Lecture 16

3rd Semester M Tech. Mechanical Systems Design

Mechanical Engineering Department

Subject: Advanced Engine Design

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Lecture 15 – Balancing of Mechanical Forces in I C Engines
Topic: Balancing the forces in multi-cylinder engines - 20-10-2020

In-Line 4-Cylinder Engine.

The in-line 4-cylinder engine has been considered in previous lectures concerning with the following:

1. Rotating forces
2. Reciprocating forces

It was shown that rotating forces create opposing dynamic couples that cancel one another out but result in internal crankshaft deflection and bearing wear.
Counterweights are used to eliminate the internal couples.
The primary reciprocating forces are balanced, but there is an inherent second-order imbalance that was explained.
The symmetric relationship between the cylinders results in balanced reciprocating moments - both first-order and second-order.
In most 4-cylinder engines the second-order force imbalance is accepted, and the mounts are designed to minimize its transmission to the vehicle.
In order to eliminate the second order imbalance counter-rotating balance shafts are sometimes used.
Two shafts are located at the same height in the block and are driven such they spin in opposite directions at twice engine speed.
Each shaft contains an equal off centered mass that generates a centrifugal force.
Because the shafts are counter rotating, the horizontal components cancel out each other.
But the vertical forces vertical components add.
They are sized such that the vertical forces add to exactly cancel the second-order forces generated by the piston assemblies.

Gas Pressure Forces:

Another important category of forces acting internally on the engine is that due to gas pressure within each cylinder. The in-cylinder pressure varies continuously with crank angle, reaching its peak shortly after TC during combustion. **These forces cannot be balanced**, and the **engine mounts are designed to minimize their transmission into the vehicle.**
In a **four stroke cycle engine** the **force generated at each cylinder** goes through a complete cycle every two revolutions **and is thus half order.**
If all of the **cylinders** in a **multi-cylinder engine** contribute equally and the spacing between combustion events is equal, the **resulting vibration order** generated by the **pressure force** is **one half the number of cylinders**.

1 Cylinder 4S Cycle Engine Forces and Force Balance					
Balancing of rotary forces		Balancing of Reciprocating forces		Balancing of gas pressure forces	
Rotary mass, m	**One**, Crank with big end of connecting rod	**Reciprocating mass**, Mp	**One**, Piston with rings, piston pin and small end bearing of connecting rod	Gas – **air fuel mixture** - combustion	A **single** air-fuel mixture
Rotary force	One $F_C = m\omega^2 r$	Reciprocating force	One	Gas pressure force	One
Frequency of force , number of such forces in one revolution of crankshaft	One only - acts radially outwards and changes its direction continuously	Frequency of force, number of such forces in one revolution of crankshaft	One only, but its direction is from TC to BC for 180 degree of crank angle and from BC to TC for next 180 degree of crank angle	Frequency of force, number of such forces per revolution or 2 revolutions of crankshaft	Once in two revolutions of crankshaft, but its direction is from gas to piston or from piston to gas as verified by P-V diagram
Order of Force	First order force	Order of Force	First order, second order, and other higher orders	Order of Force	Half order force
Order of vibration	First order vibration	Order of Vibration	First order vibration, second order and other higher orders	Order of vibration	Half order vibration
Method of balancing the force	A pair of counter weights at crank shaft	Method of balancing the force	The second order force is balanced by using two counter rotating shafts in the cylinder block. Each shaft contains an equal off centered mass that generates a centrifugal force.	Method of balancing the force	Its radial component at crankshaft cannot be balanced – the main bearing blocks supporting the crank shaft transfer these forces to engine mounts.

Multi-Cylinder Engine Design:

Multi-cylinder engine design versus single cylinder engine design.

1. **From the above table and the previous lectures, it is clear that in order to reduce the centrifugal force based load on main bearings we use counter weights.**
2. **Further a many orders of piston based reciprocating forces remain unbalanced for any engine design for any number of cylinders.**
3. **Moreover the combustion based gas pressure forces are never balanced in any engine design.**

For heavy duty application, the magnitude of the counter weights, the magnitude of the unbalanced reciprocating forces and the magnitude of the gas pressure force will be much higher for lower number of cylinders.
In the first point of our discussion, we said that the more number of cylinders will increase the cost and also make the system more complex.
The unbalanced forces with higher magnitudes will finally get transmitted to the vehicle through engine mounts, chassis and suspension. The heavy duty engine based forces will cause the engine system and the vehicle to vibrate with large amplitudes at frequencies as per the terms in the equations for the forces generated in an engine.
This compels us to go for the design of a multi-cylinder engine in order to make the engine and vehicle design commercially acceptable.

Example:

Heavy duty engine design:

The unbalanced first order forces and second order forces will be of large magnitude if a single cylinder engine is used. These unbalanced forces will vibrate the vehicle with larger amplitudes.
It should be preferable to design the suspension and chassis of the vehicle for vibration with smaller amplitudes by going towards a multi-cylinder engine design, as it will decrease the magnitude of forces accordingly.

Further a single cylinder engine design for medium or heavy duty will need a very large flywheel to control the fluctuation of energy available at crankshaft.

A large fly wheel based engine design is simply unacceptable commercially.
A multi-cylinder engine design based small flywheel makes the system more acceptable.

Further the number of cylinders in an engine design and its corresponding crankshaft design should be chosen such that the forces are generated in the engine preferably in one plane or lower number of planes. This will make the task of force balance more simple.

The magnitude of unbalanced gas pressure forces gets reduced for a multi-cylinder engine design by a factor of the number of cylinders being used. These gas pressure forces will get generated at regular intervals, as per the firing order, along the length of the crankshaft.

This will make the corresponding design and selection of the components of the suspension and chassis of the vehicle more economical.
This will increase the frequency but decrease the amplitude of vibration of the components of suspension and chassis of the vehicle.

For example:

An inline 4 cylinder engine can be designed with a crankshaft resulting in force generation and therefore force balance in one plane only.
This type of engine and crankshaft design has all its 4 cranks in one plane with 2 cranks facing upwards and other 2 cranks facing downwards at an angle of 180 degrees.
This type of engine and crankshaft design, further makes it possible to balance a more number of the forces automatically than otherwise.
Further the production and manufacturing cost of a component designed for one plane should be lower than the cost of same component designed for more than one number of planes.
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So a 4 cylinder inline engine design is highly successful commercially
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Text Book:
Vehicular Engine Design
By Kevin L. Hoag
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