Module 5 : Turning Moment Diagram for Engines and Speed Fluctuation; Power Smoothening by Flywheels.
Lecture 8 : Turning Moment Diagram for Engines and Speed Fluctuation; Power Smoothening by Flywheels.

Objectives

In this module, you will learn the following

- The driving torque generated in an IC Engine due to gas forces
- Issues in Matching of driving and load torques
- Use of flywheels to smoothen the fluctuations in speed within a cycle

Consider a typical four stroke IC Engine. The internal pressure as a function of crank angle is as shown in Fig. 5.1. In a four stroke engine, the four strokes are identified as suction, compression, power and exhaust. Power due to combustion is actually generated ONLY in one of the four strokes and hence the resulting torque on the crank shaft will also fluctuate in a similar manner. We shall now attempt to derive an expression for the gas torque.

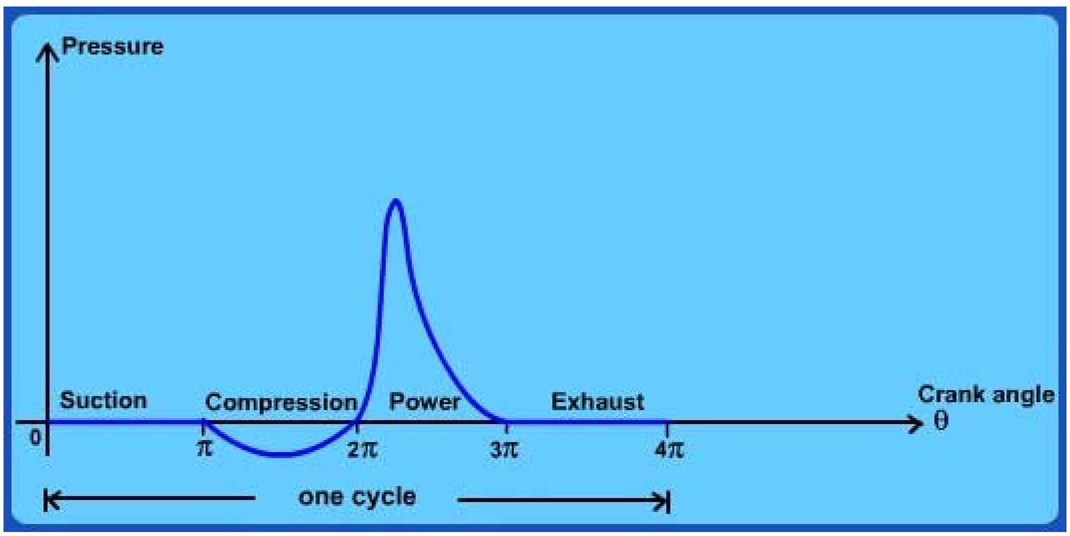

Figure 5.1. Typical Pressure Vs Crank angle for a four stroke engine

For the purpose of gas torque analysis, let us assume for the time being that all the links have negligible mass and ignore any inertia force affects. Of course some of the gas torque will have to be used to overcome the inertia of the moving parts. From the free body diagram shown in Fig. 5.2 and the considerations of static equilibrium, we find that the normal force on the cylinder frame at the piston is given by:

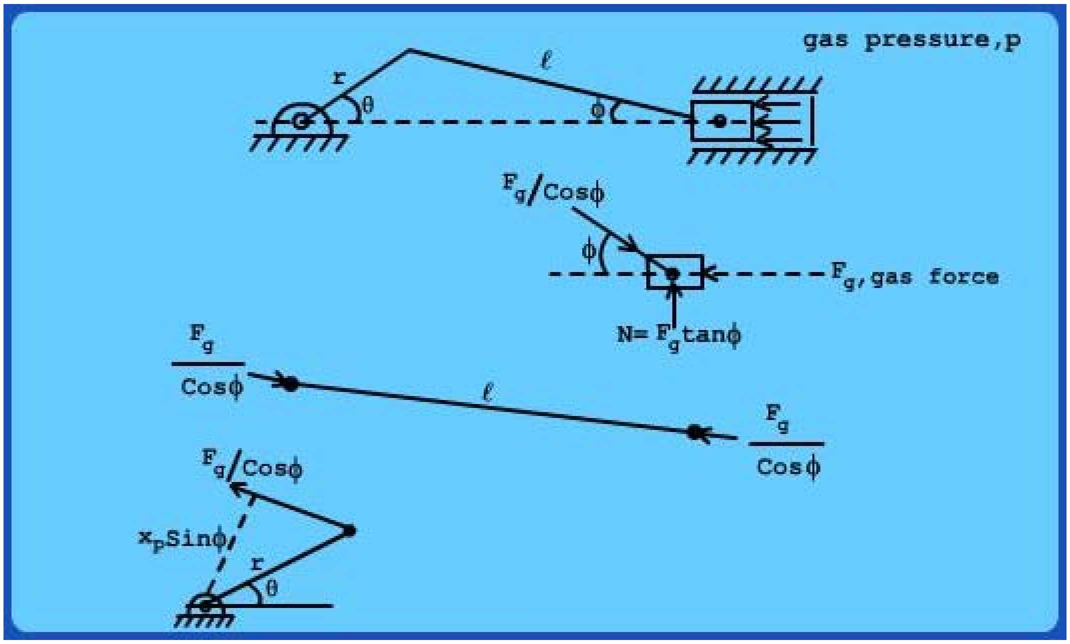

Figure 5.2 Free Body Diagram for gas Pressure loading

$$N = F_g \tan \phi \qquad (5.1)$$

Similarly the force transmitted through the connecting rod is given by:

$$F_{CR} = \frac{F_g}{Cos\ \phi} \qquad (5.2)$$

Taking moment of this force on the crankshaft pivot, we get the gas torque as:

$$T_g = \left(\frac{F_g}{Cos\ \phi}\right)(x_p\ Sin\ \phi) = F_g \tan \phi \qquad (5.3)$$

From the geometry of the IC Engine mechanism, we can write

$$\tan \phi = \frac{r\ Sin\theta}{\ell\left(\sqrt{1-\left(\frac{r}{\ell}\right)^2 Sin^2\theta}\right)} \qquad (5.4)$$

Thus the gas torque varies as a complex function of time (since $\theta = \Omega t$, where Ω is the speed of rotation).

When an IC engine is used as a prime mover, the driving torque available at the crank shaft may not in general match the load torque demanded from instant to instant. For example, if the load torque is uniform with respect to time, the load and driving torque will have same value in an average (or mean) sense as shown in Fig. 5.3 but won't match at every instant of time. For steady state operation, it is required that over a cycle average torques match. In other words we can say:

$$\oint T_g\, d\theta = \oint T_L\, d\theta \qquad (5.6)$$

If on an average, the load torque over each cycle is more than the supply torque, system will soon come to a halt.

If on an average, the load torque over each cycle is less than the supply torque, system speed will keep increasing indefinitely.

If on an average, the load torque over each cycle is equal to the supply torque, system will operate in a steady state.

However even if the average torques match, in the portion of the cycle when the load torque is instantaneously smaller than driving torque, there will be instantaneous acceleration of the crank shaft. When the load torque momentarily exceeds the driving torque available, crank shaft will decelerate. Thus even though the crankshaft has a “steady” speed of rotation, there will be small fluctuations in speed within each cycle as shown in Fig. 5.4. At steady state, the same cycle will of course repeat itself. We wish to minimize the speed fluctuations, to the extent possible. This is achieved through the addition of a flywheel to the system shaft as shown in Fig. 5.5.

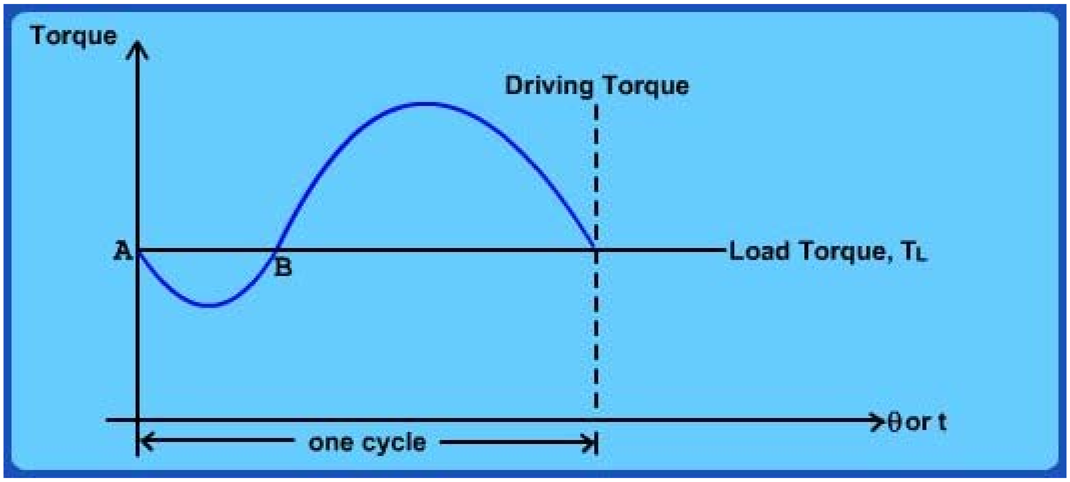

Figure 5.3 Typical torque of prime mover & load

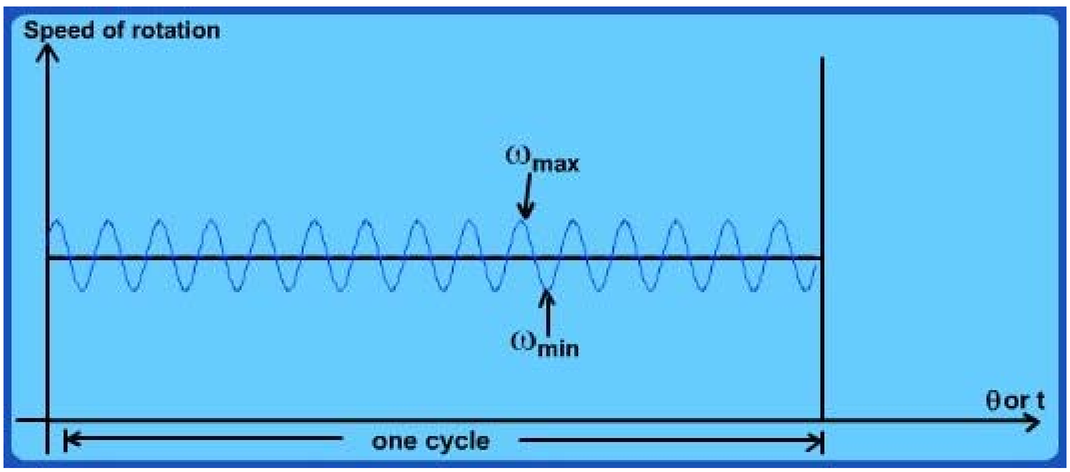

Figure 5.4. Fluctuation in Speed of Rotation within a cycle

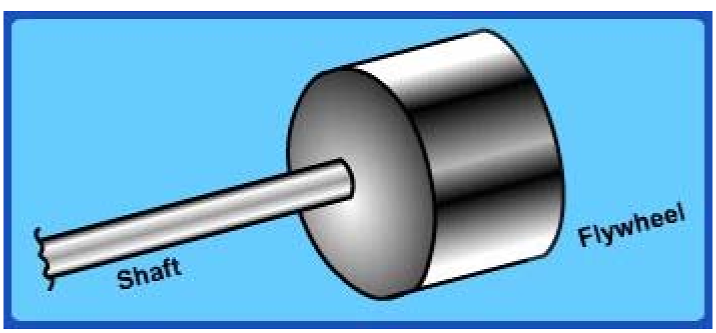

Fig 5.5 Typical shaft-flywheel

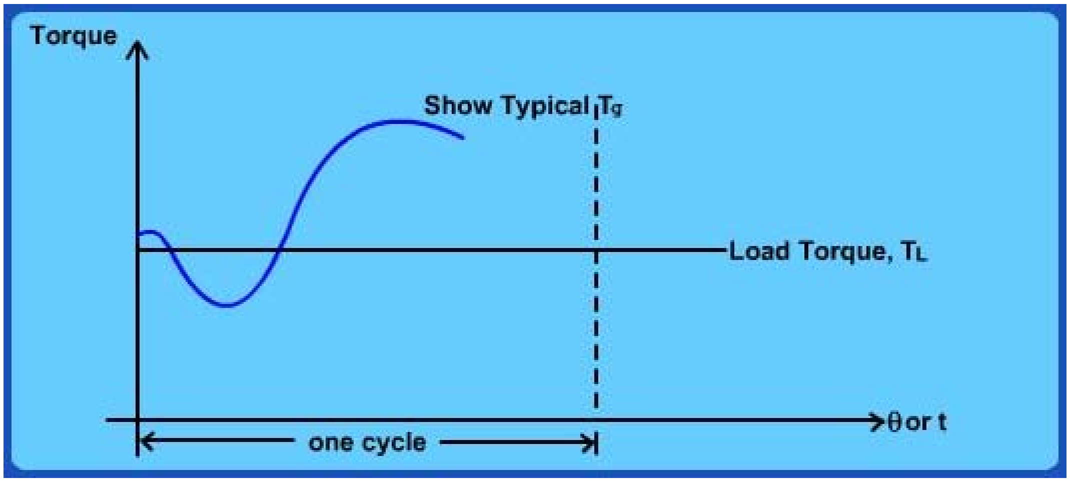

Fig 5.6 Supply and load torque Representative

Let us look at Fig. 5.6 which is a general representation of load and supply torques over a cycle and investigate the dynamics of the system. From point A to B in the cycle, the load torque exceeds the available torque. So the shaft speed falls from A to B. During B-C, the load torque will further slow down the shaft making point C perhaps the minimum speed point. During C-D, the system gains in speed as the supply torque is much more than the load torque. During D-E, the system again slows down gradually coming back to the speed at A (beginning of cycle). Thus we could identify the points in the cycle that correspond to the maximum and minimum speed and write the following energy balance equation:

$$\int_{\theta_1}^{\theta_2} \left(T_g - T_L\right) d\theta = \frac{1}{2} J \left(\omega_{\max}^2 - \omega_{\min}^2\right) \tag{5.6}$$

where θ_1, θ_2 correspond to the points of maximum and minimum speeds and J is the mass moment of inertia of the system including crank shaft, other rotating parts along with flywheel. Assuming that the speed fluctuation is actually quite small after the installation of a flywheel, we could approximately write:

$$\omega_{avg} = \frac{\omega_{\max} + \omega_{\min}}{2} \tag{5.7}$$

If we define a coefficient of fluctuation of speed k_s as:

$$k_s = \frac{\omega_{\max} - \omega_{\min}}{\omega_{avg}} \tag{5.8}$$

We can re-write eq. (5.6) as:

$$\int_{\theta_1}^{\theta_2} \left(T_g - T_L\right) d\theta = J\, k_s \left(\omega_{avg}^2\right) \tag{5.9}$$

In order to simplify our calculations, we could further assume that the mass moment of inertia of the flywheel (J_f) is perhaps much larger than that of the other rotating parts and hence simply take $J \approx J_f$.

Therefore given the supply torque from the prime mover (say an IC Engine, electric motor etc) and the load torque, we can size the flywheel required to ensure that the fluctuation in speed will remain within the desired limits (as prescribed by k_s). It must be noted that by taking $J \approx J_f$ in the above calculation, we would have overestimated the flywheel size somewhat or in other words, the actual fluctuation in speed will be even smaller than demanded. Thus we see that a flywheel acts similar to a reservoir in a fluid line which tries to maintain pressure fluctuations within limits.

A typical flywheel would appear as shown in Fig. 5.7 wherein more material is kept towards the outer radius so as to get maximum moment of inertia. For designing the cross-section of the spokes etc. it is important to realize that the maximum stress would occur towards the root – at any section the internal resisting force developed is the force required to keep the material from flying away. Thus as we go from tip to the root, more and more material tries to fly away at great speed and therefore greater and greater force is required to be developed internally between the sections towards the root.

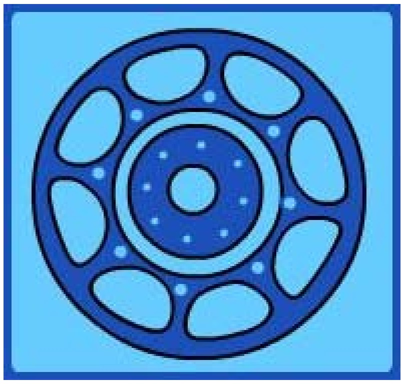

Fig. 5.7 Typical flywheel

A few issues are left for you to think further about viz.,

Is there an upper limit on the inertia of the flywheel – obviously the bigger the wheel, the lesser will be the fluctuations in speed?

Typically we have a transmission unit between the prime mover and the load, in the form of a speed reducer gear box. Which side of the gear box will you keep the flywheel and why?

Recap

In this module you have learnt the following

- Issues in Matching driving and load torques
- Role of a flywheel in a drive
- Estimation of size of flywheel required to keep the speed fluctuations within a specified limit