MATHEMATICAL OPTIMIZATION OF VARIABLE VALVE TIMING FOR REDUCING FUEL CONSUMPTION OF A SI ENGINE

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Abstract:

In this study, the sensitivity analysis and Quasi-Newton algorithms are used to optimize valve timing XU7/L3 engine in order to reduce fuel consumption and increase engine performance. At first, all components of engine are modeled in GT-POWER and a comparison with experimental results is performed to confirm the accuracy of the model. Then, GT-POWER model is coupled with MATLAB-SIMULINK to control inputs and outputs with sensitivity analysis and Quasi-Newton algorithms. The results obtained indicate that optimal valve timing significantly reduces brake specific fuel consumption (BSFC). Moreover, the convergence rate of Quasi-Newton algorithm for reaching the optimal point is higher than the one of sensitivity analysis algorithm.

1 Introduction

The universal regulations governing the control of green-house gas emissions are now being tightened so that vehicle manufacturers have to satisfy these constraints. The reduction of engine fuel consumption becomes a primary requirement to meet current and future emission legislations [1]. For this purpose, several methods such as fast combustion, lean burn, variable valve timing and gasoline direct injection have been suggested in the literature. Variable valve timing is one of the most efficient methods which not only reduces fuel consumption and engine emissions but also, solves low end torque problem.

In automotive applications, the variable valve timing was first developed by Fiat in late 1960 [2]. Considering the ability of the system, it was soon used by other companies like Honda, General Motors, Ford and other automobile manufacturers. Liguang et al. [3] examined intake and exhaust valve timing effects on spark ignition engines. They experimentally investigated the effect of these two factors on power, torque, fuel consumption and the HC emissions. Bohac et al. [4] studied the effect of variable exhaust valve opening (EVO) and exhaust valve closing (EVC) on HC emissions reduction. They studied the effect of different EVO and EVC timings under steady-state and start-up conditions, and concluded that the early EVO could be helpful for engine HC emission reduction in steady-state conditions but not in start-up condition.

Shayler [5] experimentally investigated the effects of intake and exhaust valves timing on remaining output gases. He concluded that timing of intake and exhaust valves will have considerable influence on the extent of fuel and fresh air entrance to the combustion chamber. Leroy et al. [6] conducted a series of research into controlling intake air path in an engine having a variable valve system without

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EGR. They considered internal EGR effect in engines having variable valve systems and studied their effects on reducing fuel consumption and emissions as well as negative effects of increased internal EGR on torque and air-fuel ratio. They presented a new control way by which beneficial effects of variable valve system would be added and its negative effects would be reduced. Wu et al. [7] optimized valve timing of a gasoline engine using a neural network algorithm. The result of this study was to reach optimal timing by using neural network in a variable valve system engine. Therefore a mathematical model of the target engine has been made, then the model was validated by using experimental information and also the constants and performance zone of engine have been realized. Then to maximize the output torque, timing of valves is changed and the best timing in each speed in full throttle condition using a neural algorithm was determined.

Variable valve systems also are able to enforce considerable effects on cylinder processes. The most important advantage of a variable valve system that is known in reducing both pumping wastes and fuel consumption has been considered due to this system [8]. As optimization is a very important issue in all sciences and fields, researchers in all sciences have used different kinds of optimization algorithms. Some examples of using conjugate gradient, sensitivity analysis [9] and Quasi-Newton optimization algorithms that are considered in this study have been provided in previous work.

As noted before, up to now only one of these following cases have been generally optimized separately: either intake valve timing or exhaust valve timing, or opening valves timing or closing valves timing. The case in which all four timings might have been optimized is rare or has never been carried out in literature. In addition, in previous studies a neural network algorithm has been used for optimization and the lack of variety in mathematical optimization algorithms was significantly felt. In this study, timing of each four intake and exhaust valves is optimized. Moreover, sensitivity analysis and Quasi-Newton algorithms are implemented to optimize valves timing.

2 GT-POWER model

Specifications of the XU7/L3 engine are shown in Table 1. XU7/L3 engine model in GT-POWER software is a one dimensional model whose input consists of those related to engine specifications, boundary and initial conditions and some of them are related to performance conditions of the engine. Engine specifications include intake and exhaust manifold maps, combustion chamber map, piston map, crankshaft map of XU7/L3 engine obtained from IPCO Company. The valves timings based on the cam angle are given in the following Table.

Table 1. Specification of XU7/L3 engine [9]

Bore (mm)	83
Stroke (mm)	81.5
Maximum lift of intake valve (mm)	9.6997
Maximum lift of exhaust valve (mm)	9.6997
Connecting rod length (mm)	150.5
Compression ratio	9.3
type	4 cylinder-in line
IVO (cam angle degree)	149
IVC (cam angle degree)	301
EVO (cam angle degree)	48
EVC (cam angle degree)	223

3 Model validation

The simulation results obtained from GT-POWER and experiments from IPCO Company are used to validate the model. For this purpose, results of torque and brake specific fuel consumption are compared to experimental ones. As shown in Fig. 1, model behavior and experimental data are nearly coinciding except in lower speeds where model’s torque is greater. Mean error percentage between model’s torque and experimental one is 3.73. According to the curve, it can be seen that in lower speeds the model used for simulation of engine behavior has significant differences with experimental results. The reason for this is that GT-POWER cannot model some phenomena such as back flow and RAM effect, although these effects can cause significant reduction in torque and power in low speeds. Fig. 2 shows the validation result for brake specific fuel consumption. It is evident that in lower speeds BSFC is smaller. Mean error percentage between simulation and experiment is about 2.71.

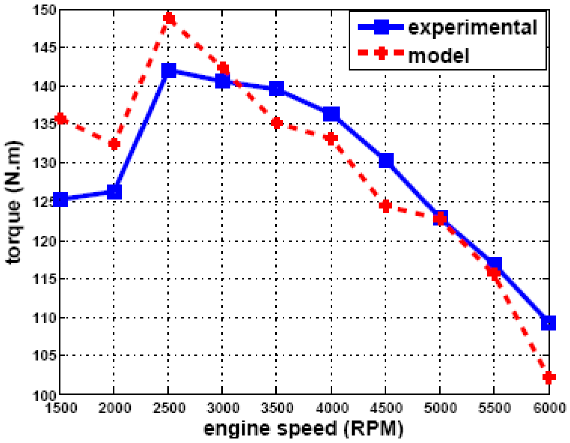


Figure 1. Simulation and experiment validation the torque results.

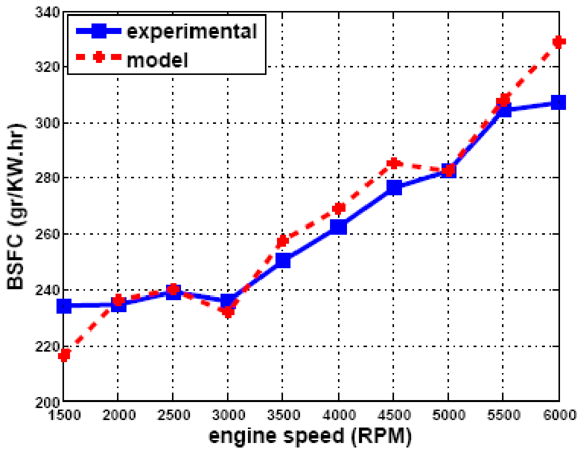


Figure 2. Simulation and experiment validation of the brake specific fuel consumption results.

4 Sensitivity analysis algorithm

In reverse problem, the aim is to minimize the sum of these squares:

$$F = \left(\vec{E}^m - \vec{E}^c\right)^T \mathbf{W}\left(\vec{E}^m - \vec{E}^c\right), \tag{1}$$

in which, this sum is a function of an unknown parameter *P*. As an example, these unknown parameters in this study are opening and closing angles of intake and exhaust valves, which is a linear matrix having four columns. So, the unknown parameter can be generally shown as follows:

$$\vec{P} = \left[\vec{P}_1 \quad \vec{P}_2 \quad \dots \quad \vec{P}_N\right]^T, \tag{2}$$

where P_n is unknown parameter in nth time stage and can be shown as follows:

$$\vec{P}_n = \left[P_{n,1} \quad P_{n,2} \quad \dots \quad P_{n,L}\right]^T, \tag{3}$$

where $P_{n,l}$ is unknown parameter l_{th} in nth time stage.

Therefore, considering that this parameter changes the $\vec{E}^c$ value, it can consider *F* as a subordinate of *P*. Using derivative in an optimized point so that *P* makes *F* value optimize the next, the equation should be relevant:

$$\left[\frac{\partial F}{\partial \vec{P}}\right] = 0. \tag{4}$$

By substituting this condition into Equation (1):

$$\mathbf{X}^T \mathbf{W}\left(\vec{E}^m - \vec{E}^c\right) = 0, \tag{5}$$

where $\mathbf{X}$ is a sensitivity matrix:

$$\mathbf{X} = \left[\frac{\partial \vec{E}^{cT}}{\partial \vec{P}}\right]^T. \tag{6}$$

To optimize, it is necessary to regard the $\vec{E}^c$ to be dependent on *P*. If *P* is known, but if it does not match Eq. (5), then it should be changed so as to be equal to Δ*P*. So, by using Taylor series and neglecting high degree sentences, the following relation is written for changing the $\vec{E}^c$:

$$\vec{E}^{c,k+1} = \vec{E}^{c,k} + \mathbf{X}\Delta\vec{P}, \tag{7}$$

where upper case k shows repetition and therefore to facilitate computation writing is omitted. By putting (7) in (3) the following equation is reached:

$$\mathbf{X}^T \mathbf{W}\left(\vec{E}^m - \vec{E}^c\right) = \mathbf{X}^T \mathbf{X}\Delta\vec{P}. \tag{8}$$

So, there is an equation to correct *P*. On this basis, the algorithm for solving a reverse problem would be as follows. Reverse problem solving with sensitivity analysis would be as follows:

Step 1. P is estimated.

Step 2. Direct equation is solved and the considered field is determined at proper time.

Step 3. Field values in measurement points, $\vec{E}^c$, are calculated.

Step 4. F is calculated

Step 5. Sensitivity matrix, $\mathbf{X}$, is determined.

Step 6. Equation 8 to reach ΔP is solved.

Step 7. P is corrected

Step 8. Direct equation is solved and the considered field is determined at proper time.

Step 9. Field values in measurement points, $\vec{E}^c$, is calculated.

Step 10. F is calculated.

Step 11. In case one, the below scales are set, then the answer has been found, otherwise calculation continues from step 5:

$$\left\|\Delta\vec{P}\right\| < \varepsilon_1, \tag{9}$$

$$\left|\frac{F^{k+1} - F^k}{F^k}\right| < \varepsilon_2, \tag{10}$$

where $\varepsilon_1, \varepsilon_2$ are small enough values [9].

5 Quasi-Newton Davidon-Fletcher-Powell method (DF)

The quasi-Newton methods that build up an approximation to the inverse Hessian are analytically the most sophisticated methods for solving unconstrained problems and represent the culmination of the development of algorithms through detailed analysis of the quadratic problem. As might be expected, the convergence properties of these methods are somewhat more difficult to discover than the ones of simpler methods.

The fundamental idea behind most quasi-Newton methods is to try to construct the inverse Hessian, or an approximation of it, using information gathered as the descent process progresses. The earliest, and certainly one of the cleverest schemes for constructing the inverse Hessian, was originally proposed by Davidon and later developed by Fletcher and Powell. It has the fascinating and desirable property that, for a quadratic objective, it simultaneously generates the directions of the conjugate gradient method while constructing the inverse Hessian. At each step, the inverse Hessian is updated by the sum of two symmetric rank one matrices, and this scheme is therefore often referred to as a rank two correction procedure. The method is also often referred to as the variable metric method, the name originally suggested by Davidon. The procedure is this: Starting with any symmetric positive definite matrix H_0 at any point x_0, and with $k = 0$,

Step 1. Set. $d_k = -H_k g_k$,

Step 2. Minimize $f(x_k + \alpha d_k)$ with respect to α to obtain x_{k+1}, g_{k+1} $p_k = \alpha_k d_k$,

Step 3. Set $q_k = g_{k+1} - g_k$ and

$$H_{k+1} = H_k + \frac{p_k p_k^T}{p_k^T q_k} - \frac{H_k q_k q_k^T H_k}{q_k^T H_k q_k}. \tag{11}$$

Update k and return to Step 1 [11].

6 Coupled model of GT-POWER and Matlab-Simulink

The provided model on the basis of output sensitivity extent compared to inputs tries to get the nearest point to the target function. Here, the input parameters are the opening and closing timing of intake and exhaust valves and the output parameter is BSFC. In order to control inputs and outputs of the model, two pieces of software are coupled. Therefore, in this way the basis of output related to GT-POWER model, the software MATLAB-SIMULINK on the basis of sensitivity analysis and Quasi-Newton algorithms gets suitable inputs to get a model with the least error [12].

7 Optimization of brake specific fuel consumption by changing the valves timing

In this chapter sensitivity analysis and Quasi-Newton algorithms are employed to optimize the timing of valves and to minimize BSFC with the software coupling technique of GT-Power and Matlab-Simulink. Moreover, the results are compared to related basic engine in order to examine their effect on reducing fuel consumption.

Fig. 4 presents the results of BSFC versus engine speed in three modes of operation by using sensitivity analysis and Quasi-Newton algorithms and also the mode in which variable valve system is not used. As shown in Fig. 4, by using a variable valve system, BSFC is reduced in all speeds, and this reduction is especially considerable at high speeds. Also, it is noted that both optimization algorithms have very close response to BSFC. The mean improvement percentage in BSFC obtained from sensitivity analysis is nearly 5.87 and from Quasi-Newton is about 6.52.

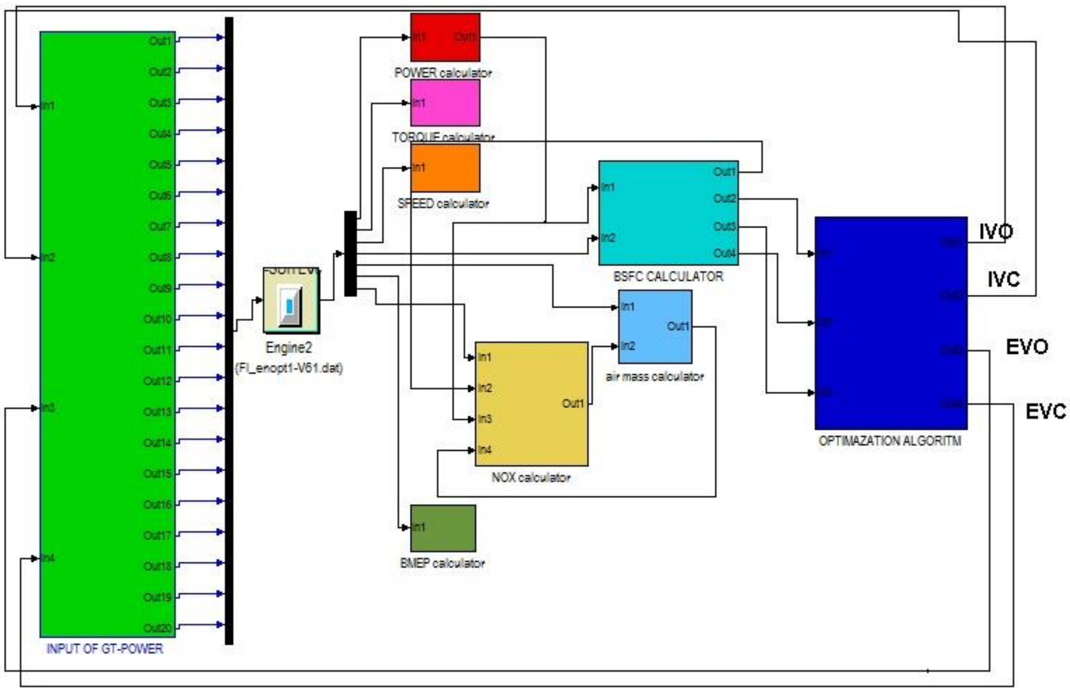


Figure 3. Coupled model of GT-POWER and MATLAB-SIMULINK.

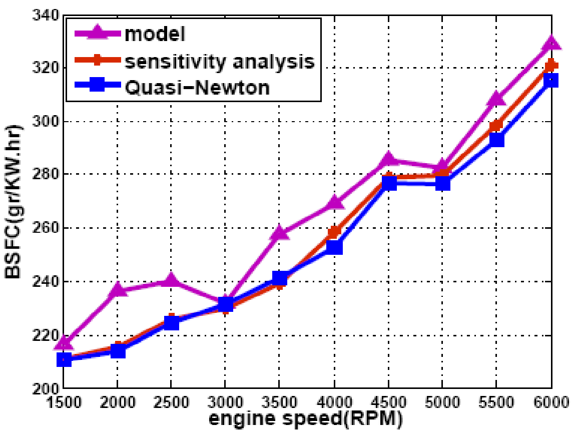


Figure 4. Variable BSFC versus engine speed in three conditions using sensitivity analysis algorithm, Quasi-Newton algorithm without variable valve system.

Fig. 5 depicts torque results versus engine speed in three conditions using sensitivity analysis and Quasi-Newton algorithms without variable valve system. As shown in Fig. 5, by using the variable valve system, the torque will be increased in all speeds. Also, it is found that when variable valve timing system for intake and exhaust valves is used, the mean improvement percentage in torque by sensitivity analysis is nearly 5.07 and by Quasi-Newton is about 6.02.

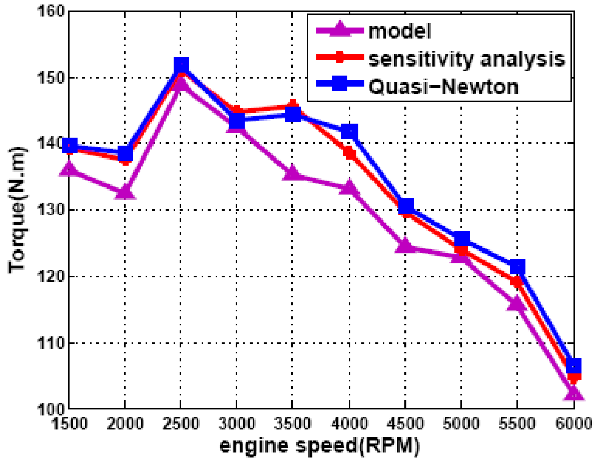


Figure 5. Comparison of torque versus engine speed in three conditions using sensitivity analysis algorithm, Quasi-Newton algorithm without variable valve system.

The results related to the number of convergent steps of both algorithms with equal initial condition in every speed are shown in Table 2. The results demonstrate that the convergent speed of Quasi-Newton algorithm in reaching an optimized point is much higher than the one of sensitivity analysis. This is due to the fact that Quasi-Newton algorithm uses suitable directions in reaching the answer.

Table 2. Results related to the number of convergent steps of both algorithms with equal initial condition at every speed

Engine speed (RPM)	Number of steps-conjugate gradient	Number of steps-sensitivity analysis
1500	4	19
2000	7	31
2500	11	17
3000	6	28
3500	15	20
4000	14	16
4500	5	15
5000	20	19
5500	17	18
6000	19	24

8 Optimized valve timing

As shown in Fig. 6, by increasing engine speed to 3500 rpm, an early opening of intake valve causes an optimized BSFC, and at 3500 rpm, this trend changes and at 4000 rpm, the late opening of intake valve causes an optimized BSFC, then up to 6000 rpm again an early opening of intake valve would be favorable for an optimized BSFC. It is also seen that both algorithms except the ones at 1500 rpm, 2000 rpm and 6000 rpm would have the same answer.

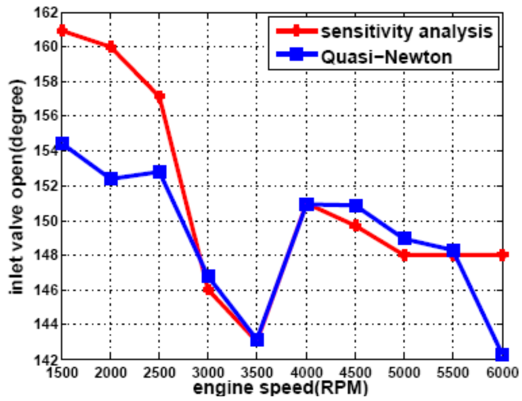
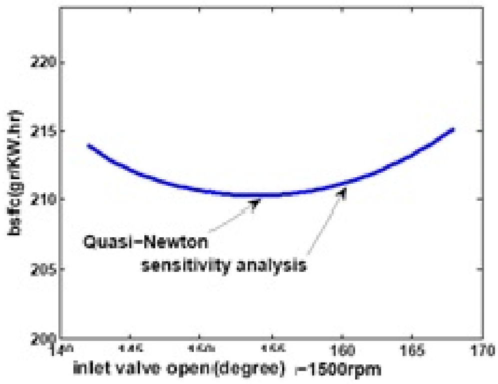
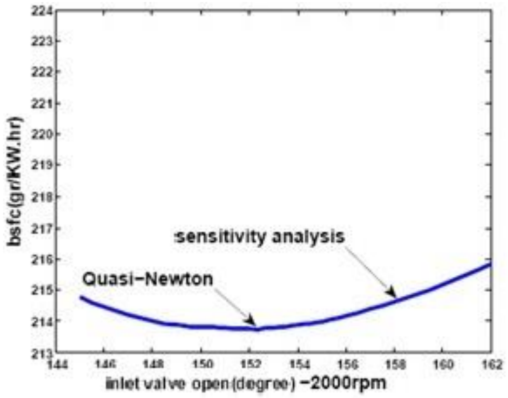


Figure 6. Variable timing of intake valve versus engine speed from sensitivity analysis and Quasi-Newton algorithms with the target of achieving an optimized BSFC.

To find out the reason for this, Fig. 7 indicate that BSFC at those rpms has trivial sensitivity at opening timing of the inlet valve and becomes smooth at the minimum point.



a)



b)

Figure 7. Variable BSFC with opening timing of inlet valve at different speeds.

Fig. 8 illustrates that by increasing the engine speed, late closing of intake valve causes the optimized BSFC and this trend slowly stops from 3000 to 3500 rpm and early closing of intake valve results in better BSFC. It can also be seen that these two algorithms exhibit the same results except for some speeds. Although, with an increasing engine speed and late closing of the intake valve, the greater air volume would enter the cylinder causing the BSFC reduction, but on the other hand, late closing of intake valve makes an amount of entrance air to the cylinder come back to the intake manifold, which finally increases the BSFC. The effects of these factors are responsible for the local maximum and minimum points in the curves.

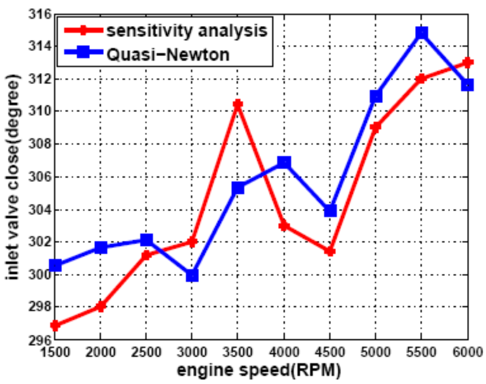


Figure 8. Variable timing of intake valve versus engine speed from sensitivity analysis and Quasi-Newton algorithms for achieving an optimum BSFC target.

The diagram for BSFC by changing the closing angle of intake valve at 2000 rpm is plotted in Fig. 9. It shows two local minima so that each algorithm is convergent with one of them, and as it is expected, BSFC of these two points are very close to each other. As shown in Fig. 10, by increasing the speed up to 3500 rpm, an early opening of exhaust valve results in optimized BSFC and with 3500 rpm this trend stops and up to 3500 rpm, late opening of the exhaust valve results in optimized BSFC, then with 4000 rpm, again, early opening of the exhaust valve results in optimized BSFC. At higher speeds, opening the exhaust valve late would be desirable.

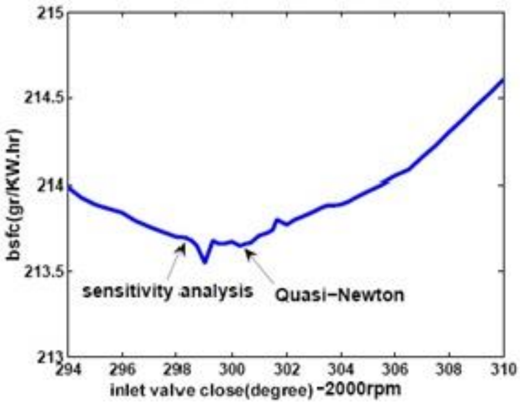


Figure 9. Variable BSFC versus the intake valve closing angle at 2000 rpm.

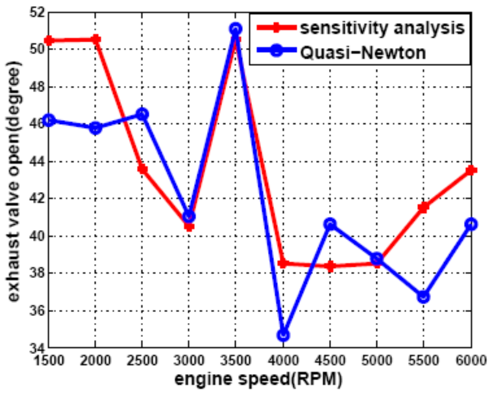


Figure 10. Changes of timing of exhaust valve versus engine speed from sensitivity analysis and Quasi-Newton algorithms for achieving an optimum BSFC target.

In Fig. 11, BSFC diagram is plotted versus the exhaust valve opening angle at 1500 rpm while other angles are fixed. It is obvious that at the minimum points, there is little sensitivity to variation of the exhaust valve opening angle because the diagram is smooth at the minimum point and every algorithm is convergent to some place of this diagram smoothness.

As shown in Fig. 12, by increasing the speed, late closing of exhaust valve results in optimized BSFC and at 4500 rpm this trend stops a little and at 5000 and 5500 rpm an early closing of exhaust valve causes an increasingly optimized BSFC. Then at 6000 rpm again closing the exhaust valve late would be desirable.

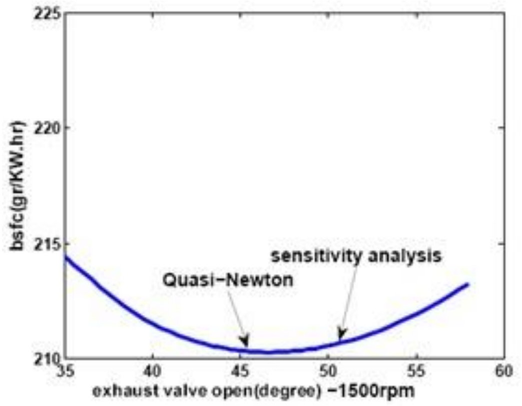


Figure 11. Variable BSFC versus the exhaust valve opening angle at 1500 rpm.

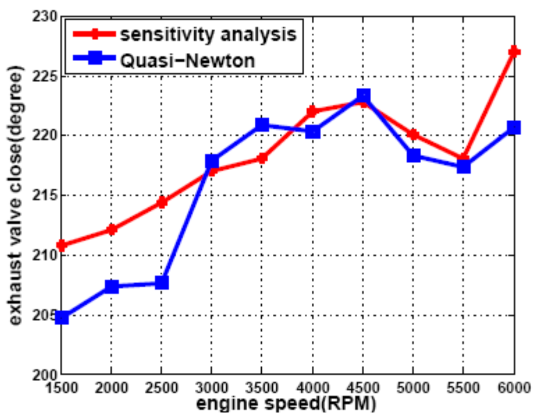


Figure 12. Changes of the opening exhaust valve angle versus engine speed from sensitivity analysis and Quasi-Newton algorithms with an optimum BSFC target.

9 Conclusions

In this paper sensitivity analysis and Quasi-Newton algorithms were presented and compared for the purpose of optimizing the control parameters such as valves timing and brake specific fuel consumption using GT-POWER. After model verification, GT-POWER model was coupled with MATLAB-SIMULINK to control inputs and outputs by sensitivity analysis and Quasi-Newton algorithms. It should be noted that these conclusions refer specifically to the investigated engine, while the derived conclusions are not generally valid for all similar engine designs. The following results were obtained:

1) The convergent speed of the Quasi-Newton algorithm for reaching the optimized point is much higher than sensitivity analysis. This results from the point that Quasi-Newton algorithm uses suitable directions for reaching the answer.
2) By increasing the engine speed to 3500 rpm, early opening of intake valve causes optimized BSFC, and at 3500 rpm this trend changes and at 4000 rpm an late opening of the intake valve causes optimized BSFC, then up to 6000 rpm again the early opening of the intake valve would be favorable for optimized BSFC. Also it is seen that both algorithms except at 1500 and 6000 rpm would have the same answer.
3) By increasing the speed, late closing of the exhaust valve results in optimized BSFC and at 4500 rpm this trend stops a little, and at 5000 rpm and 5500 rpm, early closing of the exhaust valve causes better BSFC. Then at 6000 rpm again, closing the exhaust valve late would be desirable.

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