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Using multi-objective NLPQL optimization of diesel engine

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Abstract

Optimization of engines is a delicate process due to its nonlinear nature and combustion that has to be care with finesse and extra care. In this regard, the study is programmed to address the need to fulfill the requirement for having the ideals of maximized power and spray quality and better-atomized spray. To accomplish this matter, a DoE setup and statistical approach is undertaken that the design variables include nozzle geometry and injection tilting angle in combustion chamber. The sub-objectives are considered to be indicate power (IP) and Sauter mean diameter (SMD) with equal weight in optimization process. The optimum case point is determined Case_3 with -3.813 and the injection angle is decided 162.2°, nozzle diameter of 0.156 mm. NLPQL-optimized solution has led to 2.34% increase in indicated power and 3.43% decrease of droplet size.

***Keywords*:** CFD; Diesel engine; Latin hypercube; NLPQL optimization; SMD.

1. Introduction

Internal combustion engines are very important and are indispensable part of human life to facilitate everyday curbs and difficulties. Diesel engines are very efficient but still make much noise and hazardous emissions. With all efforts in recent decades, there is room for further power boost and most of the waste is due to incomplete combustion and spray-wall impingement. Therefore optimization of engine structure and injection system has to be evaluated beforehand to prevent probable setbacks in designing stage [1-3].

The computational studies are classified to neural network architecture [4, 5], optimization, or hybrid of modeling and optimization [6]. The marine diesel engine is optimized with NSGA-II method that for better performance was coupled with support vector machine (SVM) [7]. The online optimization method the Pareto optimal front solutions were found rapidly yielding the excellent performance of diesel engine, additionally, the improved training was proposed and applied in their study. Benajes et al. [8] researched on a combustion system to optimized the DME powered CI engine computationally. In the optimization process, 21 parameters are intended to reduce the NOx emission compared to baseline case while it was observed that the net indicated efficiency is elevated by 0.6%. Yazdani et al. [9] performed an optimization job on the injection strategy of RCCI (reactivity controlled compression ignition) engine. The results of analysis revealed that the swirl ration parameter has the highest impact on the overall objective. It was also indicated that the injection rate shape achieves NIE of 54%. Gupal et al. [10] announce they are able to predict the performance and emission of dual n-octanol/diesel blended engine via RSM (response surface methodology). They succeeded in minimizing NOx, smoke, and fuel consumption simultaneously.

The review of the papers in recent years shows that there is a great capacity for modification in injection strategy of the injector installed in the combustion chamber of diesel engine. This paper considered two design variables of nozzle hole and injection angle to increase the power of the engine and also reduce spray droplet size. The mechanism for optimization is through NLPQL with incorporation of SVM and the results indicated superiority of Case_3 as optimum.

2. NLPQL optimization

The NLPQL algorithm generates a sequence of iterates **x**i, where an approximation is minimized at each major iteration. The Hessian of the Lagrange function is used to make a quadratic approximation of the Lagrange function. The principal idea is the formulation of a quadratic programming subproblem by linearizing [11]:

$$\nabla_x f(x_i) + \nabla_{xx}^2 f(x_i)(x_{i+1} - x_i) = 0 \tag{1}$$

The objective is set as Obj = IP + SMD that IP has to increase for more and more power production and SMD must be decreased to maintain qualified spray injection in diesel engine.

Optimization methods could help the engineer to find an ordered approach to the iterative design process by using mathematical programming techniques, which search for the optimal design. Optimization is very attractive, giving insight into the design process and increasing the efficiency by relieving the engineer from the decision making process. Several different optimization methods exist which can solve different optimization problems.

3. DoE method

Design of Experiment theory is a methodology that is used to gain the maximum amount of information while minimizing the number of simulations. Originally, these strategies have been developed by statisticians to estimate the effects of independent variables on the responses. The experimenter uses DoEs to get a selection of design points, for which the numerical simulations should be evaluated. In the DoE theory, design variables are called *factors* and a specific value for a factor is called *level*. Statistical tools like analysis of variance (ANOVA) and regression analysis are used to identify the sensitivity of the observed data.

The factors used in DoEs have lower and upper bounds which describe a hypercube. To increase numerical stability the factors are scaled to the range [-1, +1]. It is necessary to distinguish between DoEs that are used for screening design and to validate the dependencies between design variables and response parameters and DoEs that are used to find good starting points for the optimization process. The goal of a screening design is to remove factors that have no significant effect on the response, from further analyses. The significance of a factor may be described by the main effect the change of a single factor has on the simulation output, by interaction effects and by quadratic effects. Interaction effects (when the effect of the factor depends on the setting of another factor) or quadratic effects are identified by using DoEs that are suitable for RSM as well. The Latin Hypercube design is used as DoE approach that is capable of distributing the design space uniformly for n levels as depicted below in Fig. 1.

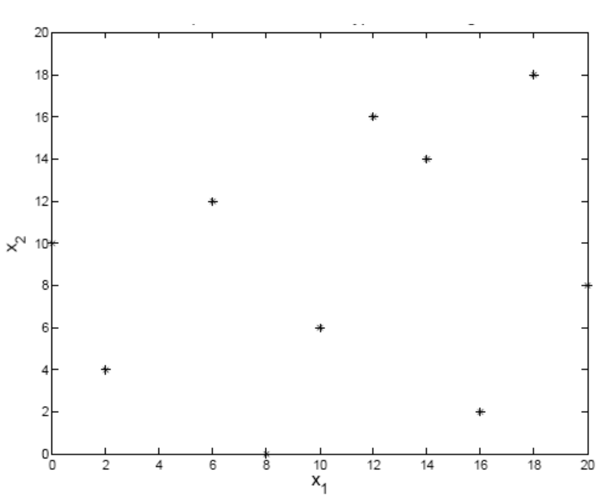

Figure 1. Latin hypercube design [11].

4. Results and discussions

Configuration of engine to synchronize injection plans and layout of the chamber is challenging for researchers since it may determine the conclusive output data. The goal is set to maximize the engine power while maintain or even decrease the spray droplet diameter so the objective function or merit function is formulated based on that (objective = IP + SMD). In the following, to further illustrate the inter connection of parameters; the interactive or statistical method is used to find any possible relation between design variables and objectives. Fig. 2 shows the history-plot that is applied for both variables and objectives. The first 10 designs are allocated for DoE generated solutions, while the rest of the cases are evaluated by optimization algorithm based on non-evolutionary mechanism to find the best candidate.

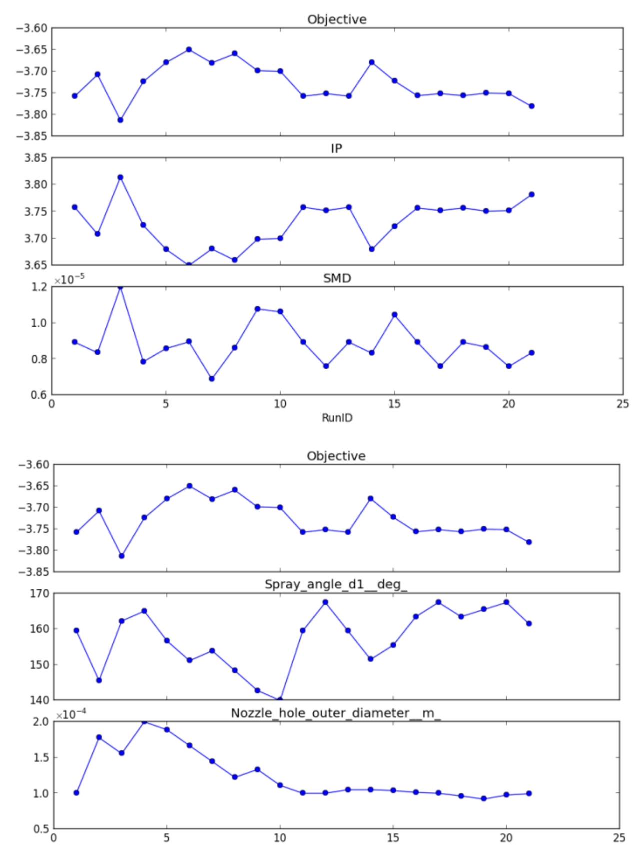

Figure 2. Multi-history plot showing the evolutionary variation of the cases

The lowest or the best case goes for RunID3 (with ~ -3.81327) and the values of corresponding array of variables leading to counterpart objective in historical order can be observed. As seen, the general trend of optimizer is capable of increasing the engine power and ameliorates the spray morphology by decrementing the droplet size. It is traced to better fuel jet breakup with narrower nozzle hole.

The bubble chart is shown in Fig. 3 to represent the design points in 4D that connects injection angle and nozzle hole diameter with objective. This plot infers that higher injection angle θ≥ 160 can produce more successful points especially when combined with lower nozzle hole diameter.

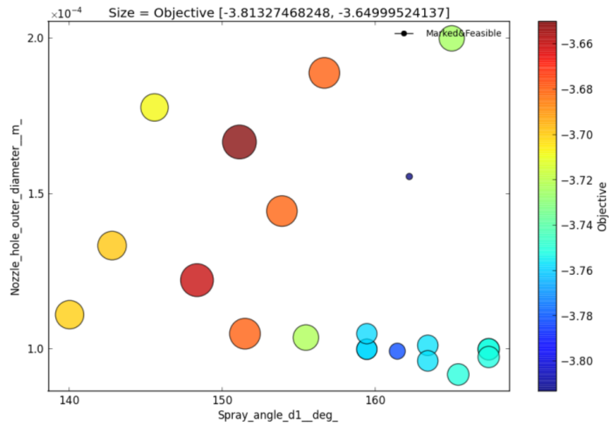

Figure 3. Bubble plot demonstration of the results of optimization

The interactive correlation study can be demonstrated in parallel coordinate system in Fig. 4. Here, 4 scalar channels are assigned that the optimum values for having the best considered target is shown. The injection angle is over average while the nozzle diameter must be kept smaller.

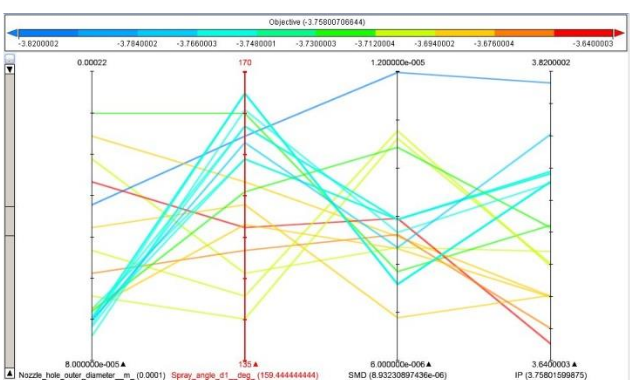

Figure 4. Parallel coordinate plot for bivariate analysis

This visualization enables 4-dimensional clustering of data in rows with polylines crossing each set of parameters. Fig. 5 is 3D scatter plot of objective-spray delta angle-nozzle hole diameter. The plot clearly shows that lower amounts of spray angle and nozzle hole diameter leads to better objective and responses.

Fig. 6 also represents 2D overview plot and univariate scaling of datasets, wherein all the computations are restricted to subsets. The characteristics pair of channels are attributed to design variables based on bivariate statistics therein the mean objective value comes to -3.758. This shows the coherency of the response solutions and the robustness of generated data by statistical view and mechanism based data.

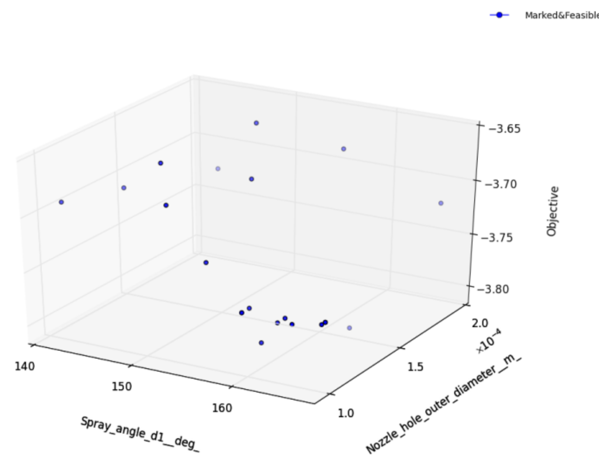

Figure 5. 3D scatter plot with respect to objective

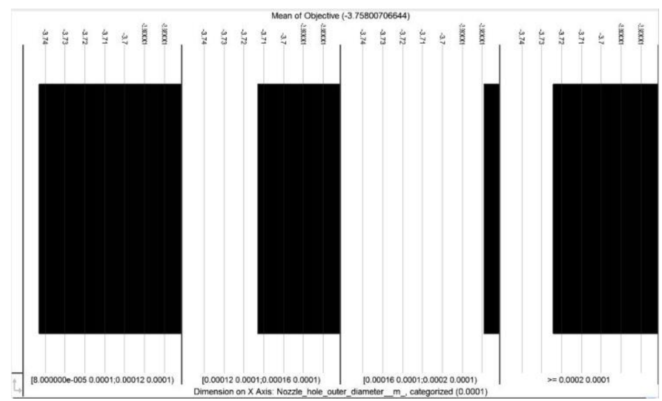

Figure 6. 2D overview visualization

The function view based on SVR prediction modeling is seen in Fig. 7 that the corresponding data are illustrated as well. It can be deduced that the deviation of the model from the predicted results are in good order and the errors are kept in low tolerance in this method.

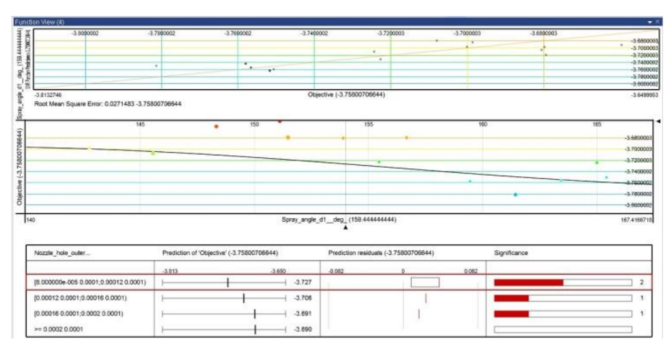

Figure 7. The function view of the SVR modeled results

The summarized results of optimization are mentioned in Table 1.

Table 1. The obtained results of optimization algorithm

	RunID	Objective	Spray-angle	Nozzle-hole	IP	SMD
Min. of IP	6	-3.65	151.1111	0.000167	3.650004	8.95E-06
Max. of IP	3	-3.81327	162.2222	0.000156	3.813287	1.20E-05
Min. of SMD	7	-3.68052	153.8889	0.000144	3.680529	6.88E-06
Max. of SMD	3	-3.81327	162.2222	0.000156	3.813287	1.20E-05
Best of Obj_IP	3	-3.81327	162.2222	0.000156	3.813287	1.20E-05

5. Concluding remarks:

The computational fluid dynamics (CFD) is used for simulation of the best case and then an optimization algorithm is applied on the general data of the basic engine model to try to get the best defined objectives in the engine by formulating a fitness function including two sub-objectives. The results showed that for the best IP, Case_3 is more powerful and for the minimum SMD, Case_7 shows strength due to injection setup. The DoE generated set points are 10 and in general 21 array of injection parameters are sampled for the study. The optimum conditions are injection angle of 162.2 with respect to x-axis and 0.156 mm for the nozzle hole diameter. These results show that for low spray droplet and higher power, the requirement for high injection angle and smaller nozzle hole diameter should be met. These guidelines can be helpful for designers and engineers to manufacture their products with more precision.

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