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Motions Study of a Single Cylinder High Speed Spark Ignition Linear Engine with Electromagnetic System as Return Cycle

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Abstract: This paper looks into the design and modeling of a linear engine. Quite a number of researches to improve the almost ubiquitous engines are going on. The linear engine is any engine that does not work by rotation but by linear reciprocating motion (a kind of up and down motion) by removing the crank mechanism of the conventional internal Combustion(IC) engines. Hence after the combustion process, a restoring force is required. Sequel to the development and design of the linear engine, it is necessary to carry out motion and torque analysis. The principle of combustion as it relates to the working of the linear engine is also explicated and its oscillation profiles are examined. The system relevant mathematical laws are modeled in 3D and engines models have been simulated. Five different software tools have been used in the simulation process. Autodesk Inventor3D has been used to design assembly and section out the engine models. However, combustion dynamics and torque profile generation was carried out in MATLAB. Electromagnetic force design and restoration process was shown using Simulink and the final simulation of the engine oscillation is carried out by Autodesk 3Ds max and VRML linked up with the Simulink package. Results have been generated in kinematics showing the pressure volume profiles and in dynamics showing the torque generation and work-done profile of the new engine model. The results have been compared to that of the conventional Otto cycle engine to observe the electromagnetic effect.

Keywords: Linear Engine, dynamic Analysis, kinematics, Electromagnetics, MATLAB.

INTRODUCTION

An engine is any device that can convert various forms of motion into mechanical energy or motion. The engine can be described as either an internal combustion engine or an external combustion engine. The external combustion engine describes any engine whose combustion takes place outside the cylinder an example of this is the steam engines where the combustion of gases to vaporize water and hence convert it to steam takes place outside the engine and then the steam is sent to the engine where it is used to drive the machine. A linear engine is a normal rotational Otto cycle engine with the crankshaft replaced by an alternator (for the purpose of electricity generation) or other forms of actuators. When this is done during the normal combustion process of the engine, at the instance of the opening of the fuel-gas mixture inlet valve, the pressure of the gas shifts then piston from the top dead center (TDC) to the bottom dead center (BDC). At the BDC there is need of a restoring force that will move the piston upward at the stage of compression of the gas. For the conventional multicylinder engines (even number of cylinders), the force here is supplied from the torque by combustion in another cylinder transmitted via the crankshaft. But in the case of a linear engine, this transmission mechanism is not available hence we will need a restring force. Other researchers have usually used spring as a restoring mechanism for the linear engine¹. But in this paper we have used an electromagnetic restoration force for the engine.

The major advantage of the use of the electromagnetic restoration force is that, unlike the spring mechanism model which requires an extra work done in compression of spring hence reducing the total efficiency of the engine as this work is quite unnecessary. In this paper we show the use of electromagnetic force restoration which will be placed in a control system such that during the movement from TDC to BDC in any of the cycles, the resistive force from the restoration mechanism will be zero and swing on at BDC in the movement of the piston to the TDC. In this research, the motion profile of a normal Otto cycle engine is generated as the piston makes its way up and down and then a model for a linear engine without the crank mechanism but where restoration is done by the electromagnets. Proximity positions sensors are also installed in this engine block which can withstand the high temperature due to the combustion process. The maximum temperature plot is generated and the sensors are used to activate and deactivate the electromagnets so as to generate the field required for attraction. Faraday's law of electromagnetism was used to model the magnets and the nonlinearities that affect the electromagnet models are also taken into consideration.

Numerical Simulation of a Linear Engine: The electromagnetic system is rarely used to generate a linear engine system. However, in this case the electromagnetic system is triggered after the expansion cycle. **Figure-1** shows the spring restoring force design and **Figure-2** shows the electromagnetic system configuration used to create a single cylinder linear engine. The numerical model is developed for a spark ignited linear engine, but can be easily adapted for the case of a compression ignition linear engine. The numerical analysis also allows a parametric study of the operation of this type of engine. The engine modelling has been validated using results from the existing works on linear engines. The numerical model represents an idealized case based on the assumptions made, while allowing a parametric study to be performed.



Fig.1: Spring system¹.

Fig.2: Electromagnet based system.

The Linear Engine Model: The free-piston term is most commonly used to distinguish a linear engine from a rotating crankshaft engine. The piston is 'free' because its motion is not restricted by the position of a rotating crankshaft, as known from conventional engines, but only determined by the interaction between the gas and load forces acting upon it. This gives the free-piston engine some distinct characteristics, including (a) variable stroke length and (b) the need for active control of piston motion. Other important features of the free-piston engine are potential reductions in frictional losses and possibilities to optimize engine operation using the variable compression ratio². Figure 2 shows the model of the linear engine as designed with inventor. The torque profile equations can be described from the dynamic analysis of the linear engine. They consider the case of a linear engine with electromagnet system that oscillates back and forth in a left-to-right motion with a fixed inlet scavenging port. The expansion is conducted by combustion pressure, while the compression force is the restoring electromagnetic force. A system of coordinates was chosen with their origin at the outermost point of the left cylinder. Considering a mechanical system represented by the piston assembly in motion, this system obeys Newton's second law. This formula was also adopted by some researchers¹. In the horizontal (motion) coordinates, Newtons second can be written as:

$$m\left(\frac{dx^2}{dt^2}\right) = \sum_n F_{xn} \qquad \dots (1)$$

Where, x represents the displacement of the piston assembly and $\left(\frac{dx^2}{dt^2}\right)$ is the acceleration of the piston. The right hand side of Equation (1) represents the summation of the forces that act in the horizontal plane of motion. During the downward stroke, the forces present will only be the combustion force, the friction between the cylinder wall and the piston ring seal, and the load force. During the upward stroke, the force present will be the force of attraction between the two magnets, the frictional force between the wall of the cylinder and the piston ring. Hence we can write the following equations:

$$m\left(\frac{dx^2}{dt^2}\right) = Fc - Ff - Fl$$
...(2)

$$Fc = A.dP = A(P2 - P1) = \pi r^2 (P2 - P1)$$

$$m\left(\frac{dx^2}{dt^2}\right) = Fg - Ff - Fl$$
...(4)

Where:

- Fc is the resultant of the combustion pressure forces
- Ff is the friction force
- Fg is the force generated by the electromagnet
- Fl is the load applied to the shaft
- r is the piston radius; p1 and p2 are the corresponding in-cylinder pressures.

In order to determine the solution of this differential equation, it is necessary to integrate it twice with respect to time. The analytic integration is somewhat complicated to evaluate due to the complex variation in the three forces with respect to space and time. However, the thrust force of the combustion process is expressed by a pressure diagram which results from a 1-D MATLAB simulation analysis.

... (3)



Fig.3: Linear engine model.

Kinematics of the engine: Based on the conventional Otto cycle engine the kinematics of the linear engine with a view to predicting its motion profile is shown below based on **Figure 3**.



Fig.4: Kinematic displacement profile.

By kinematic analysis using the laws of motion, we can write First displacement

 $x = p + q = r\cos\theta + l\cos\theta \qquad \dots (5)$

Horizontally,

 $rsin\theta = lsin\emptyset$... (6)

$$r\sin\theta - l\sin\theta = 0$$
 ... (7)

$$\emptyset = \sin^{-1}\left\{ \left(\frac{r}{i}\right) \sin\theta \right\} \tag{8}$$

Hence

By differentiating (8) and substituting into (6) we have

$$\emptyset' = \frac{r\theta'\cos\theta}{l\cos\theta}; \quad x' = r\theta'\sin\theta + l\phi'\sin\theta \qquad \dots (9)$$

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On combining the two equations of equation 9 we have

$$x' = \frac{rsin(\theta + \emptyset)}{\sigma os \emptyset} \; \theta' \qquad \dots (10)$$

But to determine the acceleration of the piston we differentiate again to get

$$\emptyset'' = \frac{r\theta^{l^2} \sin\theta - r\phi^{l^2} \sin\phi}{l\cos\phi} \dots (11)$$

$$x'' = -r\theta'^{2}\cos\theta - l\theta'^{2}\cos\theta - l\theta''\sin\theta - r\theta''\sin\theta \qquad \dots (12)$$

These mathematical equations was used to model the system

Dynamics of the Engine: For the force dynamic equations, since mass is said to be concentrated at the center of gravity, for the three masses when in motion, we denote mass of crank as mc, mass of piston as mp and mass of connecting rod as mco. For this modelling let Pressure in combustion chamber be P, force generated by the electromagnets be Fg, load moments on crank be ml, and atmospheric pressure be Patm. From experimental sources, maximum pressure in the cylinder occurs immediately after combustion³ Mohamed, 2000. But due to incomplete combustion the work done by this process is reduced but we can designed an additional controlled force to support the system which increases the net downward force as a result of repulsion between the two electromagnets **Figure 5**. Shows the dynamic force profiles which are used to generate equations for dynamic modelling.



Fig.5: Kinematic displacement profile.

$$-Fg + (Patm - P)A + Rcos \emptyset = mp.x'' \qquad \dots (13)$$

Also

$$rRsin(\theta + \phi) + Ml \sim 0 \qquad \dots (14)$$

Where MI is the load moment. From (13) and (14) we can write

$$\frac{Fg + (P - Patm)A + mp.x''}{\cos \emptyset} rsin(\theta + \emptyset) + Ml \sim 0$$
...(15)

The first term on the left of equation (15) is the turning moment. Turning moment must overcome load moment to keep crank at uniform speed. On expanding this term we have

$$Mt = \frac{Fg + (P - Paxm)A}{\cos \theta} r \sin(\theta + \phi) + \frac{mp \cdot x''}{\cos \theta} r \sin(\theta + \phi) \qquad \dots (16)$$

The first term is the moment due to pressure and forces in the chamber while the second term is the moment of inertia due to moving parts. These equations form the dynamic model of the engine and will be simulated with Matlab as shown in the results

MATERIALS AND METHODS

This system is made to design a linear engine with a restorative force from a spring now for the cyclic motion. We hope to control it in a future paper to achieve a close to perfect Atkinson cycle which is said to be more efficient than the Otto cycle which is not yet attainable to ideal states by varying the position of the piston so as to cause a delay that will result in further combustion. The basic idea behind our new design is using a well-timed optimal control system to achieve an optimized intake which will be based on the calculated pressure of the gases and the force required at the intake stage, then, we will look into generating a force for the compression stage. This force has to be provided in such a way that it does not obstruct the pressure from the gas during intake. That means, it must allow for intake or even compress itself during intake and then, release a high propelling force during compression stage. The next stage is pretty automatic and that's the combustion stage.

This stage is the key upon which all other engines work. As it is the thermodynamic energy conversion that occurs in this stage that hold the key behind the force of an engine since it is in this stage that all the chemical energy in a fuel is converted to mechanical energy for motion. In our design, we use two position sensors one at the BDC and the other at the TDC also, instead of just two, multiple sensors could be inserted at the walls of the cylinder in such a way that the triggering action from different sensors could contribute differently to the force profile generated between the magnets. A controller linked up with the sensors is used to regulate or adjust the functioning of the IC engine in order to achieve a better and much favorable cycle. The cylinder is going to be fitted with electromagnets that will delay or quicken processes. Target parameters to be controlled are the force acting on the piston at a point in time t and the position of the piston. The model design is shown below in **Figure 6**. The idea is to get a controllable oscillatory motion on the piston by the means of electromagnetic forces interaction.



Fig. 6: Conceptual diagram of the Electromagnet Based engine.

The process involved in the design is first to model an engine which will be used to observe the behavior of varying parameters on the engine profile. Inventor studio was used in the 3d modelling of the engine. **Figure 7a** shows this model. To activate the model so that it will be operated in a virtual world, via Simulink, the model was exported to 3ds Max studio from whence the Virtual Reality Modelling Language (VRML) model is formed. **Figure 7b** shows the VRML world. Then with the VRML kinematic profiles and dynamic motion profiles were generated and fed into the VRML model via MATLAB and SIMULINK. **Figure 8** shows this process.



Fig.7a: Inventor of single piston engine block. Fig. 7b: VR

Fig. 7b: VRMLmodel of single piston engine block.



Fig. 7: MatLab, Simulink and VRML simulation.

RESULTS

For generic considerations, different characteristics of conventional Otto cycle engine and the linear engine motion, such as piston displacement, velocity and acceleration, are considered. Also variations of torque with crank angle, pressure with crank angle and general motion study runs in multi-cycles mode. **Figure 9** presents the pressure volume profile of the designed engine with various timing for the electromagnetic force which shows a near-Atkinson cycle achieved. **Figure 10** shows the engine pressure in the designed engine with respect to the crank angle. With maximum pressure observed just after the combustion stage. **Figure 11-12** shows the moment variation with respect to crank angle and the work done cycle.

After these models are linked up in the Simulink environment, the oscillatory behavior of the engine is seen. **Figure 13-14** shows the piston at the BDC when the position sensors are activated to switch on the electromagnets. As seen in the modelling diagram, when this happens, the magnets are energized to attract one another. And once the piston reaches the TDC, the magnets de-energize and the Otto cycle behavior takes over. This cycle after simulation is shown in these figures.



Fig. 9: Pressure-Volume profile of the engine.



Fig. 10: Pressure vs Crank angle profile for the engine.



Fig. 11: Moment vs Crank angle profile for the engine.



Fig. 12: Work (joules) vs Crank angle profile for the engine.



Fig. 13: Engine model with Piston at BDC immediately after combustion.



Fig. 14: Engine model with Piston at TDC pulled up by electromagnets.

DISCUSSION

Based on the derived profiles, we have mimicked the behavior of a conventional Otto cycle engine with the use of electromagnets for a single cylinder piston engine. Most of the results correspond to that achieved by other researchers for Otto cycles torque and pressure profiles^{2, 4-6}. And this has been confirmed by other researchers.

CONCLUSION

Until now the forces acting in the walls of the Internal Combustion (IC) engine are self-controlled. This work has shown an electromagnet based engine is viable by using the magnets to serve as restoring forces. With this, it is possible to control, optimize and modify the behavior of the engine in order to achieve desired behavior.

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