Optimization of diesel engine performance by the Bees Algorithm

Siti Azfanizam Ahmad, Devaraj Sunthiram
Department of Mechanical and Manufacturing Engineering, Faculty of Engineering, Universiti Putra Malaysia, 43400 UPM Serdang, Selangor, Malaysia
s_azfanizam@upm.edu.my

Abstract. Biodiesel recently has been receiving a great attention in the world market due to the depletion of the existing fossil fuels. Biodiesel also becomes an alternative for diesel No. 2 fuel which possesses characteristics such as biodegradable and oxygenated. However, there are facts suggested that biodiesel does not have the equivalent features as diesel No. 2 fuel as it has been claimed that the usage of biodiesel giving increment in the brake specific fuel consumption (BSFC). The objective of this study is to find the maximum brake power and brake torque as well as the minimum BSFC to optimize the condition of diesel engine when using the biodiesel fuel. This optimization was conducted using the Bees Algorithm (BA) under specific biodiesel percentage in fuel mixture, engine speed and engine load. The result showed that 58.33kW of brake power, 310.33 N.m of brake torque and 200.29/(kW.h) of BSFC were the optimum value. Comparing to the ones obtained by other algorithm, the BA produced a fine brake power and a better brake torque and BSFC. This finding proved that the BA can be used to optimize the performance of diesel engine based on the optimum value of the brake power, brake torque and BSFC.

1. Introduction
The BA is one of popular swarm-based algorithms and it mimics the real foraging behavior of honey bees. In natural, a colony of bees extends themselves over a distance in multiple directions to explore a big number of food sources for their survival. Bees normally deployed their foragers to good fields. Theoretically, bees usually go to the flowers which contain more nectar which can be collected in minimum efforts. The foraging process of the bees starts with a colony of bees in the form of scout bees are being sent to look for some exciting flower patches which contain large amount of nectar. Once the scout bees return to the hive, they deposit their nectar and go to the “dance floor” where they perform the “waggle dance” [1]. This “waggle dance” is vital in bee’s colony because it acts as a language to communicate with other bees. This communication contains three important messages about the flower patch which are the direction of the flower patch found, the distance of the hive and their rating on the nectar found. These three pieces of information help them to return to the flower patch precisely, without any directions or maps. The “waggle dance” is also enabled the bees to spread in different flower patches to make sure the food that they are going to collect is in a quality manner and sufficient amount of energy is invested. After the dance, the scout bees return to the flower patches with other bees which are known as followers. This mechanism makes them gather their food in a quick and efficient way [1].

The BA is a well-researched study that takes place in social insects. Bees exhibit many characteristics which proved their usage as models for optimization problems. Examples of their
features are a division of labors, communication in group levels and cooperative behavior. In addition, these insects' algorithm performs a neighborhood search which is combined with random search. This makes the algorithm to perform on optimization problem. This algorithm proved that it can be used to optimize problems as other algorithms do [2], [3], [4], [5].

Meanwhile, diesel fuel in general is any liquid fuel used in diesel engines, whose fuel ignition takes place as a result of compression of the inlet air mixture and then injection of fuel. The diesel engine is an internal combustion engine in which ignition of the fuel that has been injected into the combustion chamber is caused by the high temperature. Diesel engine works by compressing only the air. This increases the air temperature inside the cylinder to such a high degree that it ignites atomised diesel fuel that is injected into the combustion chamber. This contrasts with spark-ignition engines such as a petrol engine or gas engine, which use a spark plug to ignite an air-fuel mixture.

The performance of diesel engine is significantly influenced by the biodiesel percentage in fuel mixture, engine speed and engine load [6]. The fuel consumption increases with higher biodiesel concentration [7] while different vehicle speed and engine load results in different impact on vehicle emissions [8]. The brake power is the power available at the crankshaft and brake torque is the power of the braking system. Higher brake power and brake torque is more preferable [9]. The BSFC is a measure of the fuel efficiency burns and causes rotational power. In other words, it is the rate of fuel consumption divided by the power produced. In contrast to the brake power and brake torque, the minimum BSFC is aimed in a vehicle [9]. The configuration of percentage in fuel mixture, engine speed and engine load affects the performance of the brake power, brake torque and BSFC. The use of diesel fuels blended with certain percentage of biodiesel are expected to bring positive impacts to the society and environments as this mixture fuel is able to reduce emissions along-with reduction of the petroleum fuel consumption.

2. Methodology
The BA is known for optimizing problems which uses the inspiration from natural honey bees in their characteristics which help to find an optimal solution for the problem [1]. The BA has its parameter namely, the number of scout bees (n), number of sites selected out of n visited sites (m), number of elite sites out of m selected sites (e), number of bees recruited for the elite sites (nep), number of bees recruited for other selected sites (nsp), size of patches (ngh) and stopping criterion. Optimization process starts by forming a number of scout bees (n) in their colony. The scout bees associate to a possible solution to an optimization problem. Each solution found by the scout bees is to be arranged in a descending order of the fitness. Then, the best m sites are selected for a neighborhood search. In the neighborhood search, more bees (nep) are sent to elite (e) sites whereas fewer bees (nsp) are sent to non-elite (m-e) sites. The solutions generated by this exploitative search are expected to be better than the one found by a single scout bee.

Unsettled scout bees (n-m) are used to search for random solution in space. The purpose of this explorative search is to prevent the bees from being trapped in local optima. At the end of each iteration, new scout bees are formed and each solution found by the scout bees are sorted out for the next iteration. The combination of exploitative and explorative search helps to find the best solution in an effective manner. The steps are then repeated until the intended solution is found or the stopping criterion is met.

Figure 1 shows a flowchart which illustrates the steps of the study. The research starts with the problem identification, followed by the literature review which briefly explains about the BA and diesel engine. Then, the research continues with a preliminary test to find the best configuration of biodiesel percentage (x1), engine speed (x2) and engine load (x3) that makes up the maximum brake power, maximum brake torque and minimum BSFC. The next step is to find the optimum value of x1, x2 and x3 using the BA, within a guided searching space. The optimization process is carried on until a stopping criterion is met. In this problem, 100 iterations was set as the stopping criterion. The final step is to find the optimum brake power, brake torque and BSFC using the optimum x1, x2 and x3, obtained from the previous step.
The equation (1), (2) and (3) is used to find the brake power, brake torque and BSFC respectively [6].

Brake Power ($kW$) = $-47.32 + (-0.08)x_1 + (0.056)x_2 + (0.205)x_3 + (0.0002)x_1^2 + (-1.4x10^{-5})x_2^2 + (-5.499x10^{-4})x_3^2 + (0.0004)x_1x_3 + (0.0002)x_2x_3$  

Brake Torque ($N.m$) = $-299.277 + (-0.524)x_1 + (0.302)x_2 + (4.654)x_3 + (0.00362)x_1^2 + (-7.401x10^{-5})x_2^2 + (-0.00637)x_3^2 + (-3.771x10^{-4})x_2x_3$  

BSFC ($g/kW.h$) = $298.74 + (0.5)x_1 + (-0.088)x_2 + (-0.236)x_3 + (0.0014)x_1^2 + (2.67x10^{-5})x_2^2 + (-0.00018)x_1x_2 + (-0.00336)x_1x_3$  

3. Result and Discussion

3.1 Preliminary test
A total of 15 preliminary tests were conducted by using multiple combinations of percentage of biodiesel ($x_1$), revolution per minute (rpm) ($x_2$) and percentage of engine load ($x_3$) in order to determine which combinations led to high quality of performance. Table 1 shows the combinations of biodiesel percentage, rpm and engine loads used to determine the amount of brake power, brake torque and BSFC [6]. The value of $x_1$, $x_2$ and $x_3$ was simply substituted into equation (1), (2) and (3) to find
the brake power, brake torque and BSFC, respectively. The results showed that the maximum brake power, 60.04 kW, maximum brake torque, 320.25 N.m and minimum BSFC, 198.93 g/(kW.h) all took place when the biodiesel percentage was 50%, engine speed was 1900rpm and 100% engine load.

### Table 1. The experimental design [6].

| Test number | Biodiesel percentage in fuel mixture (%) | Engine speed (rpm), x_2 | Engine load (%) | Brake Power (kW) | Brake Torque (N.m) | BSFC (g/(kW.h)) |
|-------------|----------------------------------------|--------------------------|----------------|-----------------|-------------------|----------------|
| 1           | 20                                     | 1365                     | 40             | 20.08           | 121.40            | 221.89         |
| 2           | 80                                     | 1365                     | 40             | 17.44           | 111.68            | 237.48         |
| 3           | 20                                     | 2435                     | 40             | 31.63           | 127.48            | 232.44         |
| 4           | 80                                     | 2435                     | 40             | 28.99           | 117.76            | 236.47         |
| 5           | 20                                     | 1365                     | 80             | 36.88           | 256.40            | 209.76         |
| 6           | 80                                     | 1365                     | 80             | 35.20           | 246.68            | 217.29         |
| 7           | 20                                     | 2435                     | 80             | 56.99           | 246.33            | 220.31         |
| 8           | 80                                     | 2435                     | 80             | 55.31           | 236.61            | 216.28         |
| 9           | 0                                      | 1900                     | 62.5           | 42.95           | 228.56            | 213.18         |
| 10          | 100                                     | 1900                     | 62.5           | 39.45           | 212.36            | 221.98         |
| 11          | 50                                     | 1000                     | 62.5           | 15.59           | 153.99            | 231.69         |
| 12          | 50                                     | 2800                     | 62.5           | 43.13           | 148.93            | 239.72         |
| 13          | 50                                     | 1900                     | 25             | 19.82           | 84.65             | 229.23         |
| 14          | 50                                     | 1900                     | 100            | **60.04**       | **320.25**        | **198.93**     |
| 15          | 50                                     | 1900                     | 62.5           | 40.70           | 211.41            | 214.08         |

### 3.2. Optimization of diesel engine with the Bees Algorithm

An optimum point of diesel engine was calculated by applying the equation (4) [6].

$$\text{Goal function} = -\frac{\text{equation (1)}}{\text{Power (max)}} - \frac{\text{equation (2)}}{\text{Torque (max)}} + \frac{\text{equation (3)}}{\text{BSFC (min)}} + \frac{0.00012}{0.00014} + \frac{88}{83} + \frac{560}{589}$$  \(4\)

This goal function was used to determine the optimum values of the biodiesel percentage, engine speed and engine load. The denominator of the first three terms respectively is the maximum brake power, maximum brake torque and minimum BSFC that was obtained in preliminary test. The last three terms are the emissions characteristics from the diesel engine, which are the emissions of hydrocarbon (HC), carbon monoxide (CO) and nitrogen oxide (NO\textsubscript{X}) respectively [6].

The parameter of the BA is shown in table 2 and the algorithm was run for 100 iterations. The searching space for the BA was set based on the best value of x_1, x_2 and x_3 in table 1 and optimum values gained by ABC [6], which was {50, 1900, 97} for the lower limit and {85.63, 2208, 100} for the upper limit. From this experiment, the goal function or fitness produced was 1.92951. The trend of the fitness value against the number of iteration is illustrated in figure 2. The fitness was improving drastically at the early stage of optimization but then stagnated when iteration reached 82. The fitness remained 1.92951 until 100 iterations and the optimum value gained by the BA is shown in table 3.
Table 2. Parameter setting of the BA.

| Parameter       | Value |
|-----------------|-------|
| n, number of scout bees | 10    |
| m, number of sites selected out of n visited sites | 3     |
| e, number of elite sites out of m selected sites | 1     |
| nsp, number of bees sent to non-elite sites | 2     |
| nep, number of bees sent to elite sites | 3     |
| ngh, size of patches | 1     |

Figure 2. The trend of the fitness against number of iterations.

Table 3. Optimum values gained by the BA.

| Biodiesel Percentage ($x_1$) | Engine Speed ($x_2$) | Engine Load ($x_3$) |
|-------------------------------|----------------------|---------------------|
| Optimum Values               | 74.67%               | 1907.81rpm          | 97.02%              |

Subsequently, these optimum values were substituted back into equation (1), (2) and (3) to find the optimum condition for the brake power, brake torque and BSFC, respectively. The result is shown in table 4 in which the values of the brake power, brake torque and BSFC was 58.33kW, 310.33N.m and 200.29g/(kW.h) respectively. Comparing to the Artificial Bee Colony (ABC) [6], the BA produced less brake power but outperforming the former on the brake torque and BSFC. Lower engine speed, 1907.81rpm comparing to 2208.00rpm [6] at similar percentage of engine load 97.02% has given an advantage to the BA to produce a higher brake torque and lower BSFC. This finding proved that the BA was able to estimate the optimum point in diesel engine and hence the algorithm has potential to improve the diesel engine performance.

Table 4. Performance of the BA.

|                     | Brake Power (kW) | Brake Torque (N.m) | BSFC (g/(kW.h)) |
|---------------------|------------------|--------------------|-----------------|
| Optimum Value by ABC [6] | 63.00            | 298.00             | 202.85          |
| Optimum Value by BA   | 58.33            | 310.33             | 200.29          |
4. Conclusion
In conclusion, the BA can be used to optimize the brake power, brake torque and BSFC which influence the performance of the diesel engine. The objective which was to optimize the diesel engine performance using biodiesel blended fuels was accomplished. The goal function value was obtained by setting a searching space based on a preliminary test and the optimum values from literature. The optimum conditions for biodiesel percentage, engine speed and engine load was 74.67%, 1907.81rpm and 97.02% respectively. The optimum values of the brake power, brake torque and BSFC to optimize diesel engine performance was 58.33 kW, 310.33 N.m and 200.29g/(kW.h) respectively. The brake power was less than the one obtained by the ABC but the brake torque and BSFC was improved with the BA. This finding proved that the BA can be used to optimize the diesel engine performance. For further research, it is necessary to consider the emissions of HC, CO and NO\textsubscript{x} in the problem. It is also interesting to study the sensitivity of the parameter setting of the BA in this optimization problem.

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