Mathematical Modeling and Simulation of 3-Cylinder Engine

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ABSTRACT

This work concentrates on the discussion of the engine design and mechanical relationships. We have used COMSOL 5.2 tool to analyses various thermodynamic and multi body analysis of the 3 cylinder engine. The simulation results have been justified with the theoretical results as well. Recent work on combustion development has shown that combustion systems, ports, valves and injector sizes are available for different sizes. The defining feature of an internal combustion engine is that useful work is performed by the expanding hot gases acting directly to cause movement of solid parts of the engine, by acting on pistons, rotors, or even by pressing on an moving the entire engine itself. This contrasts with external combustion engines, such as steam engines, which use an external combustion chamber to heat a separate working fluid, which then in turn does work, for example by moving a piston or a turbine.

Keywords: 3-cylinder engine, Internal combustion, PV diagram, rotation of crank shaft.

1. INTRODUCTION

The four stroke three-cylinder in-line engine features a decisively improved mass balance as compared to the two-cylinder. There are only three, each 60° crank angle long, empty strokes. Construction expenditure, internal friction (fuel consumption) and length are lower and make the engine with rising cubic capacity interesting as a substitute for four cylinder engines. Though its crankshaft is shorter, it has headers in three levels. Recent work on combustion development has shown that combustion systems, ports, valves and injector sizes are available for different sizes.

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The term Internal Combustion Engine (ICE) is almost always used to refer specifically to reciprocating piston engines, Wankel engines and similar designs in which combustion is intermittent. However, continuous combustion engines, such as jet engines, Wankel engines and many gas turbines are also internal combustion engines. Heat engines are otherwise called Thermal Engines. It is a machine which converts heat energy in to useful mechanical work. Heat engines develop more than 80% the energy generated in the world [1, 2]. In this work, we have analysed and simulated various thermodynamic parameters for IC engine design using COMSOL 5.2 tool. The thermodynamic parameters like PV diagram relationship, pressure and theta diagram and mechanical energy output are observed and justified with theoretical results also.

2. LITERATURE REVIEW

Over the centuries various developments have been carried out in regard to ICE. In 1206, Al-Jazari described a double-acting reciprocating piston pump with a crankshaft-connecting rod mechanism [3]. In 1509, Leonardo da Vinci described a compression less engine [4].

In 1876, Nikolaus Otto, working with Gottlieb Daimler and Wilhelm Maybach, developed a practical four stroke cycle (Otto cycle) engine[5]. In 1900, Rudolf Diesel demonstrated the diesel engine in the 1900 Exposition Universelle (World's Fair) using peanut oil (see biodiesel) [5, 6]. In 1902 automobiles with that engine were put into production by DMG. In 1951, Wankel began development of the engine at NSU, where he first conceived his rotary engine in 1954 (DKM 54) and later the KKM 57 (the Wankel rotary engine) in 1957. The first working prototype DKM 54 was running on February 1, 1957 at the NSU research and development department [7, 8].
Suzuki also made a production motorcycle with a Wankel engine, the RE-5. In 1971 and 1972 Arctic Cat produced snowmobiles powered by 303 cc Wankel rotary engines manufactured by Sachs in Germany. John Deere Inc, in the U.S., designed a version that was capable of using a variety of fuels. The design was proposed as the power source for several U.S. Marine combat vehicles in the late 1980s [9].

In recent years, the motor vehicle industry aims at the small sized and high power density engine, while downsizing (small size and weight saving) and measuring the improvement in fuel consumption, and cleanization. The smallest inline-three, four-stroke automobile engine was the 543 cubic centimetres (33.1 cu in) Suzuki F5A, which was first used in the 1979 Suzuki Alto/Fronte. Basic versions of the Suzuki Swift (and its related badge-engineered versions) used a 993 cc inline-three-cylinder engine, [10] with single-point injection [11]. Mitsubishi has made extensive use of three-cylinder engines, which have also been used in the Smart ForTwo, since 2004 on the Mitsubishi Colt, [12] and from 2012 on the Mitsubishi Mirage. A three-cylinder diesel engine was also used on the Mitsubishi Colt and the Smart Forfour [13]. The first generation Honda Insight (2000–2006) used a 1.0 litre inline-three engine in conjunction with an electric motor in its hybrid system.

In the last decade from years 2000 onwards there is major breakthrough in the field of ICE using supercharging concept. Ford started offering their new turbocharged 1.0-litre EcoBoost unit in the Focus from 2012 [14]. Starting from 2014, the Opel Adam will be offered with a new turbocharged three-cylinder engine, mated to a six-speed manual gearbox [15]. This engine, branded SIDI (Spark Ignition Direct Injection), uses direct injection, continuously variable valve timing and has a lightweight aluminium cylinder block [16-18]. We have used COMSOL multiphysics tool for our simulations [19, 20].

3. 3-CYLINDER ENGINE MODEL

A. Thermodynamic Analysis

A simplified thermodynamic analysis of an air-fuel mixture in an engine cylinder is performed to model the engine and parameters like. P-V diagram, variation of the cylinder pressure with the crank rotation and useful mechanical energy are calculated. This analysis is performed using the Heat Transfer and Coefficient Form PDE interfaces. Fig. 1 shows the geometry of 3-cylinder engine.

B. Multibody Dynamics Analysis

A multi body dynamics analysis of an engine assembly is performed which evaluates, displacements of the engine components, stress in the flexible connecting rod, mechanical power generated in each cylinder, Power output (BHP) of the engine, variation of the maximum stress generated in the flexible connecting rod, forces at the joint between the flexible connecting rod and crank pin. In the multi body analysis, the pressure data obtained from the thermodynamic analysis is used to compute the motion of different components of an engine assembly, the RPM of the engine, and the power output (BHP) of the engine. The variation of the maximum stress in this component with the crankshaft rotation is analyzed. This analysis is a simplified form of an actual combustion analysis. Only air is considered as a fluid in the combustion chamber. The heat energy, generated by combustion, is added uniformly over the domain. The convection effects in the combustion chamber are neglected. All the equations are solved on the original domain, and the effect of change in the cylinder volume is accounted for manually in the equations.

![Fig. 1. Geometry of the three-cylinder engine](image-url)
A very important property of 3-cylinder engine causes the expansion ratio of medium in the engine is two times greater than the compression ratio. There is increased in specific power and specific torque generated and also increased in fuel efficiency. It results in less fuel consumption. It is validated by computing the mechanical efficiency of our model. The temperature distribution in the air in the cylinder is modelled using the heat transfer equations. The pressure work is also added to account for the rise in temperature due to the work done by the piston. The pressure distribution in the air is modelled using an ideal gas equation:

\[ p = \frac{m}{V}RT \]  

(1)

where \( p, m, V, R \) and \( T \) represent the pressure, mass, current volume, specific gas constant and temperature respectively. The current cylinder volume \( V \), is computed by using the initial cylinder volume. The piston displacement \( t \) is \( x_p \), as a function of rotation \( \theta \), can be written as,

\[ x_p = \sqrt{l^2 - (r_c \sin \theta)^2} - r_c \cos \theta - (1 - r_c) \]  

(2)

where \( x_p, r_c, l \) and \( \theta \) represent the piston displacement, crank radius, connecting rod length and crank angle respectively.

4. SIMULATION RESULTS

We have used COMSOL Multiphysics Version 5.2 on Windows 7, 2Gb RAM, 32-bit OS, 3.40GHz, Core-i3 processor. The \( P-V \) diagram of the cylinders of the engine, as computed from the thermodynamic analysis, is shown in Fig. 2.

In adiabatic process through PV diagram,

\[ P_iV_j^\gamma = P_fV_f^\gamma, \]  

(3)

where \( P_i \) is initial pressure, \( P_f \) is final volume, \( V_j \) is initial volume and \( V_f \) is final volume. The factor \( \gamma \) is specific heat ratio which is taken as 1.4. By substituting values of state points from PV diagram, we have observed the following which justifies equation (3).

\[ 26.7 \times (42)^{1.4} \approx 1 \times (441.5)^{1.4} \]

5001.03 \( \approx 5045.48 \)

Fig. 2. P-V diagram for one of the cylinders

Fig. 3 shows the variation of cylinder pressure with the crankshaft rotation. We can clearly observe the compression, combustion and expansion strokes in this curve. The curve is exported and used to prescribe the pressure on the top surfaces of the piston in the multi body analysis.
The heat energy converted into the mechanical energy also computed. Table I represents the results. It is observed that during the compression stroke, the power generated is negative and it suddenly reverts its sign during the combustion, after which the power generated is positive. The time average of the power over a cycle is the net mechanical power generated in one revolution of crankshaft. The 120° phase shift between the three sets of cylinder-piston can also be seen.

**Table 1: Mechanical Energy and Efficiency**

<table>
<thead>
<tr>
<th>Time (s)</th>
<th>Method used</th>
<th>Mechanical Energy (J)</th>
<th>Efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.10 sec</td>
<td>Normal 3-cylinder</td>
<td>332.088</td>
<td>55.34% (By simulation)</td>
</tr>
<tr>
<td>0.10 sec</td>
<td>By calculations</td>
<td>-</td>
<td>60.8% (By PV diagram)</td>
</tr>
</tbody>
</table>

This efficiency is calculated below.

\[
\text{Efficiency}(\eta) = \frac{\text{Output Energy}}{\text{Input Energy}} \quad (4)
\]

By substituting the values from table I into equation (4) we get practical efficiency as,

\[
\eta_{\text{Prac.}} = \frac{332.088}{600} \approx 55.34%
\]

The practical efficiency is compared with the theoretical efficiency as,

\[
\eta_{\text{PV}} = 1 - \left(\frac{1}{r}\right)^{\gamma-1} \quad (5)
\]

where \( r \) is compression ratio. It is defined as, \( r = \frac{V_F}{V_I} \). We take \( V_F = 441.5\,\text{cc} \), \( V_I = 42\,\text{cc} \), therefore \( r = 10.51 \).

Substitute the values in equation (5) we get, \( \eta_{\text{PV}} = 60.8\% \).

Fig. 4 displays the time history of the RPM of the engine. The starting torque applied in the beginning of the simulation increases the engine RPM rapidly. After the removal of starting torque, the RPM increases steadily as there is no external load. Finally after the application of the external load, it approaches a steady-state value close to 2600, which is verified in the fig. 4.
CONCLUSION AND FUTURE WORK

In this work, the static and dynamic balances of the three-cylinder engine are investigated analytically. Using the simulation results we can justify the engine working at different time instants by computing the values of power generated in cylinders, brake horse power, stress and fatigue analysis in connecting rod, and RPM vs. rotation of crank shaft. A multi body dynamic model of the three-cylinder engine is developed where the inertia properties of the connecting rod, crankshaft, and balance shaft are extracted. The model can be modified by for better values of performance measures. We have also performed multi body analysis also.

The current popularity of internal combustion engines, such as gasoline and diesel engines, originates from the combination of their attractive driving performance due to high torque levels and low fuel consumption. The combustion pressures within the cylinders in different operating conditions are measured from the actual tests. The stress analysis is performed. It is shown that the endurance limit is within the acceptable level.

REFERENCES