lubricating Oil Pump for a Multi-cylinder Diesel Engine

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Abstract
In IC Engines, basically the oil pump is driven either by a drive gear integrated with camshaft or a gear mounted on the crankshaft. In the older engines the oil pumps were mostly camshaft driven with a skew gear arrangement which becomes unique and tailor made for the given engine as part of the engine cylinder block sub-assembly. This arrangement calls for complex machining and the number of parts involved are more compared to a crankshaft driven oil pump as being seen in the modern engines. A crankshaft driven oil pump basically calls for a study of the envelope constraints and boundary conditions and finalising the mounting and maximum envelope possible for accommodating the oil pump. The challenge lies in arriving at a very compact pump with the required delivery for the given engine within the envelope limitations.

From the different oil pump types, the external spur gear type was selected for the design as it is the most popular and cost effective with manufacturing friendliness for mass production. The basic design computation was done based on the amount of heat carried away by the lubricating oil and the circulation rate of oil in the system. Through the step by step procedure the gear size and the power required to drive the pump was calculated. Based on the gear size and the some preselected parameters, all the important gear parameters were calculated.

The pump discharge was computed and it was verified that the discharge increases in direct proportion with the increase in engine speed, by a plotting a graph of oil pump discharge against engine speed and obtaining a linear trend in it. The design of the relief valve for the pump was also carried out. The physical dimensions of the compression spring were chosen and all the other important parameters were calculated and ensured that the pressure in the lubrication circuit remains within the prescribed limit.

Keywords – Engine oil pump, Lubricating oil pump design, Crankshaft driven oil pump, External gear type pump.

Introduction
The lubrication system is an integral part of an IC Engine with the functions as reducing friction, preventing corrosion, removal of wear debris and partial cooling of individual assemblies. There are different components for a lubrication system such as oil pan, oil pump, oil filter etc. Out of these the oil pump plays a vital part of delivering the lubrication oil to main gallery and thus ensuring the circulation of oil through the channels to reach the moving parts in the engine.

The lubricating oil pump should be able to provide sufficient discharge of the lubricating oil in all working conditions of the engine such as Idling, part load condition, full load condition etc. The discharge of the pump should be increasing in direct proportion with the increase in the engine speed (rpm). This is necessary because, at high engine speeds, the friction in the moving parts is higher and thus requires more amount of lubrication. So the linear oil pump discharge characteristic is required to cater the lubrication demand at higher engine speeds.

The oil pressure in the lubrication system is also an important factor that has to be considered for maintaining proper lubrication of the moving parts. It has to be regulated properly and should be kept within the safe limits. For this purpose the incorporation of a pressure relief valve in the oil pump outlet is inevitable. Whenever the pressure in the system exceeds the prescribed safe limit, the spring loaded valve should open due to the travel of the compression spring and thus bypassing the fluid back to the oil sump, reducing the oil pressure.

The main objective was to develop an improved lubricating oil pump design for a multi cylinder diesel engine. The design is done considering the envelope constraints for the packaging and the possible mounting arrangements of the pump assembly. The conventional camshaft driven oil pump which is placed at the bottom of the engine block just above the sump adds the complexity of the engine block sub-assembly in the manufacturing point of view. So the advanced and sophisticated crankshaft driven oil pump, mounted on the side of engine block as a separate sub-assembly is put forth in this project. The new design aims at the efficient lubrication, less power loss and the compactness of the oil pump assembly.

Engine Lubrication System

Lubrication system is very important and crucial for an Internal Combustion Engine. Lot of moving parts are involved in the working of an IC Engine and friction in these parts is unavoidable. So the lubrication becomes necessary.

The lubrication system supplies the oil to different parts of the engine that requires lubrication. The main components of a typical lubrication system are the oil pump, oil sump and oil galleries. The sump or the oil pan stores the oil, generally positioned at the bottom of the engine block. The oil pump pumps the oil from the sump to the oil galleries. Oil galleries are channels in the cylinder block that takes the oil to the moving parts.[1]

The primary function of the engine lubrication system is to maintain a positive and continuous oil supply to the bearings. Engine oil pressure must be high enough to get the oil to the bearings with enough force to cause the oil flow that is required for proper cooling.

The purposes of a lubrication system include the following:

- Reduce the frictional resistance of the engine to a minimum to ensure maximum mechanical efficiency
- Lubricating all moving parts to prevent wear
- Contribute to cooling the piston and regions of the engine where friction work is dissipated
- Helping to seal piston rings and to hold gas and oil leakage at an acceptable level.
- Cleaning, and holding dirt in suspension in the oil until it can be drained from the engine
- Neutralizing acids that are formed as a result of the combustion process
- Reducing friction
- Preventing rust and corrosion

External Gear Pump

The external gear-type oil pump consists of two spur gears in a close-fit housing where one gear is driven while the other idles. As the gear teeth come out of mesh, they tend to leave a space, which is filled by oil drawn through the pump inlet[2][3]. When the pump is pumping, oil is carried around the outside of each gear in the space between the gear teeth and the housing. As the teeth mesh in the centre, oil is forced from the teeth into an oil passage, thus producing oil pressure.[4] The liquid gets trapped in the gear teeth spaces between the housing bore and the outside of the gears and it is transferred from the inlet side of the pump to the outlet side when the gear rotates. The rotating gears continue to deliver a fresh supply of oil from the suction (inlet) side to the discharge (outlet) side, with negligible pulsations. [5]The meshing of the gears on the discharge side of the pump forces the liquid out of the pump and into the discharge piping[6][7]. The advantages of an external gear pump includes: High speed, no overhung bearing loads, relatively quiet operation, comparatively high working pressures, wide range of operating speeds, wide temperature and viscosity range (i.e. flexibility), low weight, low cost etc.[8]

Crankshaft drive

On crankshaft-driven oil pump systems, the oil pump turns at the same speed as the crankshaft or in a reduced speed, attained using a reduction gear externally mounted on the drive shaft of the pump. The advantages of the crankshaft driven oil pump compared to camshaft driven pump is that it can turn at twice the speed as camshaft driven pumps, providing more oil flow at idle [9]. Other advantages of crankshaft driven lubricating oil pump includes that space savings as thinner gears can be used, easiness in servicing the pump, comparatively less amount of power is required to drive the pump etc. The schematic layout of the crankshaft drive is shown in fig.1.

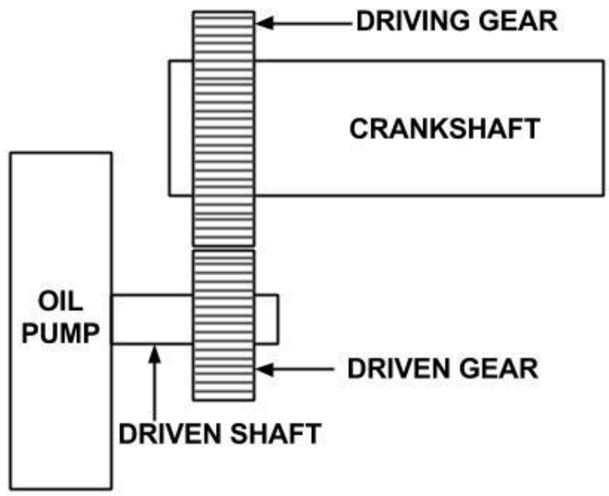


Fig. 1 Schematic layout of crankshaft drive

Methodology

The Design of lubricating oil pump follows the basic procedure of machine design. It consists of a step-by-step approach from given specifications about the functional requirements of a product to the complete description in the form of drawings of the final product. The logical sequence of steps which is usually common to all machine element design is followed. The process of arriving at the final design followed the standard step by step design procedures. Some improvisations were made, slightly deviating from the conventional approach to the machine element design, at some instances of the total design process. A direct design approach was followed wherever possible to reduce the complexity of designing.

Design Calculation Procedure

For the oil pump design, the step by step calculation procedure proposed by A. Kolchin and R. Demidov [10] was followed, explained below.

The design of the oil pump comes to defining the size of its gears. This design computation follows the definition of the oil circulation rate in the system.

Oil circulation rate V_c is dependent upon the amount of engine heat $Q_0{}'$ dissipated by the oil. According to the heat analysis, the value of Q_0' (kJ/s) in modern automobile and tractor engines is from 1.5 to 3.0% of the total amount of heat admitted into the engine by the fuel:

$$Q_0' = (0.015\ to\ 0.030)Q_0$$

The amount of heat produced by the fuel per second:

$$Q_0 = \frac{H_u \times G_f}{3600}$$

H_u - Fuel calorific value in kJ/kg
G_f - Fuel consumption rate in kg/h

The circulation rate of oil ((m^3/s) at the prescribed value of Q

$$V_c = \frac{Q_0'}{\rho_0 c_0 \Delta T_0}$$

ρ_0 - oil density
c_0- mean thermal capacity of the oil in kJ/kg K
ΔT_0 - Temperature difference in K

To stabilize the oil pressure in the engine lubrication system, the circulation rate of oil is usually increased twice:

$$V' = 2V_c$$

Because of oil leaks through the end and radial clearances in the pump the design capacity of the pump (m^3/s) is determined taking into account the volumetric efficiency η_p

$$V_d = \frac{V\prime}{\eta_p}$$

When designing the pump, it is assumed that the gear tooth volume (m^3) is equal to the volume of the tooth space:

$$V = \pi D_0 h b$$

D_0 – Diameter of gear pitch circle in m
h – Height of the tooth in m
b – Tooth face width in m

The design capacity of the pump

$$V_d = \frac{\pi D_0 h b n_p}{60}$$

n_p – Gear speed in rpm
With tooth height equals to two modules (h = 2m) and $D_0 = zm$

$$V_d = \frac{2\pi z m^2 b n_p}{60}$$

z – Number of teeth of gear
m – Module
Value of gear speed

$$n_p = \frac{u_p 60}{\pi D}$$

u_p – Peripheral velocity at the gear outer diameter in m/s
The peripheral velocity at the gear out.er diameter must not exceed 8-10 m/s. At higher peripheral velocities the pump volumetric efficiency will materially drop. With values of m, z and u_p prescribed, we determine the tooth face width (m) from equation (8)

$$b = \frac{60 V_d}{2\pi z m^2 n_p}$$

Power (kW) to drive the oil pump

$$N_p = \frac{V_d p}{\eta_{m.p} \times 10^3}$$

V_d – pump design capacity in m^3/s
p – Oil working pressure in the system in MPa
$\eta_{m.p}$ – Mechanical efficiency of the pump

Gear Parameters
Important gear parameters were calculated using the following formulas:

1. Diametral Pitch

$$P = \frac{N+2}{D_0}$$

N = Number of teeth
D_0 = Outside diameter

2. Circular Pitch

$$p = \frac{\pi}{P}$$

P = Diametral Pitch

3. Base Diameter

$$D_b = D \cos Ø$$

Ø = Pressure Angle
D = Pitch circle diameter

4. Tooth thickness at pitch circle

$$t = \frac{1.5708}{P}$$

5. Addendum

$$a = \frac{1}{P}$$

6. Whole Depth

$$h_t = \frac{2.2}{P} + 0.002$$

7. Working Depth

$$h_k = 2a$$

8. Clearance

$$c = h_t - 2a$$

9. Dedendum

$$b = h_t - a$$

10. Root diameter

$$D_r = D - 2b$$

Results

TABLE 1 oil pump design results

The amount of heat produced by the fuel per second (Q_0)	200.95 kJ/s
The amount of engine heat dissipated by the oil (Q_0')	6.0286 kJ/s
The circulation rate of oil at the prescribed value of Q (V_c)	0.000153775 m^3/s
Increased circulation rate (V')	0.00030755 m^3/s
Volume of the tooth space (V)	25099.51574 mm^3
The design capacity of the pump (V_d)	1045813.156 mm^3
The value of gear speed (n_p)	3055 rpm
Gear tooth face width (b)	16 mm
Power to drive the oil pump (Np)	0.587 kW

TABLE 2 pump gear features

Gear Profile	Involute (full depth)
Pressure Angle	20°
Outer Diameter	52 mm
Module	5 mm
Gear Thickness	16 mm
Material	18CrNiMo7- 6, Case Carburised Steel, Case Hardened, ISO 6336-5

TABLE 3 calculated gear parameters

Calculated Gear Parameters	Value
Diametral Pitch	0.195 teeth/mm
Circular Pitch	16.11 mm
Base Diameter	38.52 mm
Tooth thickness at pitch circle	8.055 mm
Whole Depth	11.284 mm
Working Depth	10.256 mm
Clearance	1.028 mm
Addendum	5.128 mm
Dedendum	6.156 mm
Root Diameter	28.68 mm

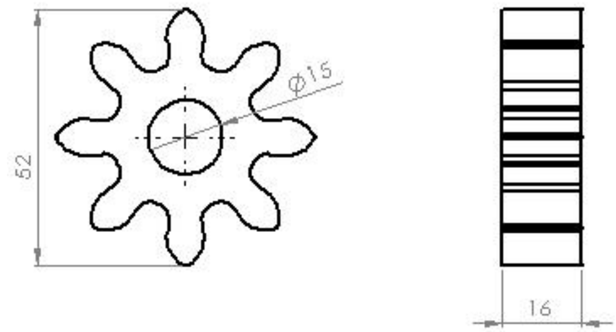


Fig. 3 Oil pump Gear dimensions

Pump Discharge

The calculated discharge of the pump = 25.71 cc/rev (0.02571 L/rev).

The total discharge at a particular engine speed is calculated by multiplying the discharge of the pump in one single revolution, which has been calculated, by engine speed in revolutions per minute (rpm). Thus the discharge of the pump is calculated for the engine speeds in the operating range of the engine.

The graph below in fig. 4, shows the oil pump discharge plotted against the engine speed.

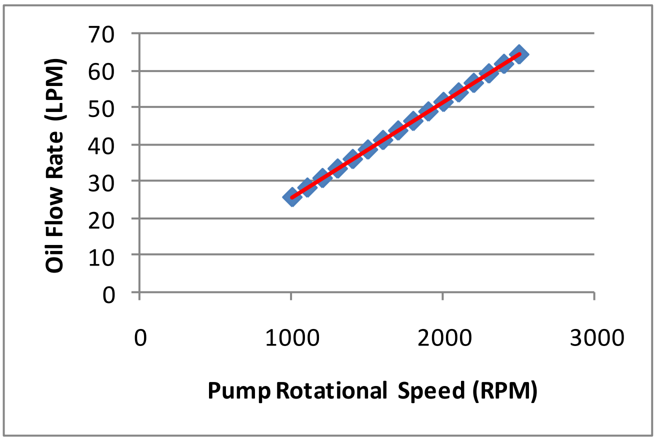


Fig. 4 Oil pump discharge vs. Pump rotational speed

The plot shows a trend which is linear. It implies that the oil pump discharge increases in proportion with the increasing engine speed. This is the required feature for an engine lubricating oil pump. At higher engine speeds the friction in the moving parts will be higher and requires more lubrication. From the plot it is evident that the newly designed oil pump suffices this requirement.

3D Model

Based on the results of design calculations 3D modelling of the oil pump was done. Individual components were modelled and then assembled to form the oil pump.

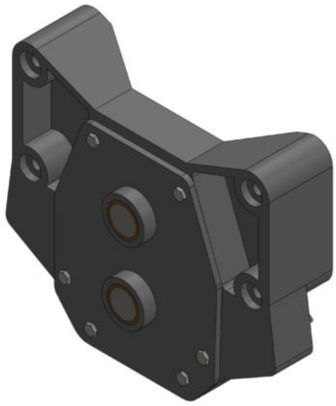


Fig. 5 Oil pump assembly - front

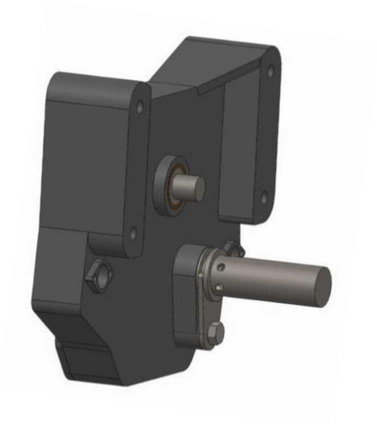
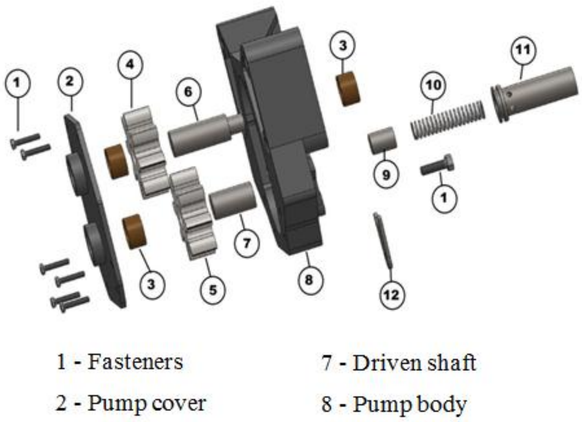


Fig. 6 Oil pump assembly - rear



1 - Fasteners	7 - Driven shaft
2 - Pump cover	8 - Pump body
3 - Bushings	9 - Valve
4 - Drive Gear	10 - Valve Spring
5 - Driven Gear	11 - Relief Valve Body
6 - Drive shaft	12 - Retainer

Fig. 7 Oil pump assembly – exploded view

Conclusion

The engine lubricating oil pump was designed such that requirements due to which the demand for new pump aroused, were all satisfied. The new design is a blend of the conventional system with new sophistications which made it unique.

The new design of the engine lubricating oil pump successfully satisfied the requirements such as: good discharge characteristics, less consumption of engine power, compactness, the ease for assembling and cost effectiveness.

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