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Parametric analysis and optimization of fuel delivered and Torque by FIP of Diesel Engine using Genetic Algorithm

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Abstract

This paper explains the optimization of control parameters used for optimum control of torque and fuel delivered by the FIP of the Automotive engine. The parameters observed were fuel delivery, input current to driving motor, rpm of the pump, control rack travel and number of strokes. The fuel-injection system is the most vital component in the working of CI engine. The engine performance (power output, efficiency) is greatly dependent on the effectiveness of the fuel injection system and its parameters. The experiment is conducted on two MICO Bosch FIP of TATA Engine (TATA 207 and TATA Sumo FIP) as per DoE using three input parameters at different ranges and conditions. The mathematical models are developed for Torque and Fuel delivery of FIP. This paper also explains the optimization of control parameters using GA to study the optimum conditions for economic fuel delivery and optimum torque control.

Key words-Fuel delivery, Torque, Fuel Injection Pump (FIP), Optimization by GA, MATLAB- GA

1. Introduction

The fuel-injection system is the most vital component in the working of CI engine. The engine performance (power output, efficiency) is greatly dependent on the effectiveness of the fuel injection system. It has the important duty of initiating and controlling the combustion process. In this project we have tried to design a Fuzzy Logic Controller to control the fuel delivery of fuel injection pump. We have replicated the characteristics of two pumps. The first pump MICO BOSCH fuel injection pump (combination number F002 A0Z 243-E 040 1264 00) is used by TATA Engineering and Locomotive Co. Ltd. for vehicular application. It is used for TATA engine model 697 D (TC) which is installed in TATA 207 vehicle and TATA Sumo. . The second MICO BOSCH fuel injection pump (combination number: 9400 030 507-E 040 0256 00) is used by TATA Engineering, and Locomotive Co. Ltd. It operates in TATA trucks and heavy duty vehicles. In order to determine the fuel delivery characteristics of the pumps we tested them on a fuel injection pump test rig. The parameters observed were fuel delivery, input current to driving motor, rpm of the pump, control rack travel and number of strokes. The outputs were fuel delivery and current. The inputs which were varied were rpm, control rack travel and number of strokes. The data collected was analyzed to generate mathematical models using regression analysis.

II. Fuel Injection Pump

The function of a fuel injection pump is to pump metered quantity of fuel into the cylinder at the right time. Therefore it's essential while testing a fuel injection pump to test and calibrate the injection timing of the various injectors and the quantity of fuel injected per injection. The advancement in electronics and measurement technologies has led to substantial improvement of engine fuel-injection control systems, both in hardware configuration and in control methodology[1]. The basic idea of fuel injection control system is to control the output of fuel through injectors based on a set of inputs. A diesel fuel injector sprays an intermittent, timed, metered quantity of fuel into a cylinder, distributing the fuel throughout the air within. Therefore it's essential while testing a fuel injection pump to test and calibrate the injection timing of the various injectors and the quantity of fuel injected per injection.

The injection timing is a crucial factor in deciding the combustion efficiency in a diesel engine[2] and to avoid knocking. Therefore the first step of calibrating a fuel injection pump is to set the injection timing of each injector as per the firing order. The second important parameter is quantity of fuel delivered. Delivery of right quantity of fuel is very essential for efficient operation of an engine. Excessive fuel leads to loss of efficiency and incomplete combustion. Such combustion leads to increased pollutants and smoke in exhaust[4]. Insufficient fuel leads to lean mixture in combustion chamber this causes excessive heating of combustion chamber. It is also necessary for all the injectors to deliver same quantity of fuel to their respective cylinders. The fuel delivered by fuel injector is controlled by two parameters, control rack and speed

(RPM) of the fuel injection pump. The following are the functional requirements of an injection system[6]. a) Accurate metering of fuel injected per cycle. b) Timing of injection of fuel correctly. c) Proper control of rate of injection. d) Proper atomization of fuel. e) Proper spray pattern. f) Uniform distribution of fuel droplets. g) To supply equal quantities of metered fuel to all cylinder in case of multi cylinder engines. h) No lag during beginning and end of injection, to prevent dribbling.

Therefore we have tested two fuel injection pumps to determine their operational characteristics and the relation between the various inputs and the fuel delivery. Mathematical models have been generated using the collected data by regression analysis. In order to determine the fuel delivery characteristics of the pumps we tested them on a fuel injection pump test rig. The parameters observed were fuel delivery, input current to driving motor, rpm of the pump, control rack travel and number of strokes. The outputs were fuel delivery and current. The inputs which were varied were rpm, control rack travel and number of strokes. The data collected was analyzed to generate mathematical models using regression analysis.

III. Experimental Method and mathematical models

1. Disassemble the pump for cleaning. 2. Clean the pump 3.Assemble the pump 4.Mount the pump on the FIP test rig 5. Make all the connections of fuel lines. 6. Calibrate the firing order and timing of each individual injector with the help of the dial provided.7. Set the lift as per the specification in the manual. 8. Set the average rpm, 500 stroke and the rack travel as per the manual and adjust the nozzle so that all the nozzles delivers equal amount of fuel. 9.Now set the required rpm, stroke and the control rack travel and measure the amount of fuel delivered 10.Also measure the current flowing in the motor using a clamp meter 11.Calculate the torque from the following formula $P=\sqrt{3}.V.I = 2\pi.(RPM).T/60$

IV. Mathematical models and Regression analysis Details:

There are six mathematical models for each of the two pumps, three for fuel delivery and three for torque. Based on the observations as per design of experiments the multiple regression results for Torque developed by pump is shown below: $T = 46212 + 7.28\ x1 - 558\ x2 + 5.61\ x3$.

Based on the design of experiments the mathematical models are developed using multiple regressions for various objectives using following FIP:

1. MICO BOSCH FIP (combination number: F002 A0Z 243-E 040 1264 00):
2. MICO BOSCH FIP (combination number: 9 400 030 507-E 040 0256 00):

Six mathematical models for each pump, fuel delivery and torque requirement equations for each delivery condition have been generated with sufficient reliability and are in table-2.

V. Genetic Algorithm (GA) based optimization

GA is based on mechanics of natural selection and natural genetics, which are more robust and more likely to locate global optimum. It is because of this feature that GA goes through solution space starting from a group of points and not from a single point. The cutting conditions are encoded as genes by binary encoding to apply GA in optimization of machining parameters. A set of genes is combined together to form chromosomes, used to perform the basic mechanisms in GA, such as crossover and mutation. Crossover is the operation to exchange some part of two chromosomes to generate new offspring, which is important when exploring the whole search space rapidly. Mutation is applied after crossover to provide a small randomness to the new chromosomes. To evaluate each individual or chromosome, the encoded cutting conditions are decoded from the chromosomes and are used to predict machining performance measures. Fitness or objective function is a function needed in the optimization process and selection of next generation in genetic algorithm. Optimum results of cutting conditions are obtained by comparison of values of objective functions among all individuals after a number of iterations. Besides weighting factors and constraints, suitable parameters of GA are required to operate efficiently. GA optimization methodology is based on performance predictions models developed from a comprehensive system of theoretical analysis, experimental database and numerical methods. The GA parameters along with relevant objective functions and set of performance constraints are imposed on GA optimization methodology to provide optimum cutting conditions.

VI.GA Implementation

The FIP parameter optimization procedure using genetic algorithm is shown in Figure 1. In this figure, initial population means the possible solutions of the optimization problem, and each possible solution is called an individual[7]. In this work, a possible solution is formed by values of the input variables (x1, x2….x3) So, these are shown as a binary string. However, they need to be changed into real numbers when being applied to the optimization problem, since the experimenter sets the FIP parameters with real values, instead of binary codes.

i) Objective function: The objective function in this problem is to minimize the Fuel delivered and Torque required.

a) The Fuel delivery, $fd = -\ 85.2 + 0.0156\ x1 + 6.25\ x2 + 0.0726\ x3$

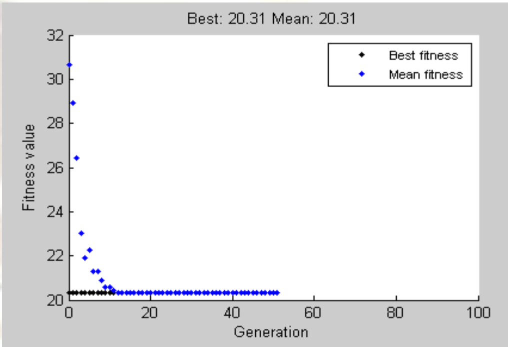
b) Torque requirement = T = 46212 + 7.28 x1 - 558 x2 + 5.61 x3
Where x1=N, x2=R and x3=S are actual values of Speed (Rpm), Control rack travel and number of strokes.
ii) Representation:
We need to decode the decision variables from the binary strings. The length of string depends on the precision required. The required bit size is denoted by 'n', as the actual value is calculated by following expression from the decoded value.
Actual value = Xmin + decimal.((Xmax-Xmin)/2^n-1) Where decimal represents the decoded value of the substring for corresponding speed and feed parameters for length of sub strings 'n'=2.
a) Xmin for speed = 800 rpm, Xmax for speed = 1200 rpm, 800<x1<1200
b) Xmin for rack travel = 11.4mm, Xmax for rack travel = 11.9mm, 11.4<x2<11.9
c) Xmin for No of strokes = 300 mm/rev, Xmax for no of strokes = 500mm/rev, 300<x3<500.
iii)Evaluation:
The next step is to evaluate each string in the population, for that the actual value of N, R and S as input parameter to calculate the output objective f(x). Then substitute f(x) in objective function expression to obtain the function value, It is denoted by f(x).Then the fitness function value is calculated as: F(x) = 1/ (1+f(x)) used in reproduction system. Similarly other strings in the population are evaluated and the selection of fitness is as per roulette wheel approach.
iv)Crossover:
The string in mating pool (Fitness) is used in crossover operation. Then two strings are selected in order and crossed at random site. For this we select the strings from top list. After cross over the strings are made to perform mutation in the intermediate population. For every bitwise mutation we flip coin with probability. If the outcome is true we alter the bit to'0' or '1' depending on bit value. Thus from the above procedure we get new population. Evaluate each string as before by identifying the string for each variable. This completes one iteration of the GA approach. Then increment the generation counter to proceed to next iteration until last count.

VI.1 Steps used in GA
1. Define the bit string with the necessary length (see explanation of the coding above)
2. Make random initial – population. 3. Start genetic algorithm as shown in algorithm.
4. After the mutation step: transform the bit string of each individual back to the model-variables.
5.Test the quality of fit for each parameter set (= individual) (Ex. using the sum of squared residuals, as the quality of fit has to be increasing with better quality, take 1 /f(x) as value for the fitness).
6. Check if quality of the best individual is good enough, if so: stop iteration, otherwise restart algorithm: do selection, mating, crossover, and mutation, calculate fitness.

VII. Genetic algorithm parameters and its plots
Population type = Double vector Population size =50 Maximum number of generation =100, Number of problem variables =6 Probability of crossover =80% Probability of mutation= 1%, Selection function = Roulette, Selection type = Double point, Mutation function = Uniform.

a)GA Output plots: Pump-1 in full load condition for Fd1.

Figure-1, Pump1,Plot of No of generations with fitness value by GA for Fuel delivered (Fd1)



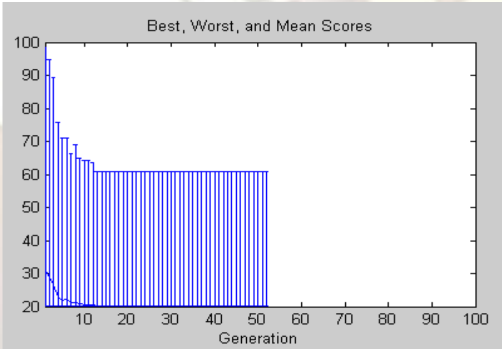
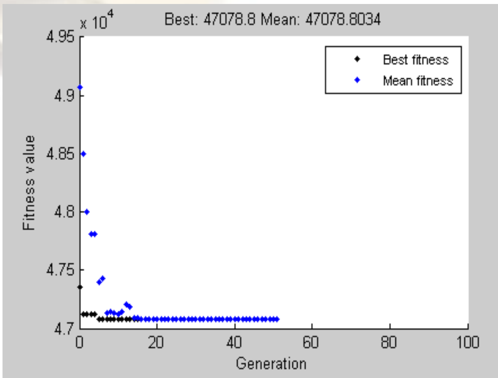
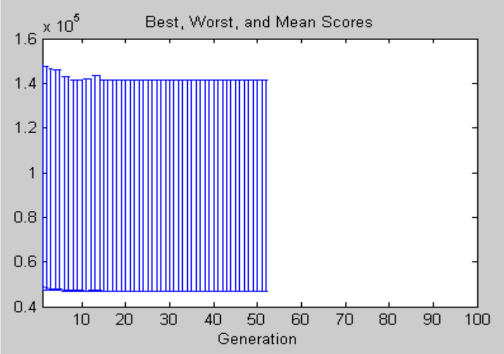


Figure-2, Pump-1:Plot of No of generations with fitness value by GA for Torque (T1).





It is found that Fitness value remains constant as generation increases. This means that output function value is optimum. The main characteristic of the GA's is that they operate simultaneously with a huge set of search space points, instead of a single point (as the conventional optimization techniques). Besides, the applicability of the GA's is not limited by the need of computing gradients and by the existence of discontinuities in the objective function (performance indexes). This is so because the GA's works only with function values, evaluated for each population individual. The major drawback in the GA's is the large use of computational effort when compared with the traditional optimization methods.

VIII. Discussions and outcome of Results:

1. From the experimental data mathematical models are developed for each pump, fuel delivery and torque requirement equations have been generated with sufficient reliability using multiple regression analysis. Each equation has three inputs: N - Speed (Rpm), R - Control rack travel, S – Number of strokes. There are two outputs viz fuel delivery and torque requirement, for each running condition.
2. From the generated mathematical models we have plotted graphs to determine effect of the variables on the outputs.
3. During full load delivery fuel delivery and torque requirement increase with increasing rpm keeping the control rack travel and number of strokes constant and also fuel delivery and torque requirement increase with increasing control rack travel keeping the rpm and number of strokes constant.
4. In course of delivery the torque decreases sharply with increase in both rpm and control rack travel independently while the fuel delivery decreases slightly and is almost constant in response to increase in rpm. It falls a bit more substantially with rise in control rack travel.
5. The fuel delivery drops sharply with increase in rpm and control rack travel but the torque requirement shows opposite trend. It rises with the increase of both inputs and rather steeply in case of control rack travel rise.

IX. Conclusions

This paper explains the parametric effect on fuel delivered and torque developed by FIP of Diesel engine to have optimum control and economic usage of fuel. The parameters observed were fuel delivery, input current to driving motor (Torque). The inputs varied are rpm of the pump, control rack travel and number of strokes. This study helps to explain the optimum parameters required to achieve optimum performance[5] of FIP system of engine. This also helps in following functional requirements of an injection system:
a) Accurate metering of fuel injected per cycle. b) Proper control of rate of injection. c) Proper atomization of fuel. d) Proper spray pattern. e) Uniform distribution of fuel droplets. f) To supply equal quantities of metered fuel to all cylinder in case of multi cylinder engines. g) No lag during beginning and end of injection to prevent dribbling.

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XI. Author

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XII. NOMENCLATURE OF TERMS USED

N = x1= Speed (Rpm), R = x2= Control rack travel, S= x3 = Number of strokes, Fd = Fuel delivered, T= Torque required, Suffix Fd1…Fd3 (T1…T3) are for Full load, Course and Idling load conditions. FIP = Fuel Injection Pump. GA = Genetic algorithm. f(x)= objective.

Table-1, Ranges of Inputs and outputs used in the study

Inputs or Parameters	Number of strokes (S)	RPM of pump (N)	Control rack extension (R)
Ranges of Inputs	800-1000-1200	11.4-11.7-11.9	300-400-500
Output Objectives	Fuel delivered (Fd) in ml.	Torque (T)	-----------

Table-2(a) Mathematical models

Working condition-Pump-1	Torque delivered
Full load delivery	T = 46212 + 7.28 x1 - 558 x2 + 5.61 x3
Course of delivery	T = 556820 - 81.1 x1 - 36712 x2 + 0.28 x3
Idling delivery	T = 242873 - 512 x1 - 7.1 x3
Full load delivery-Pump-2	T= 84528 - 32.5 x1 - 1193 x2 + 16.9 x3
Course of delivery	T = 126417 - 101 x1 - 272 x2 + 29.0 x3
Idling delivery	T= 209990 - 405 x1 + 5630 x2 - 15.0 x3

Table-2(b) Mathematical models

Working condition-Pump-1	Fuel delivered
Full load delivery	fd = - 85.2 + 0.0156 x1 + 6.25 x2 + 0.0726 x3
Course of delivery	fd = 19 + 0.0017 x1 - 1.2 x2 + 0.0560 x3
Idling delivery	fd = 8.16 - 0.0330 x1 + 0.0273 x3
Fullload delivery-Pump-2	fd = - 47.6 + 0.0338 x1 + 2.00 x2 + 0.0472 x3
Course of delivery	fd = 108 - 0.00026 x1 - 10.7 x2 + 0.0621 x3
Idling delivery	fd = - 1.46 - 0.0176 x1 + 0.692 x2 + 0.0231 x3

Table-3(a), Optimum GA results for pump-1.

Pump-1: a)Full load	Fd1	800	11.4	300	20.31
	T1	800	11.9	300	47078.8
b)Course delivery	Fd2	800	11.9	300	22.882
	T2	1200	11.9	500	23455.79
c)Idling	Fd3	1200	11.72	300	-23.169
	T3	1200	11.81	500	-373708.47

Table-3(b), Optimum GA results for Pump- 2.

a.Full load	Fd1	800	11.4	300	16.4
	T1	1200	11.9	300	36502.53
b.Course of delivery	Fd2	1196	11.9	300	10.982
	T2	1200	11.9	300	10967.62
c. Idling	Fd3	1200	11.4	300	-7.758
	T3	1200	11.4	500	-219073.42