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Optimizing Volumetric Efficiency by Conducting Engine Parameter Studies Using Design of Experiments

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Abstract - Improving the Volumetric Efficiency (VE) can boost the engine performance. However, there is no Variable Valve Timing (VVT) and variable intake manifold systems especially for most of the conventional scooter engines. Computer aided simulation has significantly reduced the product development time. Users can analyze more design options across multiple design parameters combination. In this study, 150c.c. single cylinder engine parameters were optimized for maximum VE by using design of experiments. The airbox geometry and valve timing and profile are defined as input variables, which are also controllable factors in the co-simulation work of one-dimensional engine simulation software and DOE analysis software. The advantage of this optimization method is that it allows the flexibility to increase the maximum VE for a specific operating condition or to increase the VE for all operating conditions. The results showed that the VE of the conventional engine increased by 9-17% in the speed range of 3200-5600rpm, and by 4% in the remaining speed range of 6400-8000rpm, showing an overall improvement. This method can effectively reduce product development time, budget and simulation cycle.

***Keywords*:** DOE, volumetric efficiency, airbox, valve timing.

1. Introduction

In productivity driven market, there is absolute necessity to improve the VE of the small scooter engines in order to enhance drivability of engine throughout the operating regime without compromising in cost, heaviness and fuel consumption of the engine [1].The performance of the engine depend upon the VE. Basically VE of an engine depend upon the inhaling and exhaling of the engine [2,3] and mostly breathing of the engine depends upon the parameters of the intake system. According to Radivoje B et al [4] dimensions of the intake system will have greater influence on VE, VE will impact on the engine performance and empirical studies has proven that optimization of appropriate dimensions can improve favorable VE to high VE [3,4,5,6].

In this study, the airbox and valve timing geometry are mainly focused in the intake system to improve the airflow system into the combustion chamber. Airbox is the source that draws the air into the intake system in naturally aspirated engine. The quantity of air present inside the combustion chamber can affect the VE of the engine, optimizing the complex fundamental issues of airbox like volume, intake hose size and positioning of filter can improve steady airflow into the system. According to Ciaran Branney et al [7] airbox system has not been focused much and they are very few research papers because of its complex positioning, unbalanced steady flow inside inlet and outlet hoses, inaccurate volume inside airbox [7,8].

Valve timing tuning has proven to be on one of the most efficient way to improve the flow dynamics inside the combustion chamber, harassing the airflow that peaks the torque as well as VE. Computer simulation has given ease to understand the deeply about the physical phenomenon of the valve timing in the intake system which infeasible with the experimental study. [9,10].

The traditional method that has been followed for many years during the optimizing design parameters of an engine is One Factor At a Time (OFAT). OFAT method designs experiments by changing one factor at a time instead of changing multiple factors at a time, the combinations produced by this method will not have the greatest effect on the responses because this factor does not produce every possible combination. Which results in lack of optimality in the result, expensive, consumes much time and simulation cycles. [4, 12, 13]

Disregard to the inefficient optimization technique that has been described above, using the Design of Experiments (DOE) appropriately gives optimal results by determining the combination that gives the best response. It is systematic approach in order to obtain maximum amount of output from various types of experiments while reducing the number of experiments. So far, there are many types of DOE methods and have been using them for various applications. DOE methods have been classified into Orthogonal designs and random designs. The orthogonal design is the model parameters are statistically independent. It means that the factor is an experiment are uncorrelated and can be varied independently of each other. This design is mostly used in fractional and full factorial. In today's world computers has developed with high performance, which has decreased the complexity to construct and perform the combination of DOE techniques. [12, 13, 14].

In this study Efficient Global Optimization (EGO) technique has been used to boost the performance of the engine. EGO is a hybrid optimization DOE which is most popularly used in the engineering design. This technique algorithm uses Latin hyper Cube (LH) to screen the design space of the input variable and uses Response surface Modelling (RSM) to optimize the output. The huge advantage of this algorithm is it improves itself in order reach the optimal output [15, 16, and 17]. RSM model used in in this study is Universal Kriging Surrogate model (UK) or Kriging, this type model is mostly used for multi-objective optimization especially in the engineering design, Pramudita et al [17] has done an intensive study optimization using kringing model. Figure 1 shows the process of the EGO algorithm at first it run the LH to screen the design space eliminate the unworthy combination, kriging surrogate model is built to calculate the optimization outputs until the tolerance point is reached this means the next combination is already known this cycle repeats until new promising result is obtained.

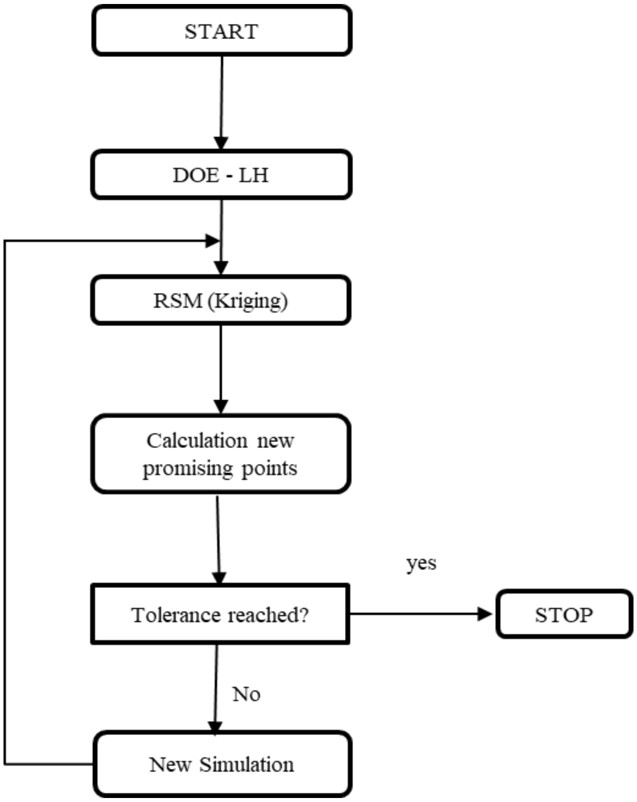

Figure 1 EGO algorithm experiment cycle

2. Methodology

The optimization investigation was performed using simulation tool. Figure 2 describes the optimization methodology. methodology. At first Ricardo Wave software was coupled with the Noesis optimus software, secondly work flow was create create with base engine computation model designed in the WAVE then EGO performs the analysis to find the promising optimized output and finally the optimized output will run 1D performance simulation to validate the wave output. The formula used to calculate the VE was defined in the wave as

$$\frac{m_{air}}{D^{*}\rho_{int}} \tag{1}$$

Where m is mass density of the intake system and D is total displacement of the engine and ρ is the density by the reference temperature and pressure in the operating parameters of the engine.

Huge advantage of using the Noesis Optimus software is its user friendly that allows easily setup the workflow and setting up the methodology. Using this software will allow the user have option set the boundary conditions for the output this will allow algorithm to run more effectively and after simulation experiments that didn’t meet the boundary conditions of the output are filtered so it is easy for the user to analyze the results.

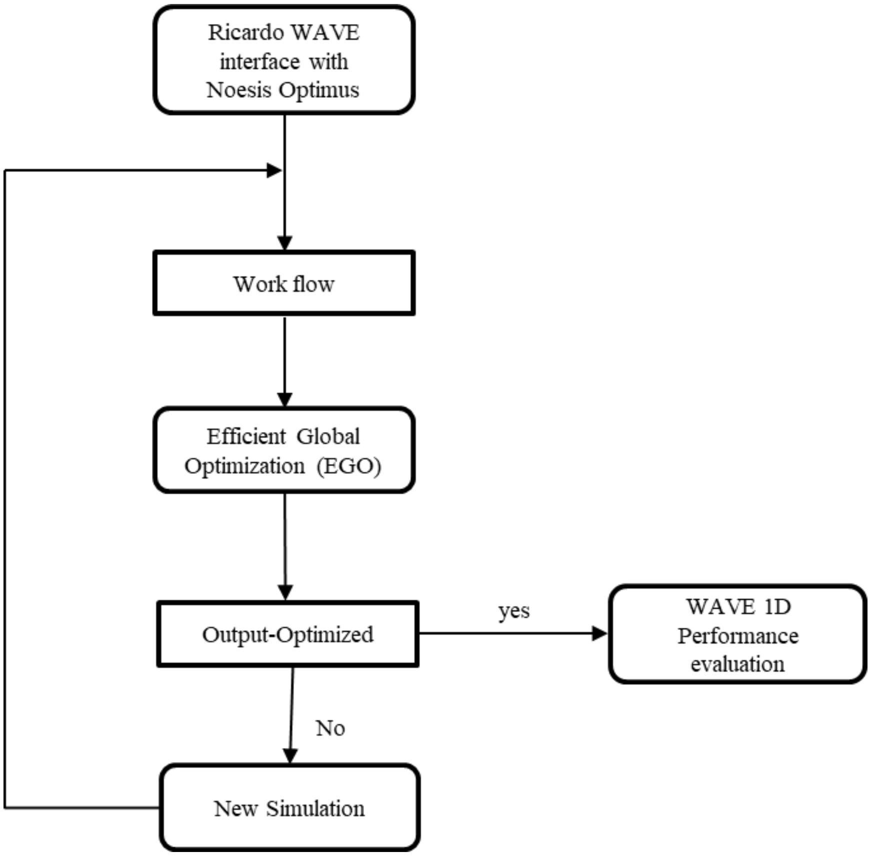

Figure 2 schematic diagram of optimization methodology.

The computation model has been designed in the WAVE with the measured base engine dimensions Table 1 shows the basic base engine specifications and performance output of the base engine, the simulation performance output result has been validated with experimental study. WAVE is one of the best simulation tool available in the market to predict the engine performance as close as possible. Figure 3 shows the brake power and mass flow dynamics compared with experimental data and simulation tested at various engine speeds from 3200 to 8000 rpm. After successfully interfacing the WAVE with Noesis

Optimus software the workflow has been set and the boundary conditions are entered in table 2 shows the boundary conditions that has been set after brainstorming the engine dynamics. The table contains parameters from the airbox and valve timing.

Table 1: Engine specification

Engine type	Single cylinder / 4 strokes / 4 valves / SOHC
Displacement (cc)	149.8
Bore diameter (mm)	57.4
Stroke (mm)	57.9
Connecting rod length (mm)	93.5
Compression ratio	9.59
Piston pin displacement (mm)	0
Intake valve seat diameter (mm)	17.6
Exhaust valve seat diameter (mm)	15
Air intake maximum valve lift (mm)	7
Exhaust valve maximum lift (mm)	6.88
Inlet valve opening and closing duration @1mm(deg)	215
Inlet valve opening and closing duration @1mm(deg)	210
Intake valve open @1mm	10 ATDC
Intake valve closed @1mm	45 ABDC
Exhaust valve open @1mm	30 BBDC
Exhaust valve closed @1mm	2 ATDC
Valve overlap angle @1mm	0
Intake and exhaust valve clearance (mm)	0.1

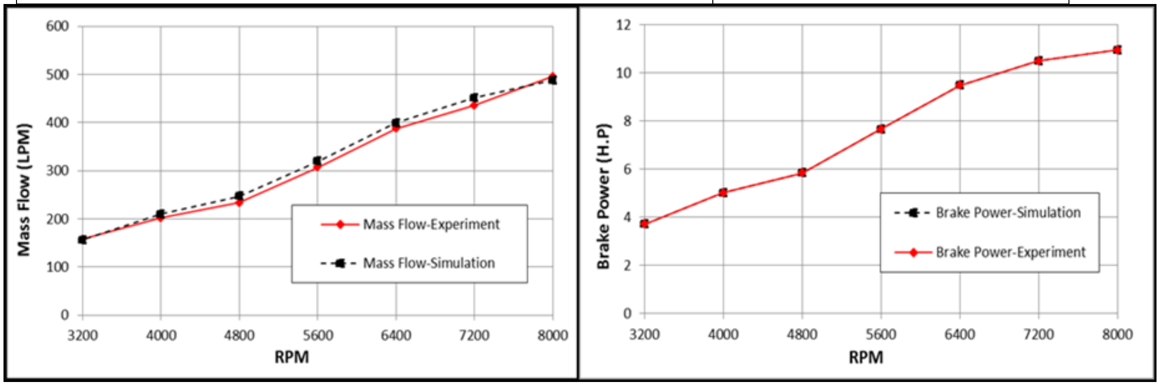

Figure 3. The simulation model vs experimental result

Figure 4 shows the airbox parameters, representing the inlet house, outlet house, and airbox volume. Figure 5 shows the diagram of the conventional engine, in order to optimize dimensions of the airbox is challenging because of its complex positioning, size and design there is hardly any room for optimization. Boundary conditions are set according to practical design guidelines and geometric constraints. The controllable factors of boundary conditions are shown in Table 2.

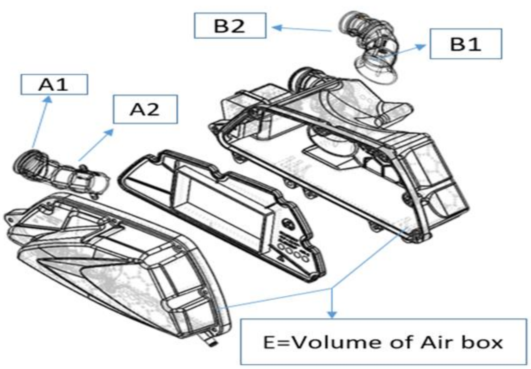

Figure 4 Airbox geometry

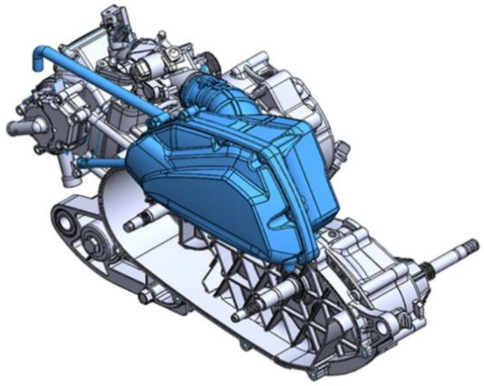

Figure 5 Conventional engine model

The intake and exhaust timing were affected by the by the variations in the valve timing. In the 1D engine simulation software, cycle, lift, duration of intake and exhaust are the complete valve timing variations that has been investigated. Cycle is defined as the crank angle corresponding to a valve profile. Lift and duration are defined as multiples of valve lift and valve duration, respectively.

Results obtained by running a co-simulation model show that the size optimization of the airbox and variable valve timing and profile improve VE. It can be seen from Figure 6 that the VE of the conventional engine increases by 9-17% in the speed range of 3200-5600rpm, and increases by 4% in the remaining speed range of 6400-8000rpm, showing a comprehensive improvement.

Table 2 Controllable factors

system	Parameters	Base Model	Minimum	Maximum	Measurement Units
Air box	Inlet hose length -**A1**	26	20	46	mm
	Inlet hose length -**A2**	26	20	46	mm
	outlet hose length -**B1**	38	28	58	mm
	outlet hose length -**B2**	30	26	32	mm
	volume of air box- **E**	3.4	2.4	5.4	L
Valve timing	Intake cycle	0	-70	70	deg
	Intake duration	1	0.9	1.1	mm
	Intake lift	1	0.9	1.1	mm
	Exhaust cycle	0	-70	70	mm
	Exhaust duration	1	1.1	1.1	mm
	Exhaust lift	1	1.1	1.1	mm

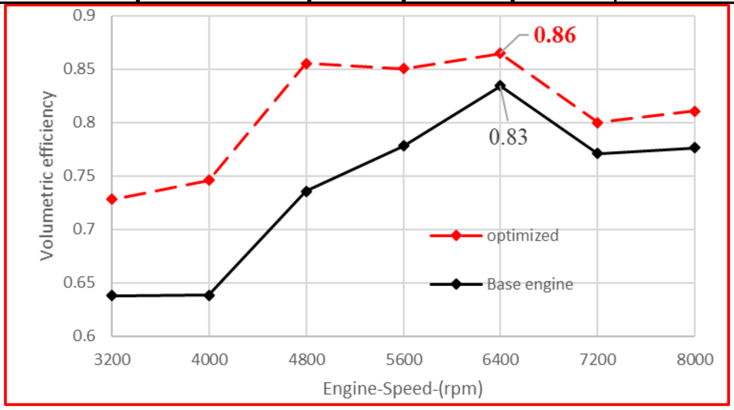

Figure 6 optimized VE across various speeds

Figure 7 shows the base engine and optimized valve timing parameters. The IVO for the optimized valve timing is at crank angle of 382 @1mm, which is late opening when compared to base IVO (370 @1mm) and optimized IVC occurs at crank angle of 574 @ 1mm, which early to base IVC (584 @1mm). whereas optimized EVC occurs early at crank angle of 347 @1mm and base engine at 360 @1mm. Table 3 shows the base engine and optimized parameters of the airbox and the valve timing.

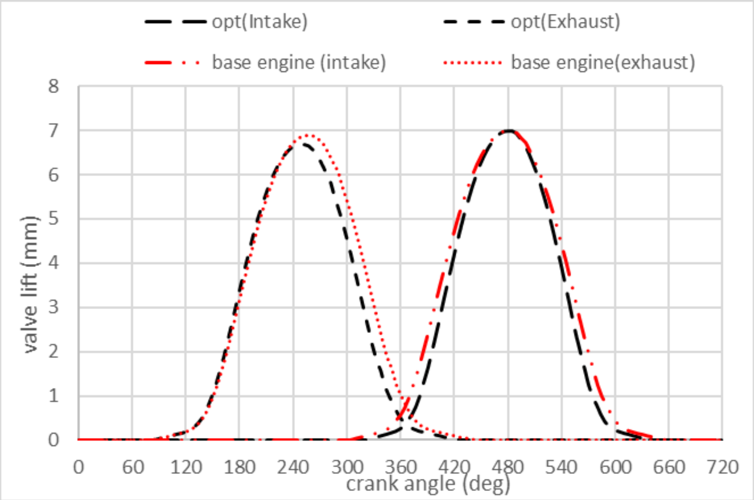

Figure 7 Base engine and optimized valve lift

Table 3 Base engine and optimized Parameters

Parameters	Parameters	Base Model	Optimus	Measurment units
Air box	Inlet hose length **-A1**	26	33.59	mm
	Inlet hose length **-A2**	26	37.06	mm
	outlet hose length **-B1**	38	45.07	mm
	outlet hose length **-B2**	30	28.07	mm
	volume of air box- **E**	3.4	4.75	L
valve timing	Intake cycle	0	48.56	deg
	Intake duration	1.0	0.90	mm
	Intake lift	1.0	0.90	mm
	Exhaust cycle	0.0	5.33	deg
	Exhaust duration	1.0	0.95	mm
	Exhaust lift	1.0	0.97	mm

4. Conclusion

In this study, 150c.c. single cylinder engine parameters were optimized for maximum VE by using design of experiments. The airbox geometry and valve timing and profile are defined as input variables, which are also controllable factors in the co-simulation work of one-dimensional engine simulation software and DOE analysis software. The advantage of this optimization method is that it allows the flexibility to increase the maximum VE for a specific operating condition or to increase the VE for all operating conditions. The results showed that the VE of the conventional engine increased by 9-17% in the speed range of 3200-5600rpm, and by 4% in the remaining speed range of 6400-8000rpm, showing an overall improvement. This method can effectively reduce product development time, budget and simulation cycle.

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