Simulation possibilities of the internal combustion engine management elements using Lotus Engine Simulation software

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Abstract. Nowadays the international regulation regarding the exhaust emission and fuel consumption are going in a progressive restricting direction. Authorities force the researchers toward an optimization of new produced engines by lowering the fuel consumption, the harmful exhaust gases and increasing the overall engine efficiency. By lowering the overall quantity of harmful produced gases, an optimization of the previously produced engines is a good study direction, where the actual engines are analysed and there may be found different ways to upgrade it to a better, more economical and less harmful way of functioning.

The paper approaches the simulation possibilities of the variable valve timing systems using Lotus Engine Simulation software. More precise, it is showed how to use this tool and introduce, modify and analyse the system mentioned above. After simulating different setups of the engine and continuously varying the functionality parameters, useful result shows different ways for further investigations on the engine optimization.

1. Introduction
Transport represents almost a quarter of Europe’s greenhouse gas emissions and is the main cause of air pollution in cities. The road transport, this is by far the biggest emitter accounting for more than 70% of all greenhouse gas emissions form the transport sector. [6]

The European Union is setting more and more restrictive targets regarding climate and energy in order to reduce the greenhouse gasses, rise the usage of renewable energy and also improve the energy efficiency. [5] The main elements of the emission reduction strategy which are identified as priorities are increasing the efficiency of the transport systems, speeding up the development of low-emission alternative energy for transport and moving towards zero-emission vehicles. [6]

As an example, the climate end energy package set for this year (2020) includes a reduction of 20% of the greenhouse gas emissions (from the 1990 levels), 20% of EU energy from renewables and an improvement of 20% in energy efficiency. [5] As for 2030, the greenhouse gas emissions should be decreased with at least 20% (from 1990 levels) as the improvement in energy efficiency should rise at least at 32.5%. [5]

In case of internal combustion engines, in order to achieve the targets, the development reaction should be really fast. To facilitate investigation over the engine behavior under different parameters, usage of simulation software is mandatory. This is a simple, rapid and cheap way to determine in which direction the internal combustion engines may be improved.
The aim of this study is to present how the Lotus Engine Simulation is capable to predict the behavior of the internal combustion engine. This is a low time-consuming method which can be used to generate the input data for an internal combustion engine optimization project. An investigation is performed over the variable valve timing systems in order to indicate the improvements that can be achieved. This paper will show how to use the simulation software and present the results obtained.

2. Introduction into the gas exchange process

Internal combustion engine functionality can be divided in 5 big subprocesses: inlet process, compression process, combustion process, expansion process and exhaust process. The internal combustion engine functionality study is performed using the different kind of graphs like: indicator diagram, the p-V diagram (pressure – volume) or P-ϕ diagram (pressure-crank shaft angle). [3]

The theoretical functional cycle of a spark ignition internal combustion engine is considered as an isochore burning cycle, due to the fact that the combustion is done in a small time period. The indicator diagram variation and the theoretical functional cycle are shown in figure 1. [3]

The actual functional processes inside a spark ignition internal combustion engine take place over the following order:

- The intake valve opens in advance of the TDC – top dead centre (IVO – intake valve opening point) and allows the combustion mixture to enter the cylinders.
- After the closing of the intake valve (IVC – intake valve closing point) the compression process take place.
- At the end of the compression process the spark plugs triggers the electric spark (c point), in advance of TDC.
- The burning of the combustion mixture (air/fuel) take place in the c-z area from the diagram.
- The gas expansion after the combustion process take place in the z-b area from the diagram.
- After these processes, the exhaust valve opens (EVO – exhaust valve opening point).
- At the end of the exhaust process the exhaust valve closes (EVC – exhaust valve closing point).
- The functional cycle starts again in the same order. [3]
Figure 1. Indicator diagram (a) and the theoretical cycle (b) for a spark ignition internal combustion engine. [3]

The theoretical cycle shown in figure 1 is formed by: adiabatic compression (a-c), isochore combustion (c-z), adiabatic expansion (z-b) and isochore exhaust (b-a). [3]

In a spark ignition engine, the intake system typically consists of an air filter, a carburettor a throttle or fuel injector an throttle or throttle with individual injectors in each intake port, and intake manifold. During the induction process, pressure losses occur as the mixture passes through or by each of these components. There is an additional pressure drop across the intake port and valve. These flows are pulsating. [2]

The drop in pressure along the intake system depends on engine speed, the flow resistance of the elements in the system, the cross-sectional area through which the fresh charges moves, and the charge density. The usual practice is to extend the valve open phases beyond the intake and exhaust strokes to improve emptying and charging of the cylinders and make the best use of inertia of the gasses in the intake and exhaust systems. [2] A graphic view over the engine process can be seen in the polar valve timing diagram (figure 2.), which express each individual stroke degrees for a four-cycle engine.

Figure 2. Valve-timing diagrams. [4]

The exhaust process usually begins 40 to 60° before BDC. Until about BDC the burned cylinder gases are discharged due to the pressure difference between the cylinder and the exhaust system. After BDC, the cylinder is scavenged by the piston as it moves toward TDC. [2] The terms blowdown and displacement are used to denote these two phases of the exhaust process. Typically, the exhaust valve closes 15 to 30° after TDC and the inlet valve opens 10 to 20° before TDC. [2] Both valves are open during an overlap period, and when the exhaust pressure is bigger than the intake pressure, backflow of exhausted gas into the cylinder and of cylinder gases into the intake will usually occur. [2] The advantage of valve overlap occurs at high engine speeds when the longer valve-open periods improve the volumetric efficiency. [2] As the piston moves past TDC and the cylinder pressure falls below the intake pressure, gas flows from the intake into the cylinder. [2] The intake valve remains open until 50 to 70° after BDC so that fresh charge may continue to flow into the cylinder after BDC. [2] All these valves opening and closing angles may vary depending on the manufacturer, type of the engine, number of valves, number of camshafts, etc.
Figure 2.a is typical of a compression ignition engine (conventional spark ignition engine), while figure 2.b is typical for a high-performance spark ignition engine.

In case of classic valve timing there are several compromises: high speed versus low speed performance, and full load versus part load performance. There has been considerable effort devoted to developing variable valve timing mechanisms. [4] In addition to minimising valve timing compromises, variable valve timing can be used to reduce the throttling losses in spark ignition engines. [4] There are different mechanisms that can make possible the valve events to be phased, valve event duration to be modified as well as maximum height opening distance. [4]

3. Construction of the engine model
The Lotus Engine Simulation program is capable of modelling the combustion and gas flow processes, computing the indicated and brake parameters while considering the influence of the heat transfer and the friction phenomena. Lotus Engine simulation program represents a powerful tool for optimization of engine dynamic parameters and processes. This software can be used to define the bore/stroke ratio, valve, sizes, cam profiles, and intake and exhaust manifold geometry which enable the powertrain unit to meet the performance target. [1]

The basic engine data include engine geometry (bore, stroke, connecting rod length, compression ratio, engine inertia (mass and inertia of various components), cylinder and valve event phasing. Initial conditions such as exhaust temperatures, intake temperatures, and wall temperatures need to be input as reasonable values. [1]

Once the basic inputs are defined, the advanced inputs need to be defined. These inputs are port flow coefficients, valve lift per crankshaft rotation, combustion and heat transfer modelling (types of models to be used for representing the combustion and heat transfer processes and the surface areas and temperatures of various components within the cylinder, phasing of cylinder firing with respect to TDC). Some intuition is used to determine the parameters due to the large difference in engine operating speed and difference in engine type. [1]

The first step in this study was to search for a suitable engine which can serve as base data for the simulation. The scope is to see and check, using the simulation program, which are the advantages or disadvantages of implementing the variable cam phase system into an engine which firstly had a preset cam phasing. For the simulation I chose the C18NZ engine from Opel, which equipped different models as “Astra” (several variants) or “Vectra”. The manufacturer data of this engine can be seen in figure 3.
The first step in creation of the model was entering the manufacturer data into the system. There are two different type of creating a model: using the combustion chamber tool, or placing one by one the engine components and enter the data for each one. For the model it was used the second option. Cylinder data, valve data, port data and intake/exhaust piping with the afferent data.

After entering all this component data, there starts the phasing of the cylinders and the valve. C18NZ works with 1-3-4-2 firing order. The phasing is done by entering the start point in crank rotation degrees for each cylinder (1st cylinder – 0°; 2nd cylinder - 540°; 3rd cylinder - 180°; 4th cylinder - 360°). The cylinder phasing can be seen in figure 4.

The next step is to create the phasing of the valve opening. Again, here are two methods: one by entering the opening and closing point for each valve, or the second method, by using the polar diagram. In the figure 5. is shown the valve timing using the polar diagram.
Figure 5. Valve timing

For the valve max lift (11.2mm), it was used the data from an “fast road” car according to Piper cams. [7].

Next, the fuelling system (Gasoline, indirect injection), combustion model (Single Wiebe) are entered. At the end, the basic model is shown in figure 6.
4. Simulations

For the simulations there is another step that needs to be accomplished. The simulation environmental and working sequence was entered (test conditions). So, the data necessary is: number of tests or the speed increment for each step, minimum engine speed (rpm), maximum speed (rpm), ambient air pressure (bar), ambient air temperature (°C), exit pressure (bar), trapped air fuel ratio and specific humidity (kg/kg).

The simulations were done for different model variations:
1. Basic model – manufacturer data
2. Valve phase variator – 15° in advance
3. Valve phase variator – 15° retard
4. Valve maximum opening height – up to 15mm

The first simulation was done for the basic data of the engine. The result can be seen in figure 7. This express the total brake power and total brake torque over the engine speed.
The results show, for this simulation, that the maximum torque achieved is 164NM at around 2500rpm and the maximum power achieved is 66kW at around 5400 rpm. These results are slightly different from the manufacturer data due to the test conditions which can be different from the conditions used in testing at the manufacturer side. The first results will serve as benchmark for the following model variation.

For the second simulation there were introduced two new elements into the model: a sensor, which will sense the engine speed and an actuator, which will modify the valve phases. The modification of the valve timing will be done by modifying the MOP (maximum opening point of the valve). In this way, the opening period and the valve profile will remain the same. The variation of the valve timing is shown in figure 8. It was used a 15° linear variation starting with 2500 rpm.

![Figure 8. Phasing variation graph.](image)

The results for this kind of simulation are shown in figure 9.

![Figure 9. Result for the variable valve phasing simulation (advance 15°)](image)
As results, the highest torque is 161Nm at around 2500 rpm and the maximum power is 76kW at around 5400 rpm. Also, there can be seen an increase in torque in the 3000rpm – 4000rpm range. For this type of valve timing, at high rpm, due to the bigger angle of the intake valve opening point, the fuel mixture has more time to enter the cylinder and the pumping effect is lowered. In other words, the volumetric efficiency is increased.

The 3rd simulation was made on the same data as the second, but the MOP angle was decreased linear with 15° starting with 2500 rpm. The results can be anticipated as the time for the combustion mixture to enter the cylinders is decreased. Figure 10 represents the results for this simulation.

In this case there can be seen a negative behaviour starting with 3000 rpm, where the torque and the power encounter a drop. The most visible effect is between 4000 and 5000 rpm where the torque goes down as the engine speed rises.

This type of cam phase variator is already used in the industry starting from 1980, when Alfa Romeo had the first one. This cam variators are operated in different ways, using oil pressure or magnetic field. Usually the oil pressure operated variators work on mechanical principles. So, as the engine speed gets higher, the oil pressure rises and this will action the system. In the case of the magnetic field, there is needed an electronic control unit which has already a program which controls when and how to action the variator.

The last simulation was done on a different valve variator. In this case the variator is able to rise the maximum opening height of the valves. With this modification the access area of the combustion mixture into the cylinder is bigger and mainly the volumetric efficiency is increased. The first system of this type was brought into the market by Honda, with their well known VTEC. This system is operated by two different height cams on each intake valve. At high rpms these two cams are linked together by a pin which is actioned by the oil high pressure and in this way the valves are opened by the bigger profile cam.

The main parameter for this simulation is the maximum opening height of the intake valves which, starting with 2500 rpm, the opening height will rise linear from 9.2 mm up to 15mm. We inspect an increase of power and torque due to the increasing of the volumetric efficiency.

In the figure 11 the results for the last simulation are shown.
Figure 11. Result for the variable valve opening height (up to 15mm)

As a result, we can observe an increase with 3 Nm in the torque and a leaner graph, so we may say that the functioning of the engine is more stable. Regarding the power, there was identified an increase with 4kW of the maximum value reached.

5. Results and conclusions

- 2nd Simulation – variable valve phase (MOP increased with linear with 15°):
  - Torque was increased with 6Nm at around 3500 rpm, and the values of the torque between 3000 and 4000 rpm are increased with around 3Nm. The maximum power was increased with around 5kW.
- 3rd Simulation – variable valve phase (MOP decreased with linear with 15°):
  - Torque was reduced with 5Nm at the maximum torque engine speed. Also, the torque curve shows a big drop starting with 4000 rpm. The power also was decrease with 9kW, caused by the small time for the combustion mixture to enter the cylinder and due to the pumping effect.
- 4th Simulation – Variable valve opening height – up to 15mm:
  - In this case increased torque and power were observed. The torque increased with 3Nm and the power with 4kW. Also, the curves are smoother, with less steep areas, which indicates a better stability in the engine running.
  - All the comparisons were made over the base model which was created mainly with the manufacturer data.
  - After investigating the C18NZ, using the Lotus Engine Simulation program, were observed different results. Some of them were better than the base model and there are ways to improve the engine. Also, using this program, was facile to express the behaviour of the engine in case of introducing different mechanisms which can help to improve the engine performance.
  - This study can be developed in a way in which there is identified the engine speed range where the opening point angle of the valves will increase the most the engine performance and also this is a big step in the gas emissions, which are in close relation with the amount of oxygen that enters the cylinder.
6. References

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