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Dynamic Force Analysis of Diesel Engine Crankshaft

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Abstract -- In this paper, dynamic force analysis of diesel engine crankshaft has been studied using theoretical and numerical methods. Crankshaft converts the reciprocating displacement of the piston into a rotary motion of the crank. The objective of this paper is to analyze the forces acting on the crankshaft and compare the theoretical results with SolidWorks Motion results. Dynamic force analysis is the evaluation of input forces or torques and joint forces considering motion of members. Evaluation of the inertia force/torque is explained first. Mechanisms are designed to carry out certain desired work, by producing the specified motion of certain output member. lt is usually required to find the force or torque to be applied on an input member, when one or more forces act on certain output member(s). The external force may be constant or varying through the whole cycle of motion. Calculation of input force or torque over the complete cycle will be needed to determine the power requirement. When the masses and moments of inertia of the members are negligible, static force analysis may be carried out. Otherwise, particularly at high speeds, significant forces or torques will be required to produce linear or angular accelerations of the various members. lt is also required to find the forces at the joints for proper design. Kinematics is the study of motion without regard for the forces that cause the motion. A kinematic mechanism can be driven by a motor so that the position, velocity, and acceleration of each link of the mechanism can be analyzed at any given time. A kinematic analysis is conducted before dynamic force analysis of the mechanism can be simulated properly. The dynamic force analysis of a mechanism is governed by Newton's second laws of motion. The main target of dynamic force analysis is to compute the values of inertia forces
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Indexed Terms -- dynamic force, external force, kinematic, motion, reciprocating

I. INTRODUCTION

Crankshaft is a large component with a complex geometry in the engine, which converts the reciprocating displacement of the piston to a rotary motion with a four link mechanism. Crankshaft must be strong enough to take the downward force of the power stroke without excessive bending. So the reliability and life of the internal combustion engine depend on the strength of the crankshaft largely. In addition, the linear displacement of an engine is not smooth; as the displacement is caused by the combustion chamber therefore the displacement has sudden shocks. The concept of using crankshaft is to change these sudden displacements to as smooth rotary output, which is the input to many devices such as generators, pumps and compressors. It should also be stated that the use of a flywheel helps in smoothing the shocks. Crankshaft experiences large forces from gas combustion. This force is applied to the top of the piston and since the connecting rod connects the piston to the crankshaft, the force will be transmitted to the crankshaft. The crankshaft numerically analyzed in this paper is modeled on the basic of the following specification. Technical Specifications of diesel engine are described as follows.

The compression ratio,	r	= 22
The rated power,	BHP	= 91 hp
The crankshaft speed	n	= 4000 rpm
Number of cylinders,	i	= 4
Calorific heating value,	CV	= 42.5 MJ/kg
The temperature of residual gases,	T_{res}	= 700 K
Displacement volume		= 2184 cm^3
Torque		= 192N-m/2000
Diameter of piston		= 85 mm
Mass of piston and pin		= 0.7184 kg
Mass of connecting rod		= 0.7139 kg
Length of connecting rod		= 140 mm
Mass of flywheel		= 13.98 kg
Bore		= 86 mm
Stroke		= 94 m

The engine assembly consists of a crankshaft, a flywheel, cylinder, piston and connecting rod. The flywheel is mounted on the crankshaft and this crankshaft-flywheel assembly is supported by journal bearings at both ends. All the cylinders are fixed, while the other components are free to move in space. Figure 1 shows four-cylinder crankshaft.

Figure.1 Four-cylinder Crankshaft

Parameters obtained from the thermal calculation of engine are described in Table I.

Table I Calculated Results of Temperatures and Pressures

Parameters	Pressure (MN/m^2)	Temperature (K)
Residual gas	0.12	700
Admission	0.09	319.41
Compression	5.41	858.88
Combustion	9.74	2145
Expansion	0.29	1001.47

II. CALCULATIONS OF DYNAMIC FORCES

To simplify this work, it is assumed that the engine is running at constant crankshaft speed and gravitational force and friction forces can be neglected in comparison to dynamic force effects.

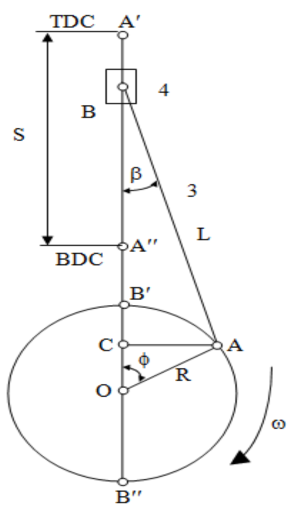

Figure.2 Crank Gear

where,

TDC = Top Dead Center,
BDC = Bottom Dead Center,
ϕ = crank angle,
β = angle between the connecting rod and the cylinder axis,
ω = angular velocity of crankshaft,
S = piston stroke,
L = connecting rod length,
R = crank radius,
λ = ratio between crank radius and connecting rod length

The forces on a crank gear are divided into: the forces of gas pressure in the cylinder, the forces of inertia of the moving parts in the mechanism, and the inertia and centrifugal forces of the rotating parts. The gas pressure can be read from the indicator diagram.

The displacements, velocity and acceleration of the piston are obtained through equations (1) to (6).

$$x = L - \frac{R^2}{4L} + R\left(\cos\phi + \frac{R}{4L}\cos 2\phi\right) \quad (1)$$

$$\lambda = \frac{R}{L} \quad (2)$$

$$v = -R\omega\left[\sin\phi + \frac{\lambda}{2}\sin 2\phi\right] \quad (3)$$

$$a = -R\omega^2\left[\cos\phi + \lambda\cos 2\phi\right] \quad (4)$$

The angular velocity, $\omega = \frac{2\times\pi\times N}{60}$ (5)

Connecting rod angle, $\beta = \sin^{-1}(R \sin\phi / L)$ (6)

The angular velocity of connecting rod can be calculated by using equation (7).

$$\omega_{rod} = \omega \frac{R}{L} \cos\phi \quad (7)$$

The angular acceleration of connecting rod can be calculated by using equation (8).

$$\alpha_{rod} = -\omega^2 \frac{R}{L} \sin\phi \quad (8)$$

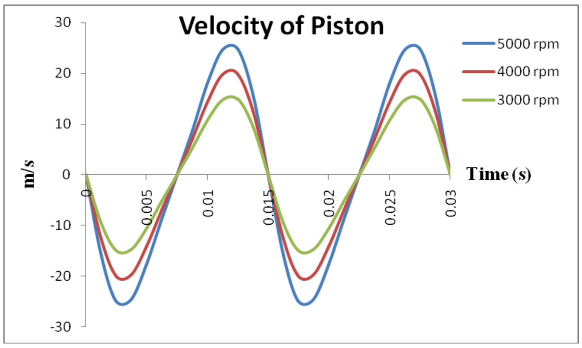

Figure.3 Velocity of Piston at Various Speeds

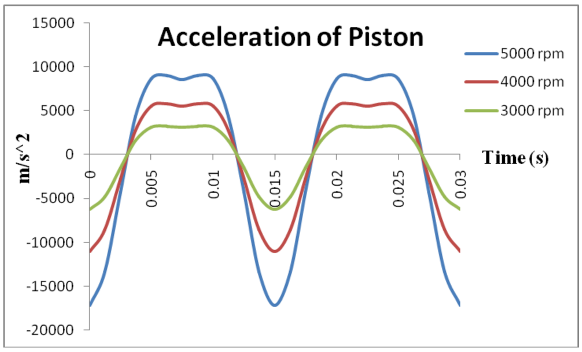

Figure.4 Acceleration of Piston at Various Speed

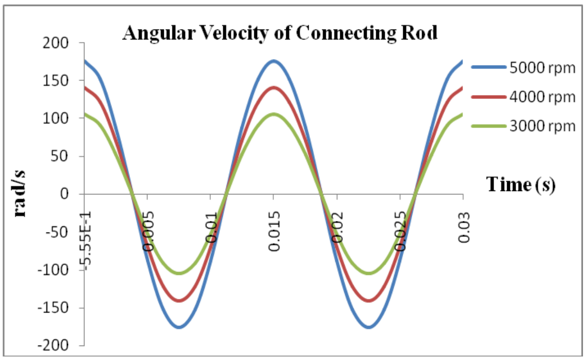

Figure.5 Angular Velocity of Piston at Various Speeds

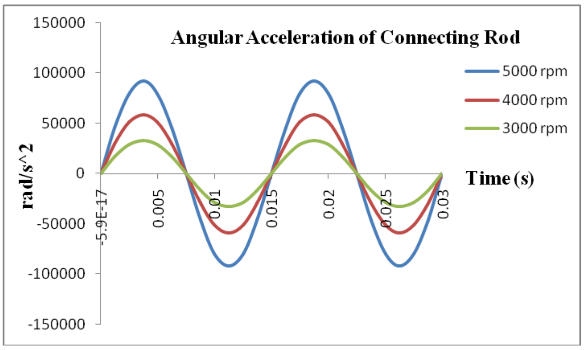

Figure.6 Angular Acceleration of Piston at Various Speeds

In analyzing the inertia forces due to the connecting rod of an engine, it is often convenient to concentrate a portion of the mass at the crankpin A and the remaining portion at the piston pin B as in Figure.7.

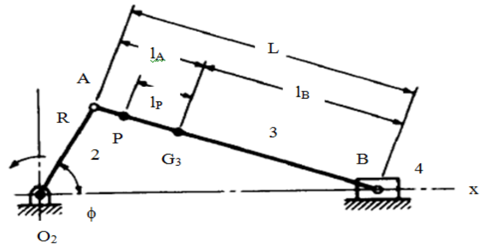

Figure.7 Equivalent Masses for Connecting Rod

Mass of connecting rod at crankpin A,

$$m_{3A} = \frac{m_3 l_B}{L} \tag{9}$$

Mass of connecting rod at piston pin B,

$$m_{3B} = \frac{m_3 l_A}{L} \tag{10}$$

Equivalent mass of crank at the crankpin (point A),

$$m_{2A} = m_2 \frac{r_G}{R} \tag{11}$$

The rotating mass at crankpin (point A),

$$m_A = m_{2A} + m_{3A} \tag{12}$$

The reciprocating mass at piston pin (point B),

$$m_B = m_{3B} + m_4 \tag{13}$$

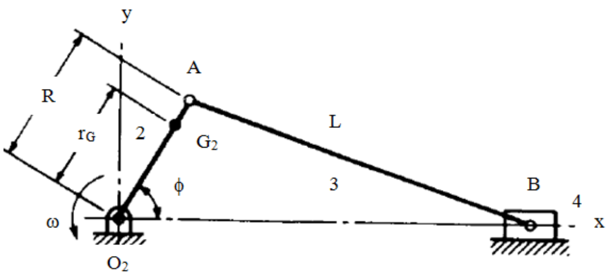

Figure.8 Equivalent Masses for Crank

In the inertia force analysis, simplification is obtained by locating m_{2A} at the crankpin.

$$m_2 r_G = m_{2A} R \tag{14}$$

$$m_{2A} = m_2 \frac{r_G}{R} \tag{15}$$

where,

m_2 = mass of crank,

m_4 = mass of piston,

m_{2A} = equivalent mass of crank at the crankpin,

r_G = distance from the axis of rotation.

The inertia force of rotating parts can be calculated by using equation (16).

$$- m_A a_A = m_A (R\,\alpha \sin\phi + R\,\omega^2 \cos\phi)\,\hat{i} + m_A (-R\,\alpha \cos\phi + R\,\omega^2 \sin\phi)\,\hat{j} \qquad (16)$$

Since the analysis is usually made at constant angular velocity ($\alpha = 0$),

$$-m_A a_A = m_A R\,\omega^2 \cos\phi\,\hat{i} + m_A R\,\omega^2 \sin\phi\,\hat{j} \qquad (17)$$

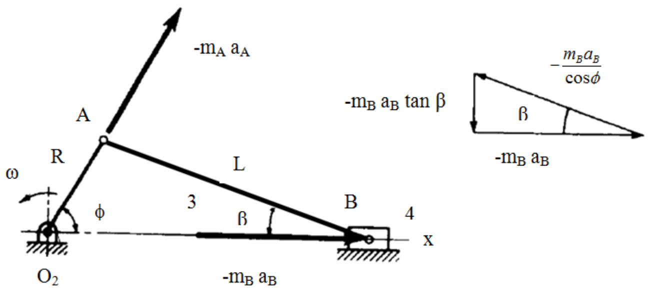

Figure.9 Inertia Forces

The inertia force of reciprocating parts can be calculated by using equation (18).

$$- m_B a_B = m_B R\omega^2 \left[\cos\phi + \frac{R}{L}\cos 2\phi \right] \hat{I} \qquad (18)$$

The total inertia force for all moving parts in the x and y directions can be calculated by the following equations.

$$F^x = (m_A + m_B)\, R\,\omega^2 \cos\phi + \left(m_B \frac{R}{L}\right) R\,\omega^2 \cos 2\phi$$

(19)

$$F^y = m_A R\,\omega^2 \sin\phi \qquad (20)$$

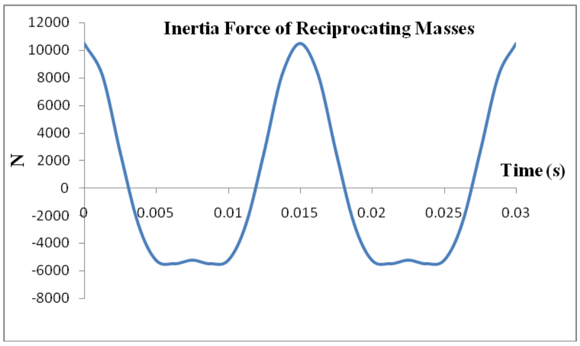

Figure.10 Inertia Forces of Reciprocating Masses at 4000 rpm

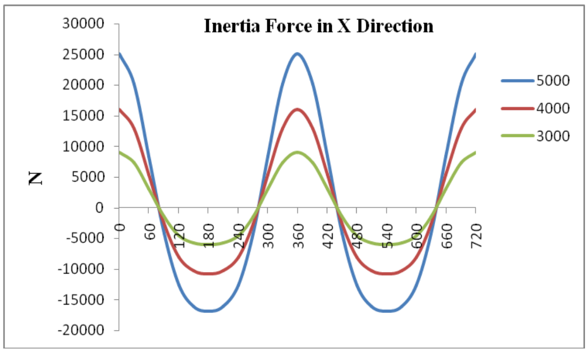

Figure.11 Inertia Force in X Direction

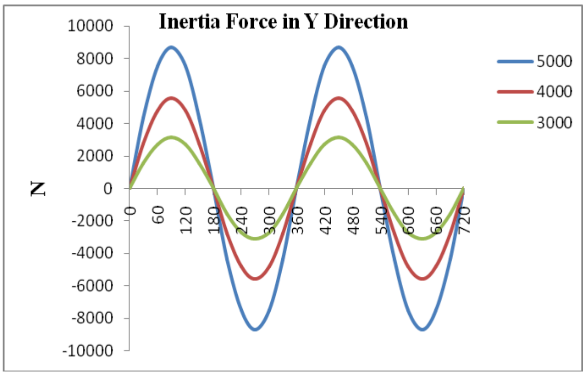

Figure.12 Inertia Force in Y Direction

III. SIMULATION FOR DYNAMIC FORCES

To get the accurate simulation result, the mesh elements have to be fine enough. Figure.13 shows the geometry of four-cylinder crankshaft with the meshing. From the mesh study statement, there are 33 domain elements, 1028 boundary elements, 2156 edge elements and 1250 vertices.

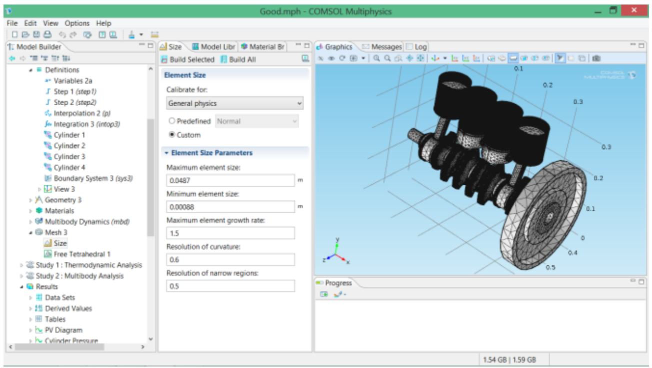

Figure.13 Crankshaft with Meshing

Figure.14 shows the velocity of piston at 4000 rpm. The maximum velocity of piston is 20.77 m/s at 0.0119 s. The minimum velocity of piston is -20.76 m/s at 0.0031 s. The maximum and minimum velocities of piston from the calculated results are 19.91 m/s at 0.0125 s and -19.68 m/s at 0.00375 s and they are shown in Figure 4.1. So, the calculated result and the simulation result are nearly the same in magnitude and direction.

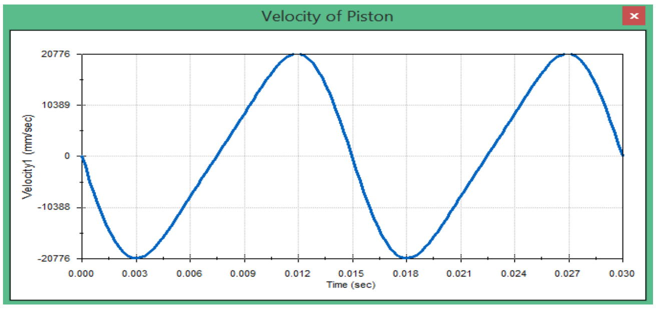

Figure.14 Velocity of Piston

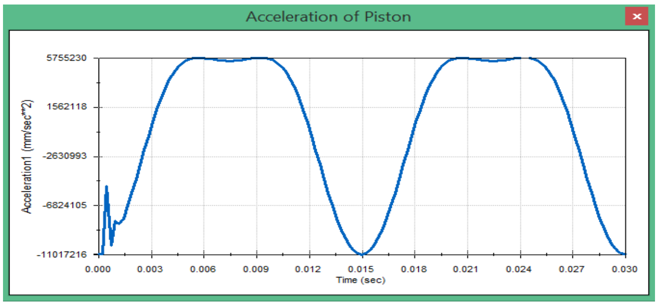

Figure.15 Acceleration of Piston

Figure.15 shows the acceleration of piston at 4000 rpm. In this figure, the maximum acceleration of piston is 5755.22 m/s^2 at 0.0093 s. The minimum acceleration of piston is -11017.21 m/s^2 at 0.015 s. The maximum and minimum acceleration of piston from the calculated results are 5757.51 m/s^2 at 0.00875 s and -11015.10 m/s^2 at 0.015 s and shown in Figure.15. So, the calculated result and the simulation result are nearly the same in magnitude and direction.

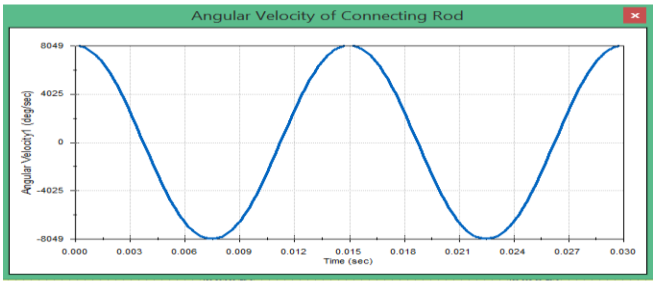

Figure.16 Angular Velocity of Connecting Rod

Figure.16 shows the angular velocity of connecting rod. In this figure, the maximum angular velocity of connecting rod is 8057.14 deg/sec at 0.015 s. The minimum angular velocity of connecting rod is -8048.26 deg/sec at 0.0074 s. The maximum and minimum angular velocities of connecting rod from the calculated results are 8057.14 deg/sec at 0.015 s and -8057.14 deg/sec at 0.0075 s. So, the calculated result and the simulation result are nearly the same in magnitude and direction.

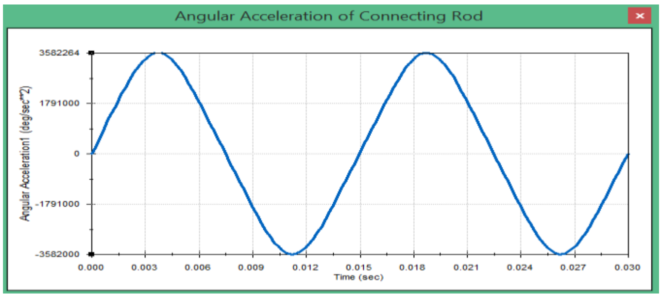

Figure.17 Angular Acceleration of Connecting Rod

Figure.17 shows the angular acceleration of connecting rod. In this figure, the maximum the angular acceleration of connecting rod is 3582264.34 deg/sec^2 at 0.0038 s. The minimum angular acceleration of connecting rod is -3582711.61 deg/sec^2 at 0.0112 s. The maximum and minimum angular acceleration of connecting rod from the calculated results are 3374968.48 deg/sec^2 at 0.00375 s and - 3374968.48 deg/sec^2 at 0.01125 s. So, the calculated result and the simulation result are nearly the same in magnitude and direction.

The main target of dynamic force analysis is to compute the values of inertia forces. The comparison of calculated value and simulation result of inertia forces are shown in Table. II. From this table, we can see that the calculated values of Figure.12 and the simulation results of Figure.18 are nearly the same in magnitude and direction.

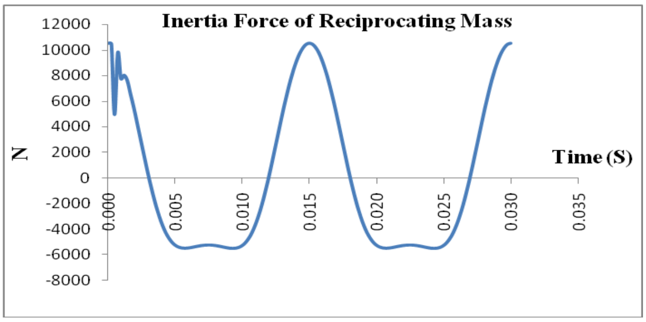

Figure.18 Inertia Force of Reciprocating Masses at 4000 rpm

Table.II Comparison of calculated values and simulation results of inertia force

Time (s)	Inertia Force (N)		% Error
	Theoretical	Numerical	
0	10505.1	10505.11	0
0.0016	6483.26	6534.37	0.78

67			
0.003333	-1115.38	-1265.19	11.84
0.005	-5252.55	-5241.55	0.20
0.006667	-5367.88	-5318.48	0.79
0.008333	-5367.88	-5325.17	0.79
0.01	-5252.55	-5256.83	0.08
0.011667	-1115.38	-1247.11	10.56
0.013333	6483.26	6585.41	1.55
0.015	10505.1	10507.12	0.01
0.016667	6483.26	6561.79	1.19
0.018333	-1115.38	-1265.19	10.97
0.02	-5252.55	-5241.55	0.20
0.021667	-5367.88	-5318.48	0.79
0.023333	-5367.88	-5325.17	0.79
0.025	-5252.55	-5256.83	0.08
0.026667	-1115.38	-1247.11	10.56

IV. CONCLUSION AND DISCUSSION

This study is the dynamic force analysis of four-cylinder crankshaft, intended for computing of velocities, accelerations, inertia forces and torques. Numerical and theoretical investigations are carried out on a four-cylinder diesel engine. All the components of the engine are assumed to be rigid. The fluctuations in the engine output torque are caused by the different strokes in a cycle, namely, compression stroke, combustion, and power stroke. For further research, experimental study will be conducted to validate the simulation results for the mentioned parameters.

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