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Technical note

ANALYSIS OF PISTON SLAP MOTION

S. NARAYAN
Department of Mechanical Engineering
Indus International University
Una-Himachal Pradesh-174301, INDIA
E-mail: rarekv@gmail.com

Piston slap is the major force contibuting towards noise levels in combustion engines.This type of noise depends upon a number of factors such as the piston-liner gap, type of lubricant used, number of piston pins as well as geometry of the piston. In this work the lateral and rotary motion of the piston in the gap between the cylinder liner and piston has been analyzed. A model that can predict the forces and response of the engine block due to slap has been dicussed. The parameters such as mass, spring and damping constant have been predicted using a vibrational mobility model.

Key words: piston slap, noise, engine acoustics.

1. Introduction

One of the major sources of noise in engines is the impact of the piston on cylinder liner walls. The crank slider mechanism in an engine has a small gap between the piston and liner which causes secondary motion of the piston generating periodic noise. The secondary motion of the piston is due to side thrust force induced by the connecting rod as a result of which the piston moves from one side to the opposite one colliding with the walls. This can be understood from Fig.1 (Cho *et al*., 2002).

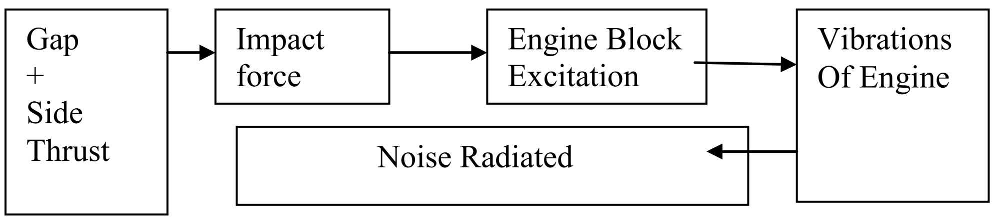

Fig.1. Generation of Piston Slap Noise.

Several models have been used earlier to understand the basics of piston motion (Unger and Ross, 1965). The Finite Element Analysis (FEA) has been used to predict the impact forces (Ohta *et al*., 1987). In this work the dynamic motion of the piston has been described and used to predict the impact force. The vibration response of the engine has been predicted using impact forces and response between the walls and engine block.

Piston motion is affected by piston geometry, bore size and lubricant used as evident from Fig.3.

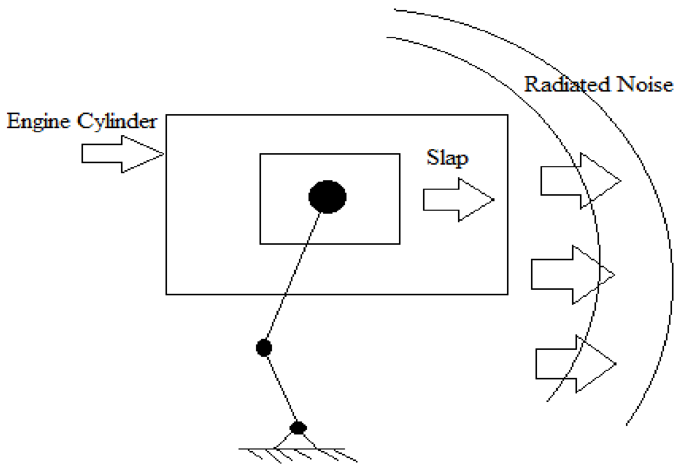

Fig.2. Occurrence of piston slap.

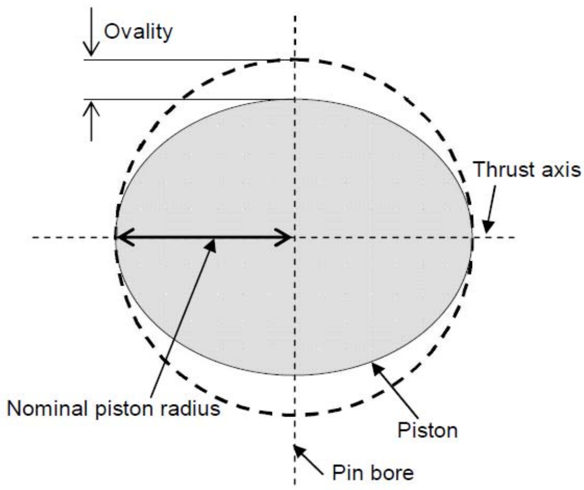

Fig.3. Ovality of piston.

Deformation of the piston skirt also occurs due to hydrodynamic pressure generated by oil between the bore and skirt as evident from Fig.4. The governing equation of pressure generated is Reynolds Equation represented by Eq.(1.1) (Nakada, 1997).

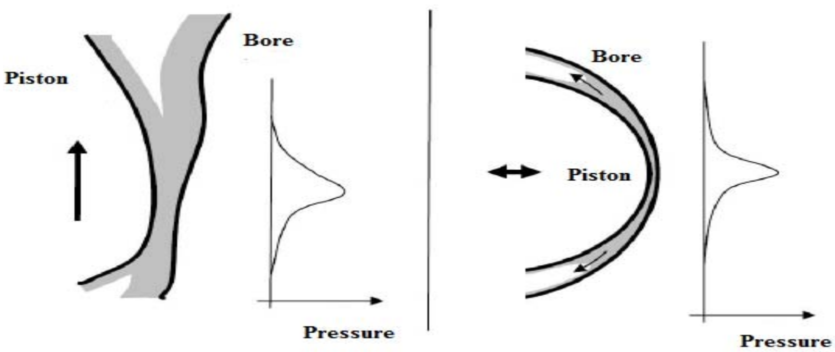

Fig.4. Piston skirt deformation.

Reynolds equation

$$\text{Grad}\left(\frac{\rho h^3}{12\mu}\frac{dp}{dx}\right)+\text{Grad}\left(\frac{\rho h^3}{12\mu}\frac{dp}{dz}\right)=\frac{d(\rho h)}{dt}+\frac{d(\rho hc/2)}{dz}. \tag{1.1}$$

Theoretically, maximum four slaps are possible during an engine cycle, however up to 16 slaps have been found in reality (Ewins, 1986). Ohta *et al.* has presented mathematical model to study the piston slap forces (Ohta *et al*., 1987). There are several factors effecting slap motion, primary of which includes the gap between the liner and skirt (João, 1995). Oil viscosity, surface tension, tension in piston rings also affects this force (Slack, 1982). Piston slap can be measured by studying the piston profile as seen in Yawata and Crocker (1983), de Luca and Gerges (1996), Chen and Randell (2012).

2. Dynamic models

Figure 5 describes the motion of the piston along the *X* and *Y* axis as well as rotary motion around the gudgeon pin. The impact (Fs) occurs when the skirt comes in contact with the walls. These models have been discussed in more detail in Cho *et al*. (2002).

The piston moves in vertical, lateral and rotational directions. Let *Xp*, *Yp* and θ denote the piston motion along the *X* axis, *Y* axis and rotary motion of the piston (Cho *et al*., 2002).

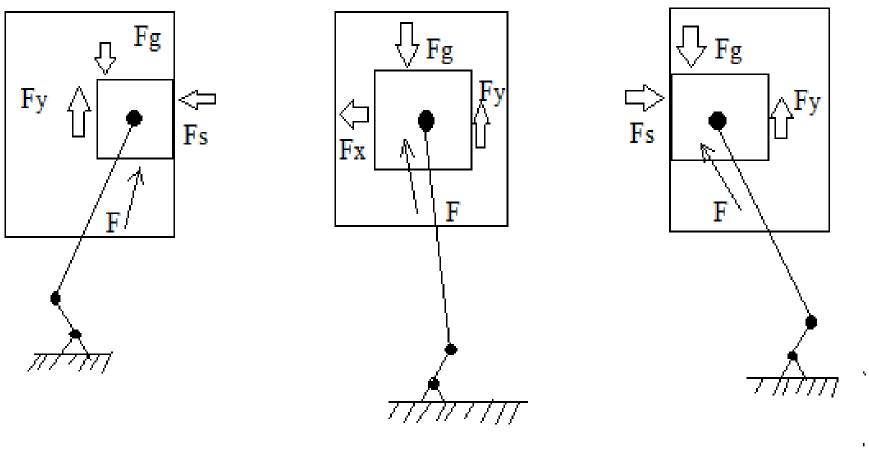

Fig.5. Piston motion.

The piston strikes the cylinder liner at four contact points A, B, C, D as can be seen in Fig.6. The offset distance (*S*) as seen in Fig.7 can be expressed as

$$S=\sqrt{L_X^2+L_Y^2}\ , \tag{2.1}$$

$$\text{Cos}(\psi)=L_y\Big/\sqrt{L_X^2+L_Y^2}\ . \tag{2.2}$$

Various equations of motion can be expressed in the form of

$$F_x = m_p\left[X_p'' + S\theta''\cos(\psi+\theta) - \theta'^2\sin(\psi+\theta)\right] = F_a + F_b + A_x - F_c - F_d\,, \tag{2.3}$$

$$F_y = m_p\left[Y_p'' - S\theta''\sin(\psi+\theta) + \theta'^2\cos(\psi+\theta)\right] = -m_p g - F_g - F_{friction} - A_y\,, \tag{2.4}$$

$$\begin{aligned} J\theta'' &= F_a L_a + F_d L_d - F_b L_b - F_c L_c - T_{friction} + \\ &-m_p g S\sin(\psi+\theta) + F_g\left(X_b - X\right) + m_p X_p'' L_y - m_p Y_p'' L_x. \end{aligned} \tag{2.5}$$

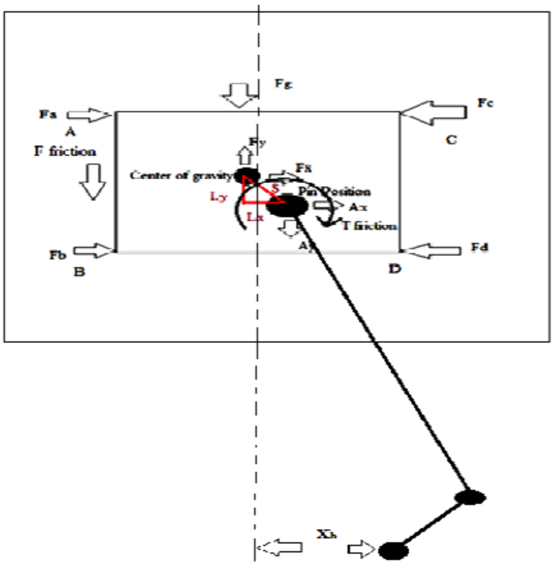

Fig.6. Free body motion of piston.

3. Analytical models

Mobility is defined as the ratio of velocity to a force. This parameter can be used to estimate the mass, spring and damping constants of a lumped system (Yawata and Crocker, 1983). The point mobility between the skirt and cylinder wall can be written as

$$M(j\omega) = \frac{-j\omega\left[\left(k - m\omega^2\right) + j\omega c\right]}{m\omega^2\left(k + j\omega c\right)}. \tag{3.1}$$

Figure 6 shows the lumped model of impact for which equations of motion can be written as

$$F_i = C_s\left(Z_2' - Z_1'\right) + K_s\left(Z_2 - Z_1\right) \qquad \text{\{when slap occurs\}} \tag{3.2}$$

$$F_i = C_o\left(Z_2' - Z_1'\right) \qquad \text{\{no slap\}} \tag{3.3}$$

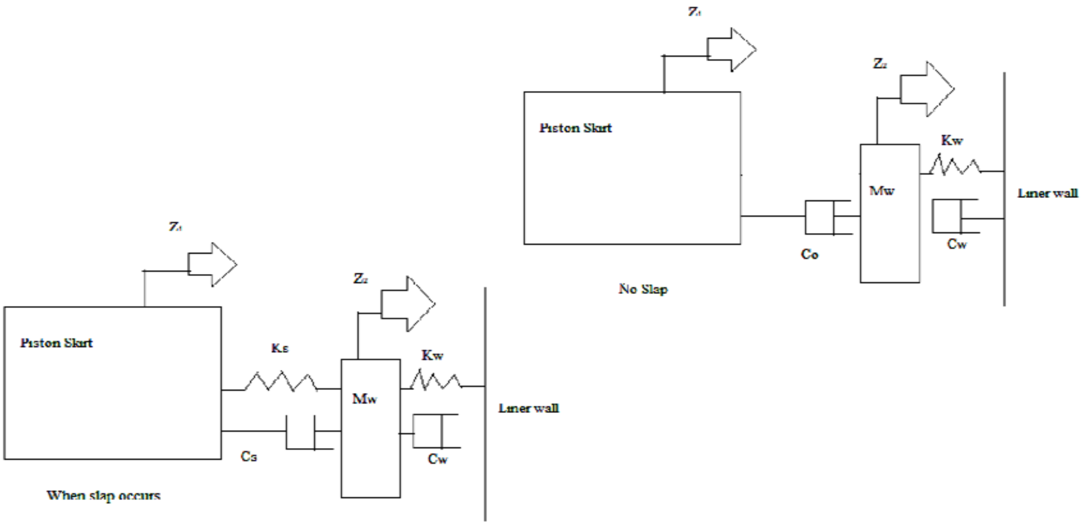

Fig.7. Lumped impact model.

Figure 7 shows the actual motion of the piston in a cylinder at instances when slap occurs. As evident from this figure, slap occurs at least four times in a cycle.

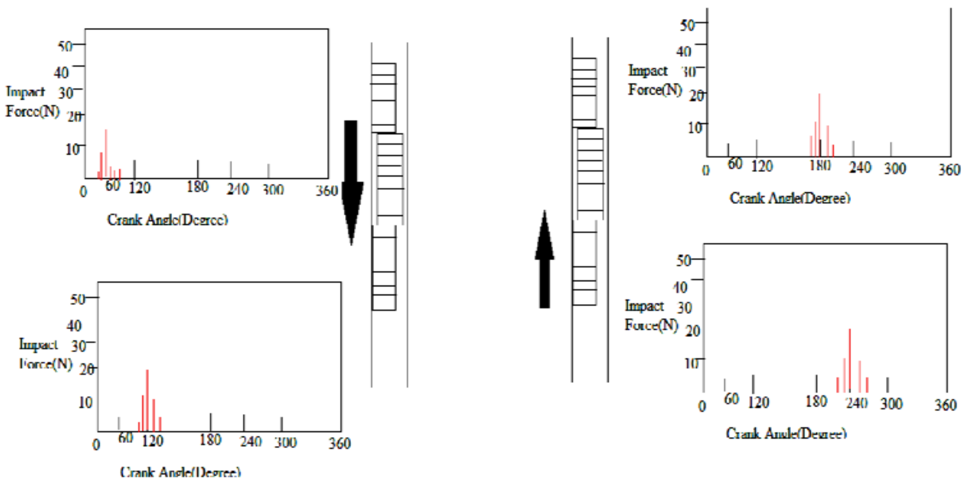

Fig.8. Simulated piston motion.

Equations (3.1), (3.2), (3.3) can be used to estimate impact forces on each piston skirt, once these have been calculated, numerical integration methods e.g., the Runge-Kutta method can be used to locate the coordinates of the center of gravity of the piston.

3. Conclusions

This work proposes a model to estimate the impact forces due to slapping motion of the piston. The skirt and cylinder walls can be modeled as a one degree of freedom vibrating system. On occurrence of collision this system becomes a two degree of freedom system which can be considered as a combination of one degree of freedom models of both the skirt and cylinder walls.

Nomenclature

A_x ,A_y – reaction force components of connecting rod
F_a, F_b, F_c, F_d – contact force at four points
F_g – gas force
F_x, F_y – reaction forces along X, Y axis
L_a, L_b, L_c, L_d – distance between piston pin and contact point
m_p – mass of piston
X_b – bore offset
X''_p – acceleration along X -axis
Y''_p – acceleration along Y-axis
Z_1 – displacement of piston skirt
Z_2 – displacement of cylinder wall

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