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Bond Graph Simulation of a Diesel Engine to Estimate the Effects of Downsizing

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ABSTRACT

a The objective of this dissertation work is modeling of a four cylinder diesel engine and to observe the effect of downsizing a 4 cylinder to 3 cylinder engine using bond graph simulation. A bond graph is modeling tool used to model inter-domain systems. The engine is composed of different subsystems such as crank-slider mechanism, cooling system and crankshaft. These parts are modeled independently according to power interaction between them. 20-sim software is used in bond graph modeling and simulation. The performance parameters of the engine such as in-cylinder pressure, jacket temperature, torque, temperature are observed through simulation and verified with experimental data to check the validity of the model. The downsizing is implemented by putting off one cylinder and the effects like torque unbalance, power change, jacket temperature, angular velocity of crankshaft are estimated.

Keywords— **a Bond Graph, Downsizing, IC engine, Modelling.**

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I. Introduction

Today market demands lighter and more efficient cars so there is a significant need for downsizing of an IC engine. The physical downsizing of an IC engine has certain limitations. Modeling and simulation is an effective problem solving methodology. It is characterized at three distinct physical levels which are overall system, sub-systems and physical process. At each physical level there are three phases namely; modeling, numerical analysis and conducting experiment with model which is called simulation The modeling and simulation have an increasing importance in the development of complex and large mechanical system, in order to design for optimum performance. There are many ways to simulate the system like finite element method, MATLAB etc. All the simulation software solve the governing differential equations, majority of times, are nonlinear, higher order and partial differential equations. In Bond Graph simulation, the solution variables are power variables as effort and flow such that product of these two variables result in power. While representing or modeling in BG, the dynamics of the system is obtained by basic laws of the physics of respective system or domain. The BG modeling is unified approach especially useful when the system becomes more complicated or multidisciplinary. A bond graph is a graphical representation of a physical dynamic system. It is similar to the better known block diagram and signal-flow graph, with the major difference that the arcs in bond graphs represent bi-directional exchange of physical energy, while those in block diagrams and signal-flow graphs represent uni-directional flow of information. In the bond graph modeling technique, a physical system can be represented by symbols and lines, identifying the power flow paths. Various symbols used in the bond graph are categorized into four groups. First group constitutes of the one port passive elements viz. inertances (I), compliances (C), and dissipaters (R). The external source inputs to system are expressed as source of effort (SE) or source of flow (SF) elements. Two multi-port elements transformer (TF) and gyrator (GY) are also used. TF element performs flow to flow or effort to effort conversion, whereas GY element converts flow to effort or effort to flow. System constraints are represented using ‘1’ junction (representing constant flow) and ‘0’ junction (representing constant effort) elements. The elements are connected by line segments called bonds. Each bond carries the associated effort and flow information. The half arrow on the bond represents the assignment of power direction to the bond.

The basic objective of this work is to model a four stroke diesel engine and test the engine for morse test. This test can be used only for multi-cylinder IC engines. In a Diesel engine, a particular cylinder is made inoperative by cutting off the supply of fuel. It is assumed that pumping and friction are the same when the cylinder is inoperative as well as during firing. In this test, the engine is first run at the required speed and the brake power is measured. Next, one cylinder is cut off by cutting of the fuel supply if it is a diesel engine. Since one of the cylinders is cut of from producing power, the speed of the engine will change. This change in the speed, torque and other parameters are to be observed due to downsizing.

II. LITERATURE REVIEW

a The Bond graph modelling is an inter-domain modelling tool which has been used for modelling of engine and engine parts. The literature states that modelling and simulation is an effective problem solving methodology [1]. The Bond graph of two-stroke IC engine has been developed for a constant speed and parameter such as power and torque are observed. The performance of the two stroke engine depends on how the fresh fuel is handled and how it is varied with engine geometry and dynamics. The author has divided the two-stroke engine into separate subsystems such as input system, exhaust port, transfer port etc. depending on their dynamic interactions. Each important dynamic characteristic such as pressure, temperature etc. is developed separately along with mathematical equations and bond graph. The subsystems are then combined to form a model of complete system of the engine. According to the author; the two stroke engine is optimized with high power to weight ratio through variation in exhaust system geometry, port shapes, cylinder head etc. [4]. The prime demands of an automobile engineering are engines with low weight, high efficiency and minimum exhaust. A diesel engine needs 30% less fuel due to better thermal efficiency and the lack of throttling losses as compared to the SI engine. The weight reduction has significant impact on fuel consumption of an engine. The small, lightweight and hybrid cars show significant reduction in fuel consumption and exhaust. The fabrication of small combustion system up to bore size 65mm is possible but the same cannot be done about the injection systems [2].

20SIM software is a tool where bond graph model can be built, edited and simulated for various variables and attributes. It is software for modelling and simulation of dynamic behaviour of systems which is also useful in design, analysis and diagnosis of engineering system and uses object-oriented physical system modelling. 20-SIM models are hierarchical structured bond-graphs and block-diagram models [3].

III. SYSTEM MODEL

A. a Crank-slider Mechanism

The simplest mode of operation for determining the engine performance is that of constant engine RPM. The linear velocity of the piston is converted into angular velocity of the crankshaft through connecting rod. The pressure on the other side of the piston varies continuously as a result of combustion and piston motion. This pressure times area is the force acting on crank through connecting rod through piston. The piston motion is assumed to be y direction and x direction is horizontal component. The motion of piston in x direction is zero and motion of piston in y direction is addition of velocity of crank end in y direction and velocity of connecting rod end at piston in y direction. The angular velocity ω of the crank gives the vertical component of the crank end to be r sin θ, and horizontal component is r cos θ. The angle θ is the angle subtended by crank it is calculated by integrating angular velocity ω. Similarly the perpendicular force at the crank end gives torque at the crank.

$$\dot{Y}_{CR}=L_{CR}sin(\theta)\,\omega \qquad (1)$$

$$\tau = F_{CR}\times L_{CR} \qquad (2)$$

These constitutive relations are employed in the BG. This element is similar to the TF function. It has two ports i.e. input and output port. The input port is in mechanical rotational domain and output port is in mechanical linear domain. The input port has having preferred flow out causality parameters. The reciprocated power variable i.e. is torque. The torque is estimated by the force exerted by the combustion on the piston top. The component of this force perpendicular to crank direction times crank length is nothing but the torque.

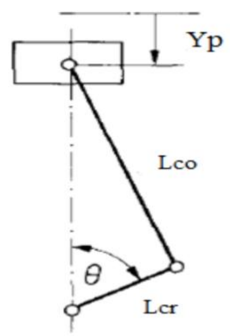

Fig 1. Crank slider mechanism

The linear velocity of crank in y direction theta is angle subtended by crank it is computed by integrating angular velocity. p2.e is the perpendicular force at the crank end and p1.e is the torque at the crank end. The connecting rod subtends an angle φ at the piston pin; the φ is worked out from the geometrical relationship as

$$\varphi = sin\, L_{CR} \sin\theta / L_{CO} \qquad (3)$$

The linear velocity of the connecting rod at the crank end is

$$Y_{CR} = -L_{CR}sin(\Phi)\, d\Phi/dv \qquad (4)$$

The perpendicular force at the crank end is transferred through connecting rod as it is from the piston. Therefore force of connecting rod and that of piston is same. The connecting rod is modelled as single port element. This is because it gives out linear velocity and force across the connecting rod is same. The interface for the port of connecting rod is mechanical linear motion. It works on preferred flow out casualty. The angle phi is input for connecting rod which is in fact a public variable shared with the slider crank mechanism. The bond graph program for the crank-slider mechanism is given below.

B. Single Cylinder Model

The single cylinder model consists of crank-slider mechanism connected to crankshaft. The pressure on the crank-shaft and connecting rod is nothing but pressure times area of the piston. The four strokes of engine consist of two crank-shaft rotations so, the cycle is of 0 to 720 degrees.

```
if theta > 4 * pi then
        theta = theta - 4 * pi;
else
        theta = theta;
end;
```

The theta is varied from 0 to 4 pi and the cycle is repeated.

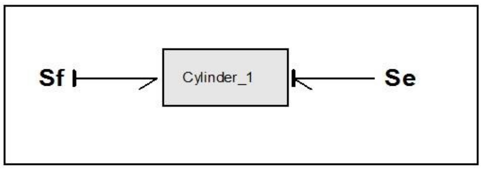

Fig 2 Bond Graph Model.

Fig 2. shows the partially complete single cylinder model where the SF element is constant flow source and has a constant flow out causality. The model works at const RPM so the SF flow is nothing but angular velocity of the crank-shaft. The SE element is constant effort source and has constant effort out causality.

```
phi = (arcsin(CrL*sin(theta)/CoL));
p2.f = CrL * sin(theta) * p1.f + CoL * sin(phi) * ddt(phi);
p1.e = CrL*p2.e;
vdot = piston_area*p2.f;
vol = int(vdot);
v1 = cylinder_vol-vol;
```

The velocity of the piston is given by p2.f and p2.f times the piston area is nothing but rate of change of volume in the cylinder. The swept volume of the cylinder is given as integral of the rate of change of volume. The minimum volume in the cylinder is the clearance volume and maximum volume is the clearance plus swept volume.

```
if theta > 0 and theta < pi then
        compression = true;
        c = 0.655328416;
        p = c/v1^1.4;

else
        compression = false;
        p = 1.013e5;
end;
```

In an initial condition the crank angle theta is 0 degrees which means that piston is at BDC so, the cycle starts from compression stroke. During the compression stroke the pressure varies according to gas law

$$pv^{\gamma} = \qquad (5)$$

First the constant value is calculated at total volume and atmospheric pressure and then this value is used to estimate the pressure inside the cylinder in the compression stroke. The simulation result shows the variation in the pressure in the compression stroke, other stokes are yet to be modelled.

IV. RESULTS & DISCUSSION

The partial model of single cylinder engine is developed. All four cylinders of the engine work with same operation but with phase difference of 180 degrees. The single cylinder model is to be replicated four times with firing order of 1-3-4-2 and phase difference of 180 degrees. Initially the angular velocity of the starter is given as flow which is put-off after 5 cycles. This model is connected to crank-shaft of moment of inertia 0.030251 Kg/m^3 and flywheel.

Fig 3 shows the crank-slider mechanism simulation over 600 RPM, so the cycle is repeated every 0.2sec. The Fig shows the change in the volume of the cylinder. The minimum volume in the simulation is 1.40e-5 m^2 which is clearance volume of the cylinder. The maximum volume of the cylinder is the 0.000196545 m^2 which is total volume of the cylinder.

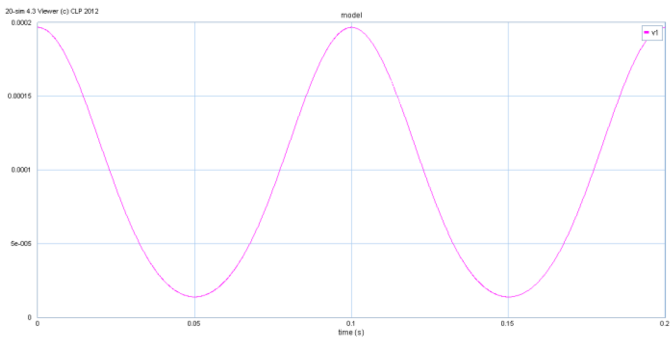

Fig 3. Change in the volume in Cylinder

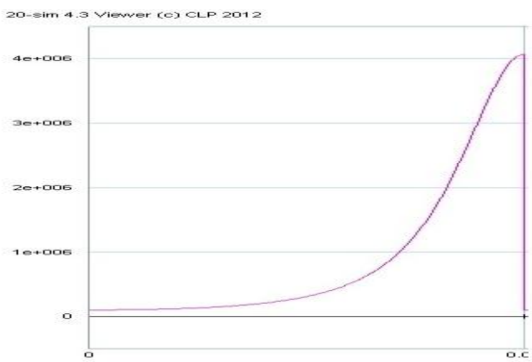

Fig 4. Pressure change in compression stroke

The Fig 4 shows the simulation result of the compression stroke of the single cylinder model. The pressure increases in the cylinder according to the gas law till the piston reaches TDC.

V. CONCLUSION

- Crank-slider mechanism is developed with perfect effort-flow relation and causality.
- Piston displacement, velocity over the cycle is achieved along with change in volume of the cylinder at constant RPM.
- Compression stroke is modelled and simulated for pressure and temperature in the cylinder.

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