16th International Research/Expert Conference
”Trends in the Development of Machinery and Associated Technology”
TMT 2012, Dubai, UAE, 10-12 September 2012

THE OPTIMIZATION OF CRANKSHAFT OFFSET OF SPARK IGNITION ENGINE

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ABSTRACT

The paper presents influence of the crankshaft offset of spark ignition engine regarding the engine friction, torque and power. It is known from the literature that crankshaft offset has a potential to reduce normal piston force during the expansion stroke at lower engine speeds. The results of lower normal force are reduced mechanical losses due to friction between the piston and liner of the cylinder. The crankshaft offset can significantly change the piston kinematics because the piston moves slower around TDC and BDC. If spark timing is referenced to the piston position from the TDC, the crankshaft offset increase in-cylinder pressure during the combustion as a result of lower change of the cylinder volume close to the TDC and engine performances can be improved. Two operating points of spark ignition engine were analyzed and optimization of crankshaft offset was performed by the NSGA-II genetic algorithm. In order to calculate the active piston force during the combustion process Vibe function were applied. The minimization of friction losses that occur between piston and cylinder liner as well as minimization of difference between peak values of resultant force of the piston in the normal direction were the main objectives of the optimization. The optimization results show that crankshaft offset has potential to improve engine performances at lower engine speeds.

Keywords: internal combustion engines, crankshaft offset, optimization, engine friction, genetic algorithm

1. INTRODUCTION

In order to reduce mechanical losses of the engine and to increase its durability a few engine manufactures have designed an engine configuration with the crankshaft offset (BMW N20 engine [5]).The crankshaft longitudinal axis is displaced from the vertical axis of the cylinder causing the smaller angle between the vertical cylinder axis and the connecting rod during the power stroke. The crankshaft offset reduces the normal piston force during the expansion stroke reducing the mechanical losses caused by the friction between the piston and the liner of the cylinder. The crankshaft offset also changes the piston kinematics; the piston velocity is lower around the TDC which increases the in-cylinder pressure during the combustion improving the engine performance (torque and power output). In order to investigate the influence of the engine crankshaft offset regarding the engine performance, a mathematical model of the engine together with optimization method was created and applied. The mathematical model is designed so that the engine displacement is constant by variation of the crankshaft offsets (adaptive length of connecting rod and stroke). The main task of this research was to optimize the crankshaft offset regarding the minimization of engine friction and minimization of normal piston forces that have high influence to the engine durability.

2. MATHEMATICAL MODEL OF THE SI ENGINE

In order to maximize the power output the mechanical losses caused by friction between the piston and the cylinder liner has to be minimized. Difference between the peak values of normal piston force also has to be minimized so that the engine durability can be improved. To calculate the optimal crankshaft offset (e) a mathematical model of a four stroke SI engine was created. Relative friction losses between the piston and the cylinder liner represent the first goal function (f_1) and the minimization of the difference between peak values of resultant force of the piston in the normal direction (f_2).

The mathematical model of the engine consists of three modules:

1. The module that calculates the in-cylinder pressure.
2. The module that calculates the kinematics and the dynamics of the engines crankshaft drive with crankshaft offset.
3. The optimization module that incorporates the NSGA II genetic algorithm for multi-objective optimization.

The input parameters are the cylinder bore (D), the crankshaft radius (r), the connection rod length (l), the compression ratio (ε), the oscillating mass (m_{osc}), spark timing, the engine speed and the number of populations and generations for the NSGA II(**N**on-dominant **S**orting **G**enetic **A**lgorithm **II**) optimization algorithm. The output of this model is a set of solutions for crankshaft offset (Pareto-front) that represents optimal solutions for both goal functions (f_1 and f_2). During the optimization process the length of the connecting rod and the crankshaft radius are changed according to the crankshaft offset defining the constant engine displacement. This model feature enables the comparisons of engine performances with the performances of conventional engine design.

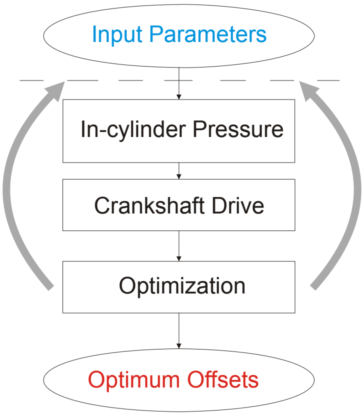

Figure 1. Structure of the mathematical model

2.1. Modeling of in-cylinder pressure

Several assumptions for calculation of in-cylinder pressure were adopted:

- Intake stroke takes from TDC to BDC and pressure during this period is constant;
- The compression stroke starts at BDC, ends at the beginning of combustion;
- Compression and expansion are calculated as polytrophic changes with defined polytrophic exponents;
- Expansion stroke takes to BDC;
- Exhaust stroke takes from BDC to TDC and pressure during this period is constant.

In order to define the active piston force during the combustion, combustion process has to be calculated. The presented model is calibrated by variation of the combustion duration (α_{comb}) and the shape parameter (m) of the Vibe function achieving a very good agreement of pressure profiles compared to the results from the CFD simulations.

2.2. Crankshaft drive

The module for the crankshaft drive calculates the geometrical changes of the crankshaft drive (the new crankshaft radius r_{new} and the new connection rod lenght l_{new}) according to the equation (1) and (2).The geometry is changed in order to keep the engine stroke volume constant so that the new engine configuration could be compared with the original engine design.

$$l_{new} = \frac{1}{2} \cdot \left(\sqrt{h_1^2 + e^2} + \sqrt{h_2^2 + e^2} \right) \tag{1}$$

$$r_{new} = \sqrt{h_2^2 + e^2} - l_{new} \tag{2}$$

The instantaneous piston position (h) is calculated with the following equation:

$$h(\alpha) = h_1 - \left(r_{new} \cdot \cos\alpha + l_{new} \cdot \sqrt{1 - \left(\frac{e}{l_{new}}\right)^2 + 2 \cdot \left(\frac{e}{l_{new}}\right) \cdot \left(\frac{r_{new}}{l_{new}}\right) \cdot \sin\alpha - \left(\frac{r_{new}}{l_{new}}\right)^2 \cdot \sin^2\alpha} \right) \tag{3}$$

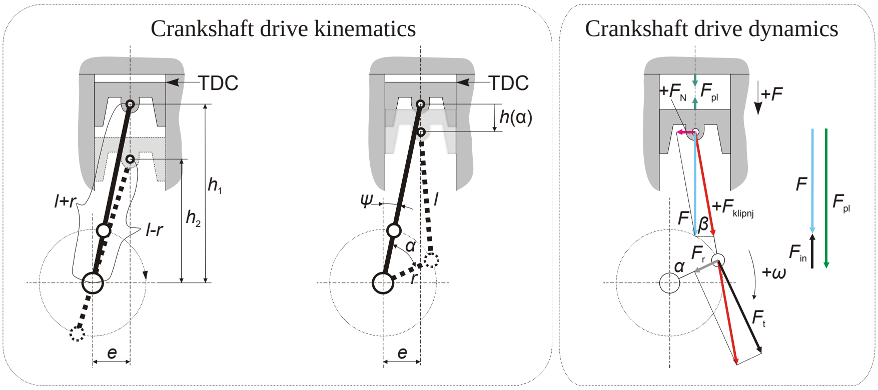

Figure 2. Kinematics and dynamics of the crankshaft drive

The active force (F) on the piston is calculated with the following equation:

$$F = F_{\mathrm{pl}} + F_{\mathrm{in}} \tag{4}$$

The gas forces (F_{pl})are calculated from the in-cylinder pressure profile which is acquired from the in-cylinder pressure module:

$$F_{\mathrm{pl}} = p(\alpha) \cdot A \tag{5}$$

The oscillating masses are set as an input parameter, so the inertial force is calculated via following equation:

$$F_{\mathrm{in}} = m_{\mathrm{osc}} \cdot \frac{d^2 h(\alpha)}{d\alpha^2} \tag{6}$$

Finaly the normal force between the piston and the cylinder liner is calculated via following equation:

$$F_{\mathrm{N}}(\alpha) = F \left(\frac{\left(\frac{e}{l_{\mathrm{new}}}\right) - \left(\frac{r_{\mathrm{new}}}{l_{\mathrm{new}}}\right) \cdot \sin\alpha}{\sqrt{1 - \left(\frac{e}{l_{\mathrm{new}}}\right)^2 + 2 \cdot \left(\frac{e}{l_{\mathrm{new}}}\right) \cdot \left(\frac{r_{\mathrm{new}}}{l_{\mathrm{new}}}\right) \cdot \sin\alpha - \left(\frac{r_{\mathrm{new}}}{l_{\mathrm{new}}}\right)^2 \cdot \sin^2\alpha}} \right) \tag{7}$$

The profile of the normal force is the output of the crankshaft drive module.

2.3. Optimization

For the optimization of the crankshaft offset the NSGA-II genetic algorithm was used. The NSGA-II genetic algorithm has become the standard approach to solving multi-objective optimization problems. In this case the crankshaft offset is optimized through two goal functions.

$$f_1 = \min \left| F_{\mathrm{Nmax}} - \left| F_{\mathrm{Nmin}} \right| \right| \tag{8}$$

$$f_2 = \max \left| \int_{\alpha} \mu \cdot F_{\mathrm{N}}(\alpha, e=0) \cdot h(\alpha, e=0) d\alpha - \int_{\alpha} \mu \cdot F_{\mathrm{N}}(\alpha, e) \cdot h(\alpha, e) d\alpha \right| \tag{9}$$

The first goal function is expressed by the equation (8) and it represents the absolute difference between maximal and minimal normal forces that occur between the piston and cylinder liner during the entire cycle. Smaller difference between those two forces directly contributes to the lower wear of the piston and cylinder liner. Also, the peak value of the normal force achieved by the application of the crankshaft offset is smaller compared to the engine configuration without it. The second goal function is expressed by the equation (9) and it represents the reduction of engine friction. If the difference between the work necessary to overcome the friction between the piston and the cylinder liner in the original configuration (no offset) and in the new configuration is grater the mechanical loses are smaller. As a starting point the number of populations and generations is needed. By the number of populations a number of random values which represent the value for the crankshaft displacement is defined. The number of generations defines the number of population sets. Each next population is created from the best values of the previous population. The last generation represents the set of values for crankshaft displacement that are best fit values for both goal functions.

3. OPTIMIZATION RESULTATES

The optimization was performed on a four stroke SI engine with following characteristics: D = 79mm, H = 81,4 mm, l = 137 mm, ε = 11,11, m_{osc} = 0,75 kg. The Pareto front for full load cases at two engine speeds (2000 rpm and 5500 rpm) can be seen in Figure 3.

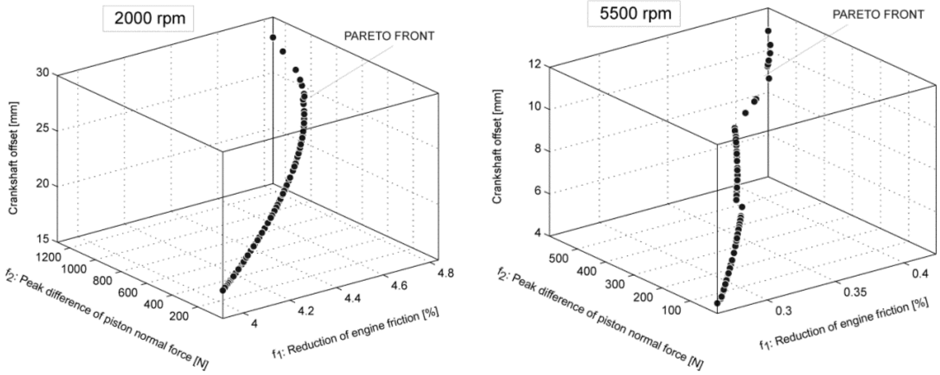

Figure 3. Optimization results

By full load and 2000 rpm the optimal displacement of the crankshaft regarding the peak difference of piston normal force is e_{2000} = 17,5 mm and for full load at 5500 rpm the displacement is e_{5500} = 4,9 mm. The reduction in engine friction compared to the conventional engine is 3,9 % fore_{2000} = 17,5 mm at 2000 rpm and 0,26 % for e_{5500} = 4,9 mm at 5500 rpm. In both cases with crankshaft offset application the maximal normal force of the piston is decreased compared to the conventional engine configuration without crankshaft offset (at 2000 rpm: $F_{\mathrm{Nmax},e=0}$=3075 N, $F_{\mathrm{Nmax},e=17,5}$= 1394 N; at 5500 rpm: $F_{\mathrm{Nmax},e=0}$=2687 N, $F_{\mathrm{Nmax},e=4,9}$= 2327 N).

4. CONCLUSION

The application of crankshaft offset reduces the normal piston force causing lower mechanical losses in the engine. In the case of crankshaft offset the piston velocity is lower around the TDC which increases the in-cylinder pressure during the combustion and additionally improves the engine performance (torque and power output).The optimization results show that the reduction of mechanical losses with crankshaft offset decreases with increase of engine speed due to the influence of inertial forces. It can be concluded that the engine configuration with crankshaft offset has a high potential for reduction of mechanical losses at lower engine speeds. The optimization results show that different values of crankshaft offset are optimal ones at different engine speeds. In order to adopt the single value of the crankshaft offset for the certain engine configuration the additional criteria should be implemented into the presented model, such as the mean engine speed at which the engine works the most of its life. The overall realistic potential for reduction of mechanical losses in engines is about 3 %.The optimal offset could be calculated with the mathematical model shown in the paper.

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