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Design and Concept of Single Cylinder Test Engine Modular Balancing System

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Abstract—*The term single cylinder test engine describes a variety of power units used for development activities in many areas of engine research and development with very specific requirements. It is crucial for automotive industries to primarily focus on the initial combustion process design during pre-production development for new engine development activities. The initial virtual developments of new engines are complemented by test bench runs with single cylinder test engines. Single cylinder versions of multi-cylinder production engines are used world-wide to reduce testing costs, minimize testing times and carry out high performance quality research. This paper presents the design and concept development of the modular balancing system of single cylinder versions of multi-cylinder production engine for heavy duty applications. The balancer shaft has to be modular in nature so as to allow its use for various sizes of bores and strokes which will be tested on the test engine. This paper explains the strategy of development of concept design of 1st order and 2nd order balancer shafts for test engines.*

1. INTRODUCTION

The research work is been carried out to design and develop balancing system of a single cylinder test engine for heavy duty application. These test engines are used for combustion and charge motion development in terms of fuel consumption, emissions, fuel properties and fuel quality for different stroke and bore. In addition to this, following are some more application areas where these engines are used.

- Flow visualization and combustion research activity (flame visualization and flame spectroscopy)
- Fuel and lubrication oil industry
- Friction measurement in between piston and liner
- Combustion with alternative fuel
- To test injection system, valve train, combustion chamber geometry, cam phasing
- After treatment testing
- Air motion studies

The imbalance forces in single cylinder engine are the results of inertia forces during reciprocating motion of piston assembly in engine. These imbalance forces cause vibrations in the engine which are not desirable from test engine point of view. As the vibrations can interrupt the test environment for the various tests which are carried out on such engines; hence, it is important to employ suitable balancing system to isolate the test environment from any vibration sources. These test engines have to be completely balanced so as to attain favourable test conditions for the combustion development activities. Various bore-stroke combinations has to be tested on such test engines, hence, it is of utmost importance to design such balancer shafts which should allow sufficient modifications so as to balance inertia forces for various combinations.

Reciprocating engines majorly used as power plant for the passenger vehicles over the years. Depending upon the engine type and configuration they result external forces and moments in engine which, in turn, leads to vibration and noise in vehicles itself. Hence balancing plays a vital role in modern vehicles as vibration originated from engine and which largely affecting ride comfort. These vibrations also affect other vehicle subsystems like transmission and whole body structure ultimately affecting performance of vehicle and occupants ride perception respectively.

2. MODULAR BALANCER SHAFTS CONCEPT DESIGN

Before designing the balancer shafts for the single cylinder test engine, it was necessary to account the sources of imbalance inertia forces majorly contributed by the reciprocating motion of piston assembly inside the cylinder and rocking motion of connecting rod during the operation of engine. The mass of piston assembly and some portion of mass of connecting rod are responsible for the imbalance forces generated due to reciprocating motion during operation. In principle, the total imbalance forces can be accounted by using the following equation.

$$F = m \times r \times \omega^2 \times cos\theta \pm m \times r \times \omega^2 \times \frac{cos2\theta}{n}$$

Where,
m- Reciprocating mass contributing in imbalance

r- Crank throw
θ- Crank angle movement from TDC
ω- Crank angular velocity
n- Crankshaft speed

In the above equation, the term $m \times r \times \omega^2 \times \cos\theta$ represents first order (primary) inertia forces. The primary inertia force is the force produced by the piston mass due to the rotating crankpin along the line of stroke being relayed to the piston via connecting rod. i.e, first order inertia forces are the forces which reach to their maximum value twice per revolution at θ=0° and 180°.

While the other term $m \times r \times \omega^2 \times (\cos 2\theta / n)$ represents second order (secondary) inertia forces. It is produced by the piston mass due to the rotating crankpin outward and inward projected movement perpendicular to the piston via the inclined connecting rod. i.e, second order inertia forces are the forces which reach to their maximum value four times per revolution at θ= 0°, 90°, 180° and 270°.

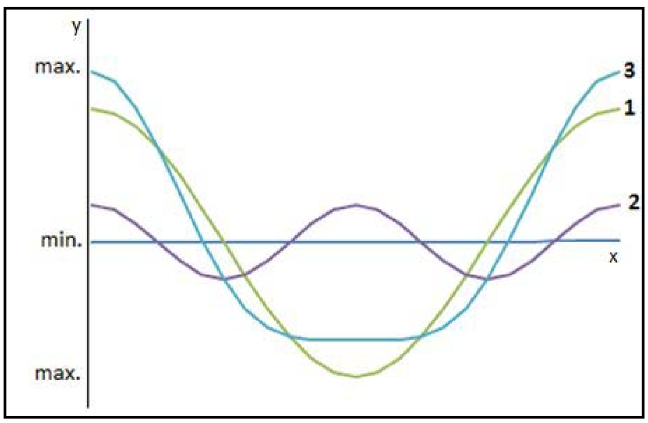

Fig. 1: First order, Second order and Instantaneous imbalance forces

In the above figure, crank angle is taken on X-axis and amount of imbalance force in Newton (N) is taken on Y axis; line 1 indicates first order imbalance forces; line 2 indicates second order imbalance forces and line 3 indicates instantaneous imbalance forces. The total balancing of all these primary and secondary inertia forces caused by the reciprocating masses can be achieved using twin countershaft concept given by Frederick W. Lanchester in 1914. While designing balancing system for a single cylinder engine, it was first necessary to first decide the type of balancing system to employ. The Lanchester balancing system consists of equal but counter rotating weights designed and aligned to eliminate the frequency terms of the frame shaking force resulted from inertia forces. This harmonic balancing technique is one of the most widely employed balancing techniques, which allows the reduction of vibrations in high-speed IC engines.

Based on the actual engine data, the balancing weight which will be needed to balance out the inertia forces for different combinations of bore-stroke is calculated and according to it two design concepts were generated keeping modularity in mind.

Concept design 1

The idea behind this design is to have a machined cylindrical housing shaft on which external balancing weights are bolted. This design provides adequate modularity; balancing weight can be increased or decreased just by altering the width of balancing blocks. There is no need to design cross-section of balancing weight as location of centre of gravity is kept fixed and only the width of balancing block has to be calculated according to the required balancing weight. This procedure is common for both first order and second order balancer shafts. The cross-sections of balancing weights for both the shafts are different and are designed keeping overall packaging and ease of accessibility in mind. The use of bolted joint facilitates ease of handling and replacing for the weights. Fig. 2 shows the concept design 1 for the first order balancer shaft for one of the piston-cylinder configuration kept in mind during this development activity.

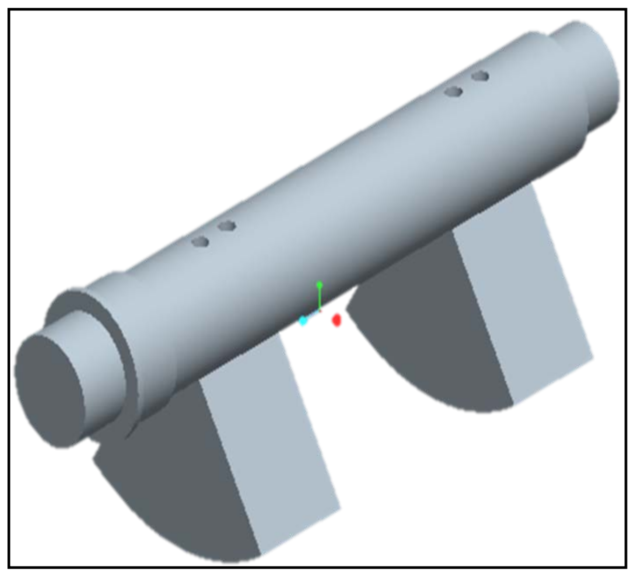

Fig. 2: Concept design 1 – First order balancer shaft

Above Fig. indicates first order balancer shaft assembly concept design 1 having machined housing shaft and bolted balancing weights placed symmetrically about YZ plane. YZ plane is a plane passing from cylinder center axis and is perpendicular to the length of crankshaft. Twin but symmetrically placed balancing weights each of 2Kg and of 49.8mm width are bolted to the first order balancer shaft. All these dimensions are achieved after doing mathematical calculations keeping balancing weight material as AISI4140 (42CrMoS4) alloy steel in consideration. The second order balancer shaft is geometrically similar, only the dimensions are scaled proportionally.

Concept design 2

Fig. 2 diagram indicates another design concept for balancer shafts. It comprises of a machined housing shaft on which base module of minimum balancing weight of 20mm is bolted. The required balancing weight on the balancer shafts can be adjusted by adding or removing suitable number of balancing plates designed in 2 mm and 1 mm thickness so as to provide flexibility for the perfect balancing weight selection. Maximum 14 plates are needed to make the width of balancing weight to meet the desired width of 50 mm for having maximum balancing weight on the first order balancer shaft. All these dimensions are achieved after doing suitable calculations keeping balancing weight material as AISI4140 (42CrMoS4) alloy steel in consideration. The shaft material is also kept same as that of base module and balancing plates. Again use of bolted joint facilitates flexibility and ease of accessibility for the balancing weights. Following diagram shows the concept design 2 for the first order balancer shaft. The second order balancer shaft is geometrically similar, only the dimensions are scaled proportionally.

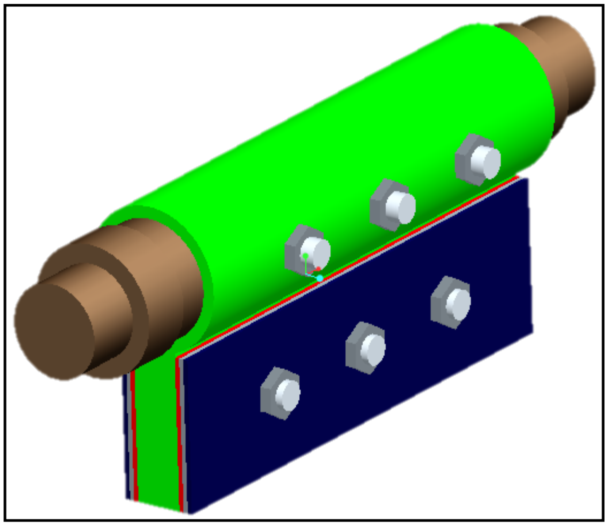

Fig. 3: Concept design 2 – first order balancer shaft

Above Fig. indicates first order balancer shaft assembly concept design 2 having machined housing shaft, bolted base module of minimum balancing weight and bolted thin multiple plates placed symmetrically about YZ plane. YZ plane is a plane passing from cylinder center axis and is perpendicular to the length of crankshaft.

3. CONCLUSION

A study is done for balancing of single cylinder research engine which will be tested on the test bench. Based on the requirement from the engine, two concept designs for first and second modular balancer shafts for a piston – cylinder configuration according to Lanchester balancing technique are designed keeping modularity and ease of manufacturing in mind.

The research work can be extended to the balancer shaft bearing selection and balancer shaft drive mechanism design taking drive power from engine crankshaft.

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