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Optimisation of Fuel Injection Pump Parameters of Tata 1613 & Tata 609 Engine Using Diesel & Biodiesel

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Abstract

Often called 'the heart of the engine', the fuel injection system is without any doubt one of the most important systems. It meters the fuel delivery according to engine requirements, it generates the high injection pressure required for fuel atomization, for air-fuel mixing and for combustion and it contributes to the fuel distribution in the combustion system-hence it significantly affects engine performance emissions and noise. In this Investigation optimization of control parameters used for optimum control of fuel delivered by the FIP of the Automotive engine is Analyzed. 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 1613 and TATA 609 FIP) as per DoE using three input parameters at different ranges and conditions. The mathematical models are developed for Fuel delivery of FIP using taguchi,anova regression. This paper also explains the optimization of FIP parameters using biodiesel.

Key words-Fuel delivery, InjectionPump (FIP), DoE, Taguchi,Anova.

I. Introduction

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. 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 as shown in fig 1 The injection timing is a crucial factor in deciding the combustion efficiency in a diesel engine 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. 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. 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.

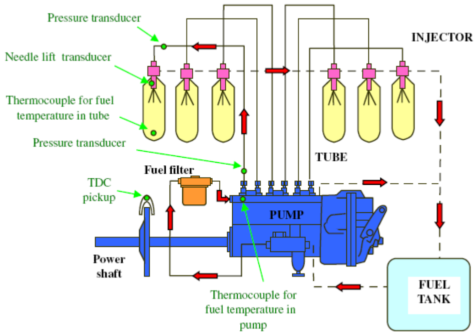

Figure 1 Fuel Injection Pump

II. Experimental details

a) Design of experiments

Taguchi and Konishi had developed Taguchi techniques.[8] These techniques have been utilized widely in engineering analysis to optimize the performance characteristics within the combination of design parameters. Taguchi technique is also power tool for the design of high quality systems. It introduces an integrated approach that is simple and efficient to find the best range of designs for quality, performance, and computational cost [9]. In this study we have consider 3 factors which affect majorly on performance characteristic such as (A)No of strokes., (B) control rack travel (C) RPM. The design of experiment was carried out by Taguchi methodology using Minitab 14 software. In this technique the main

Fig.2.1 Fuel Injection Pump Test Rig

Fig. 2.2 Fuel Pump(TATA 1613, 6 Cylinder)

objective is to optimize Fuel delivery of fuel injection pump that is influenced by various process parameters

b) Selection of orthogonal array

Since 3 controllable factors and three levels of each factor were considered L9 (3**3) Orthogonal Array was selected for this study

c) Experimental set up

A Series of experiment was conducted to evaluate the influence of fuel injection pump parameters on fuel delivery. The test was carried out on fuel pump test rig. Following steps were performed to conduct the experiment. 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.Repeat the same procedure for biodiesel.

d) Work material

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. The second MICO BOSCH fuel injection pump (combination number: 9400 030 659-E 040 0592 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 bio diesel used in this experiment is extracted from soybean Oil having following properties viz. Calorific value (MJ/Kg) - 39.76, Relative density 0.885, kinematic viscosity at 40^0C is 4.08,cetane number is 40-53.

III. Experimental conditions

The experiments were carried out on fuel injection pump test system for fuel delivery testing . There are three input controlling factors selected having three levels. Details of parameters and their levels used shown in the table 3.1

Table 3.1(a): Process parameters and levels for pump 1

A	No of strokes	400	500	600
B	Control rack travel	11.3	11.5	11.7
C	rpm	800	900	1000

Table 3.1(b): Process parameters and levels for pump 2

A	No of strokes	400	500	600
B	Control rack travel	9.2	9.4	9.6
C	rpm	650	750	850

Table 3.2(a): Layout for Experimental Design according to L9 Array for pump 1

EXP. NO.	A No of strokes	B Control rack travel	C rpm
1	400	11.3	800
2	400	11.5	900
3	400	11.7	1000
4	500	11.3	900
5	500	11.5	1000
6	500	11.7	800
7	600	11.3	1000
8	600	11.5	800
9	600	11.7	900

Table 3.2(b): Layout for Experimental Design according to L9 Array for pump 2

EXP. NO.	A No of strokes	B Control rack travel	C rpm
1	400	9.2	650
2	400	9.4	750
3	400	9.6	850
4	500	9.2	750
5	500	9.4	850
6	500	9.6	650
7	600	9.2	850
8	600	9.4	650
9	600	9.6	750

IV. Results and Discussion

a) S/N Ratio Analysis-

In the Taguchi method, the term 'signal' represents the desirable value (mean) for the output characteristic and the term 'noise' represents the undesirable value for the output characteristic. Taguchi uses the S/N ratio to measure the quality characteristic deviating from the desired value. There are several S/N ratios available depending on type of characteristic: smaller is better (SB), nominal is best (NB), or larger is better (LB). Smaller is better S/N ratio used here. Smaller the better quality characteristic was implemented and introduced in this study.

Smaller the better characteristic

S/N = -10 log10 (MSD)

Where MSD= Mean Squared Division

$$MSD = (1/Y_1^2 + 1/Y_2^2 + 1/Y_3^2 + \cdots\cdots\cdots)/n$$

Where Y1, Y2, Y3 are the responses and n is the number of tests in a trial and m is the target value of the result. The level of a factor with the smallest S/N ratio was the optimum level for responses measured. Table 4.1 and Figure 4.1 depict the factor effect on fuel delivery . The smaller the signal to noise ratio, the more favorable is the effect of the input variable on the output.

Table 4.1(a): Summary Report for Different trials conducted during Experimentation for pump1

Trial No.	Fuel delivery (ml) Trial 1	Trial 2	Trial 3	Avg. Fuel delivery (ml)	S/N Ratio
1	20	19	20	19.67	25.86
2	23	22	23	22.67	27.10
3	26	25	27	26	28.28
4	33	34	34	33.67	30.54
5	36	35	36	35.67	31.04
6	38	39	38	38.34	31.66
7	45	44	45	44.67	32.99
8	42	42	43	42.34	32.53
9	40	41	40	40.34	32.11

Table 4.1(b): Summary Report for Different trials conducted during Experimentation for pump2

Trial No.	Fuel delivery (ml) Trial 1	Trial 2	Trial 3	Avg. Fuel delivery (ml)	S/N Ratio
1	20	21	20	20.34	26.15
2	22	21	22	21.67	26.70
3	25	23	24	24	27.58
4	28	27	28	27.67	28.83
5	32	33	32	32.34	30.27
6	31	30	31	30.67	29.73
7	38	37	38	37.67	31.51
8	34	33	35	34	30.62
9	36	35	36	35.67	31.04

Table 4.2(a) Estimated Model Coefficients for SN ratios for pump 1

Term	Coef	SE Coef	T	P
Constant	-30.2752	0.2771	-109.23	0.000
Strokes 400	3.0903	0.3919	7.884	0.016
Strokes 500	-0.8419	0.3919	-2.148	0.165
Ctr 11.3	0.3703	0.3919	0.945	0.444
Ctr 11.5	-0.0000	0.3919	-0.000	1.000
Rpm 800	0.2481	0.3919	0.633	0.592
Rpm 900	0.3067	0.3919	0.783	0.516

Summary of Model-
S = 0.8314 R-Sq = 97.2% R-Sq(adj) = 88.8%

Table 4.2(b) Estimated Model Coefficients for SN ratios for pump

Term	Coef	SE Coef	T	P
Constant	-29.2281	0.1016	-287.81	0.000
Strokes 400	2.2854	0.1436	15.91	0.004

			3	
Strokes 500	-0.3964	0.1436	-2.760	0.110
Ctr 9.2	0.3749	0.1436	2.611	0.121
Ctr 9.4	0.0344	0.1436	0.239	0.833
Rpm 650	0.4023	0.1436	2.801	0.107
Rpm 750	0.2555	0.1436	1.779	0.217

Summary of Model-

S = 0.3047 R-Sq = 99.4% R-Sq(adj) = 97.5%

Table 4.3(a) Response Table for Signal to Noise Ratios Smaller is better (pump1)

Level	strokes	ctr	rpm
1	-27.18	-29.90	-30.13
2	-31.12	-30.28	-29.97
3	-32.52	-30.65	-30.83
Delta	5.34	0.74	0.86
Rank	1	3	2

Table 4.3(b) Response Table for Signal to Noise Ratios Smaller is better (pump2)

Level	strokes	ctr	rpm
1	-26.94	-28.85	-28.83
2	-29.62	-29.19	-28.97
3	-31.12	-29.64	-29.89
Delta	4.17	0.78	1.06
Rank	1	3	2

From the Table 4.1 and Figure 4.1 it is clear that, the optimum value levels for fuel delivery are at a No of strokes(400),ctr (11.3), and rpm (800). Also, for fuel delivery, from it can be seen that, the most significant factor is No of strokes, followed by rpm, and control rack travel.

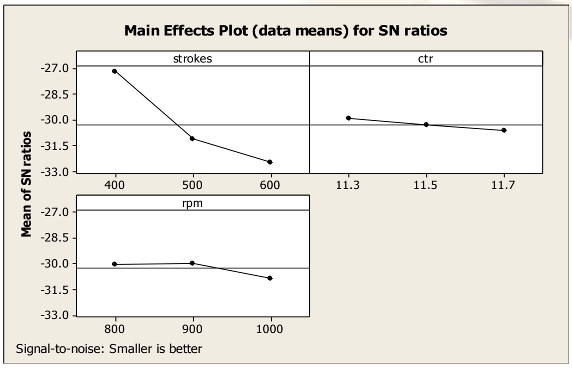

Figure 4.1(a): Effect of process parameters on S/N Ratio for pump 1

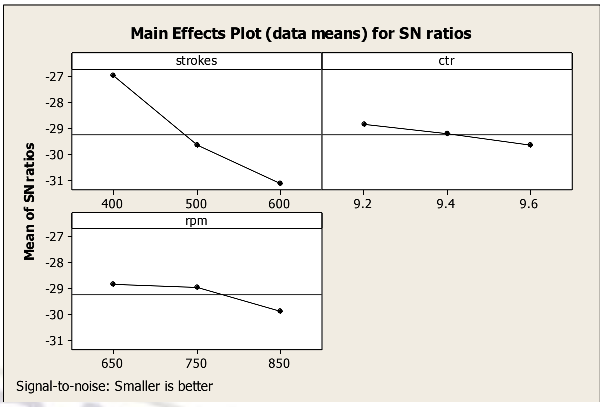

Figure 4.1(b): Effect of process parameters on S/N Ratio for pump 2

b) Analysis of Variance (ANOVA)

Analysis of variance is a standard statistical technique to interpret experimental results. It is extensively used to detect differences in average performance of groups of items under investigation. It breaks down the variation in the experimental result into accountable sources and thus find the parameters whose contribution to total variation is significant. Thus analysis of variance is used to study the relative influences of multiple variables, and their significance.

The purpose of ANOVA is to investigate which process parameters significantly affect the quality characteristic. The analysis of the experimental data is carried out using the software MINITAB 14 specially used for design of experiment applications. In order to find out statistical Significance of various factors like No of strokes (A), rpm (B), and control rack travel (C), and their interactions on fuel delivery, analysis of variance (ANOVA) is performed on experimental data. Table 4.2 shows the result of the ANOVA with the fuel delivery . The last column of the table indicates p-value for the individual control factors. It is known that smaller the p-value, greater the significance of the factor. The ANOVA table for S/N ratio (Table 4.4a) indicate that, the No of strokes (p=0.029), control rack travel (p= 0.627) and rpm (p=0.499) in this order, are significant control factors effecting fuel delivery. It means, the No of strokes is the most significant factor and the control rack travel. has less influence on the performance output.

Table 4.4(a) Analysis of Variance for SN ratios

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Strokes	2	45.941	45.941	22.9705	33.23	0.029
Ctr	2	0.8228	0.8228	0.4114	0.60	0,627
rpm	2	1.3901	1.3901	0.6951	1.01	0.499
Residual Error	2	1.3826	1.3826	0.6913		
Total	8	49.5365				

Table 4.4(b) Analysis of Variance for SN ratios

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Strokes	2	26.846	26.846	13.4233	144.6	0.007
Ctr	2	0.9278	0.9278	0.4639	5.00	0.167
rpm	2	1.9792	1.9792	0.9896	10.66	0.086
Residual Error	2	0.1856	0.1856	0.0928		
Total	8	29.939				

c) Percent contribution-

Percent contribution to the total sum of square can be used to evaluate the importance of a change in the process parameter on these quality characteristics

Percent contribution (P) = (SS'A / SST) *100

Table 4.5(a): Optimum Condition and Percent Contribution for pump 1

SR. No.	Factors	Level Description	Level	Contribution (%)
1	A: No of strokes.	400	1	92.74
2	B: rpm	800	2	2.80
3	C:ctr	11.3	3	1.66

Table 4.5(b): Optimum Condition and Percent Contribution for pump 2

SR. No.	Factors	Level Description	Level	Contribution (%)
1	A: No of strokes.	400	1	89.67
2	B: rpm	650	2	6.61
3	C:ctr	9.2	3	3.09

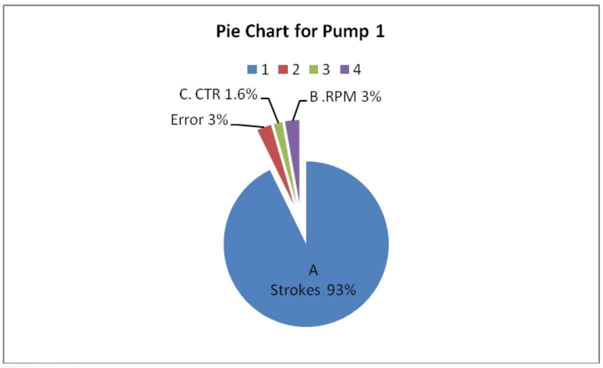

Fig 4.2(a) pie chart for pump 1

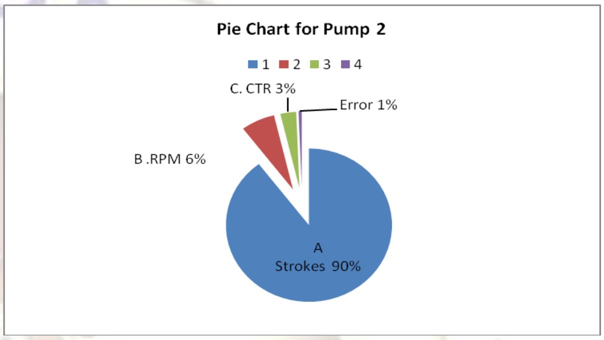

Fig 4.2(b) pie chart for pump 2

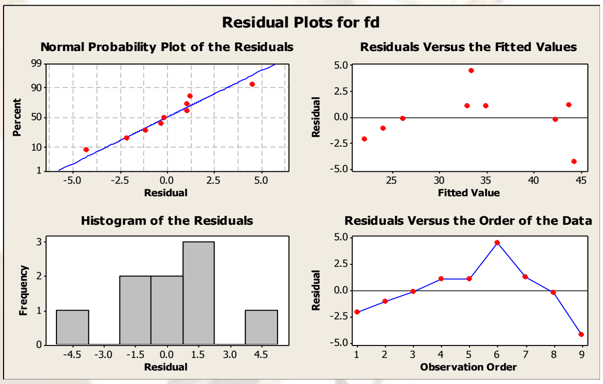

Figure 4.3(a): Residual Plots for fuel delivery of pump1

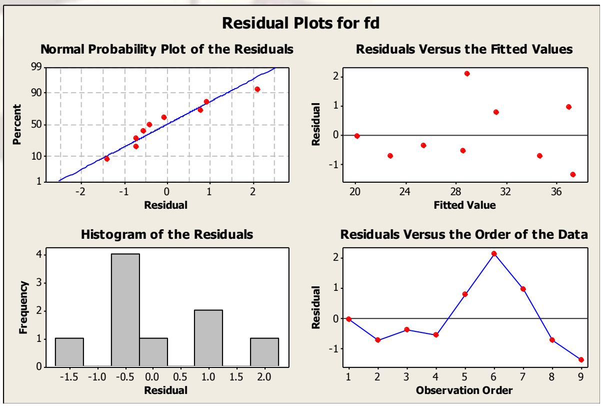

Figure 4.3(b): Residual Plots for fuel delivery of pump2

c) Regression Analysis

Regression analysis is used for explaining or modeling the relationship between a single variable Y, called the response, output or dependent variable, and one or more predictor, input, independent or explanatory variables Mathematical models for process parameters such as No of strokes,rpm & control rack travel were obtained from regression analysis using MINITAB 14 statistical software to predict fuel delivery .

The regression equation for pump 1 during course off is

Y = -73.0+0.0967A+0.0117B+4.17C
S = 3.11627 R-Sq = 92.2% R-Sq(adj) = 87.5%

Where,
Y = Response i.e Fuel delivery (ml)
A = No of strokes, B = Rpm, C = control rack travel (mm),

If we put optimum parameters which are drawn by ANOVA in equation 1 it will give optimum value of quality characteristic which will minimum fuel delivery.

Yopt = -73.0+0.0967A1 + 0.0117B2 + 4.17C3
Y opt = -73.0+0.0967*400+0.0117*800+4.17*11.3
Y opt = **22.161 ml** (Predicted by Regression Equation)

In multiple linear regression analysis, R2 is value of the correlation coefficient and should be between 0.8 and 1. In this study, results obtained from fuel delivery in good agreement with regression models (R2>0.80).

Similarly, The regression equation for pump 2 during course off is

Y = -64.1+0.0683A+0.0167B+5.00C
S = 1.37032 R-Sq = 97.0% R-Sq(adj) = 95.2%

Where,
Y = Response i.e Fuel delivery (ml)
A = No of strokes, B = Rpm, C = control rack travel (mm),

If we put optimum parameters which are drawn by ANOVA in equation 1 it will give optimum value of quality characteristic which will mimimize fuel delivery.

Yopt = -64.1+0.0683A1 + 0.0167B2 + 5.00C3
Y opt = -64.1+0.0683*400+0.0167*650+5.00*9.2
Y opt = **20.075 ml** (Predicted by Regression Equation)

In multiple linear regression analysis, R2 is value of the correlation coefficient and should be between 0.8 and 1. In this study, results obtained from fuel delivery in good agreement with regression models (R2>0.80).

e) Conformation Experiments:

In Order to test the predicted result, confirmation experiment has been conducted by running another four trials at the optimal settings of the process parameters determined from the Analysis i.e. A1B2C3 for pump1 & pump 2.

Table 4.6 (a) Trial for pump 1

Observation	Trial 1	Trial 2	Trial 3	Trial 4	Avg.fuel delivery (N)	S/N Ratio
1	22	23	23	22	22.5	27.03

Table 4.6 (b) Trial for pump 2

Observation	Trial 1	Trial 2	Trial 3	Trial 4	Avg.fuel delivery (N)	S/N Ratio
1	20	21	21	21	20.75	26.33

The results are shown in above table and it is observed that the average fuel delivery i.e. 22.5 and average S/N Ratio 27.03 which falls within predicted 80% Confidence Interval. Similarly for pump 2 average S/N ratio is 26.33 which falls in predicted interval.

With the use of biodiesel in fuel injection pump, process parameters does not show any variations but the influence of biodiesel on some tribology characteristics of fuel injection system cannot be neglected. The tests have been performed on a fully equipped fuel injection test bed and surface roughness measurement device. The tested fuel was neat biodiesel produced from soyabeen oil. Attention was focused on the biodiesel influence on the pump plunger surface roughness The influence of biodiesel on the pump plunger surface is studied. The surface area, positioned close to the top of the pump plunger, has been selected. It is known that this surface has a very important influence on the injection pressure. It turned out that under the microscope the surface looked always pretty the same, regardless of the fuel used.

Table 4.7 (a) Biodiesel Influence on Surface Roughness of Plunger skirt

Plunger skirt Surface	Before biodiesel (μm)	After Biodiesel (μm)
Plunger of Pump 1	0.07 0.06 0.07 0.04	0.09 0.08 0.09 0.08
Plunger of Pump 2	0.08 0.08 0.08 0.08	0.10 0.09 0.10 0.12

Table 4.7 (b) Biodiesel Influence on Surface Roughness of Plunger Head

Pump Plunger Head	Before biodiesel (µm)	After Biodiesel (µm)
Plunger of Pump 1	0.04 0.04 0.03 0.04	0.08 0.10 0.09 0.08
Plunger of Pump 2	0.04 0.04 0.05 0.03	0.10 0.10 0.11 0.11

Fig. 4.4 Pump Plunger

In order to obtain the surface roughness parameters, five mea-surements were performed on both, plunger skirt and head, for each parameter. It turned out that the influence of biodiesel usage is rather minor for the plunger skirt. On the contrary, the roughness parameters of the plunger head exhibited significant changes after biodiesel usage.

One can see that the surface roughness at the pump plunger head increased by a factor of two when biodiesel was used. Luckily, the surface roughness at the pump plunger head is not as important as the roughness at the plunger skirt .For this reason, the obtained results are not alarming, although some further tribology investigations would be necessary to evaluate the situation more precisely.

V. Conclusions

The Taguchi method was applied to find an optimal setting of the fuel delivery parameters process. The result from the Taguchi method chooses an optimal solution from combinations of factors if it gives optimized combined S/N ratio of targeted outputs. . The results are summarized as follows:

- Among three process parameters No of strokes followed by Rpm and Control rack travel was most influencing parameters on damping force
- The Optimal level of process parameter were found to be **A1B2C3**
- The prediction made by Taguchi parameter design technique & Regression analysis are in good agreement with confirmation results
- The result of present investigation are valid within specified range of process parameter.
- The parametric effect on fuel delivered by FIP of Diesel engine have optimum control and economic usage of fuel. The parameters observed were fuel delivery. 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 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.

The influence of biodiesel on the pump plunger surface is studied and concluded that greater roughness, obtained after biodiesel usage, will not worsen the sliding conditions at pump plunger skirt. After biodiesel usage, the average value of the root mean square roughness decreased which could even be an indication for improved lubrication conditions.

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