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ENGINE PERFORMANCE VALIDATION OF THE OPTIMAL DESIGN OF EXPERIMENT VALVETRAIN PARAMETERS

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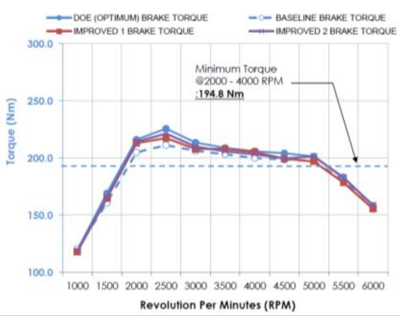
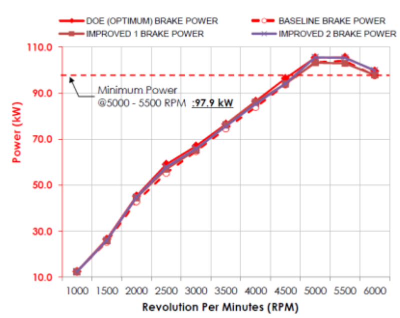
Graphical abstract





Abstract

Early stage of engine valvetrain noise improvement involves the implementation of Design of Experiment (DOE) specifically the Taguchi methodology to identify the optimum valvetrain parameters which resulted in significant noise improvement. The parameters are consist of seven controlled factors such as cylinder head tappet bore diameter, mechanical tappet diameter, valve spring load, camshaft exhaust and intake waviness together with tappet exhaust and intake clearance. The confirmation run which was previously completed yields the valvetrain noise level at 67.07db SPL by 1 meter distance in completed vehicle during idling condition. In order to satisfy the final quality of the optimal valvetrain, a test is carried out to validate the performance curve on a dynamometer according to benchmark specification. The objective of the test is to validate the optimal valvetrain based on the experimental result which minimum manufacturing target shall be achieved to indicate that the engine is operated within its intended design. The performance test was conducted at the manufacturing plant on an eddy current dynamometer which runs for 11 hours. As results, the performance are within the standard with approximate increased by 6.9% as compared with baseline valvetrain and confirmed by several follow-up tests made on the improved valvetrain. In order to verify and address the main engine output of the optimal valvetrain, brake specific fuel consumption (BSFC) and emissions test results are then presented at the end of this paper.

Keywords: Valvetrain noise, DOHC (Double Overhead Camshaft), gasoline engine, performance test, brake torque, brake power

1.0 INTRODUCTION

The optimal valvetrain parameters is an engine built for an improved version of the baseline valvetrain (engine before improvement), a double overhead camshaft (DOHC) regarding the valvetrain noise level based on Taguchi experiment. The method which based on an Orthogonal Array L8(27) employs two levels of maximum and minimum parameters with seven factors in inner array and two 'noise' factors in outer array, making the product robust to uncontrolled factors [1]. Related components that involved in the test are shown in Fig.1. The DOE testing was conducted to investigate the significant factors affecting the response and determining the optimum parameters combination according to the Signal-to-Noise (S/N) ratio value. The study brought the best version of engine in terms of noise level as predicted by the experiment. However, although the engine could be the best version, but the engine performance may be decreases. In worst condition, the engine could be less than the minimum target of designated performance provided by the Original Engine Manufacturer (OEM). Therefore, a test shall be conducted on the optimal valvetrain to verify its maximum performance curve on a dynamometer. The results shall be compared with baseline engine to identify similarities or any changes on the pattern of performance.

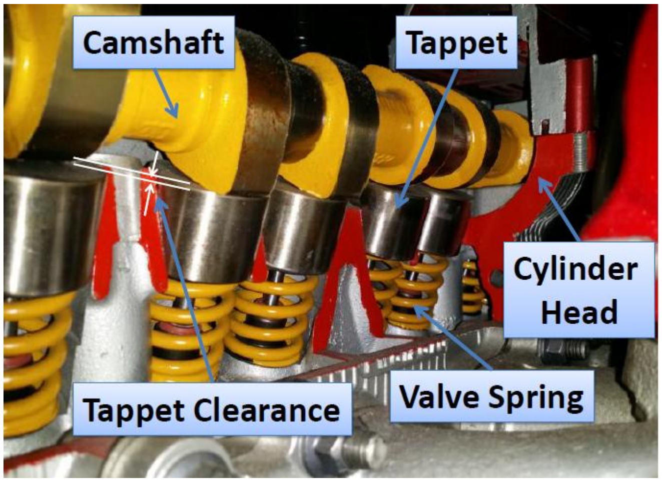


Figure 1 Engine valvetrain components (Cross-Cut View)

2.0 EXPERIMENTAL

2.1 Optimum (DOE) Engine Parameters

The parameters are basically a pair of camshaft for both intake and exhaust having the minimum waviness parameter (Less than 2.0µm WCM) on the lobe surface which differs from the baseline valvetrain (More than 2.0µm WCM). For cylinder head, the tappet bore diameter has been set to maximum size with the combination of minimum tappet diameter, while the valve spring load is maximum. Next, the tappet clearance for both intake and exhaust clearance are set to a maximum to complete the optimal parameters sample. As the parameters of the valvetrain components have been purposely set to different value from the nominal according to the component design as shown in Table 1, therefore validating the performance of the engine is highly necessary.

Table 1 Optimal (DOE) engine characteristics and parameters

No	Components (Factors)	Characteristics	Level	Optimal Parameters	Baseline Parameters
1	Cylinder Head	Tappet Bore Diameter	Max.	32.018 cm	32.021 cm
2	Mechanical Tappet	Tappet Diameter	Min.	31.973 cm	31.973cm
3	Valve Spring	Spring Load	Max.	367 N	351 N
4	Camshaft Exhaust	Waviness Curve-Max	Min.	1.5 µm	2.3 µm
5	Camshaft Intake	Waviness Curve-Max	Min.	0.5 µm	1.5 µm
6	Tappet Clearance Exhaust	Clearance Distance	Max.	0.326 mm	0.298 mm
7	Tappet Clearance Intake	Clearance Distance	Max.	0.215 mm	0.205 mm

Note: Max: Maximum, Min: Minimum, WCM: Waviness Curve-Max

Related information regarding the engine basic specifications are summarized in Table 2 as well as the fuel type used throughout the experimentation and validation test. The engine has 4 cylinders with size 76mm of bore diameter and 86mm of stroke height which make it 1561cc with turbocharger adoption to produce around 205Nm of peak torque and 103kW of peak power.

Table 2 Engine specifications

No	Items	Specification
1	Bore (Diameter) × Stroke (Height)	76mm × 86mm
2	Compression ratio / Cylinders	8.9:1 / 4 (1561cc)
3	Peak Torque (Design target)	205Nm@5000rpm
4	Peak Power (Design target)	103 kW@2000 - 4000rpm
5	Fuel Type	RON95
6	Engine Oil	Mach 5 SL 10W-30

2.2 Typical Engine Performance

The function of a typical automobile reciprocating engine speed and displacement is basically measured through the brake power and torque. Fig. 2 shows power and torque curves for typical engine in which the speed at peak torque is called maximum brake torque or maximum best torque. According to Williard W. Pulkrabek [2], the indicated power increases to a maximum and then decreases due to the friction increases with engine speed to a higher power and becomes dominant at higher speed. Regarding brake torque, A.A. Abuhabaya and J.D Fieldhouse [3] had concluded that the brake torque will increase with engine speed up to the maximum at certain speed, then extremely remained decrease at maximum speed.

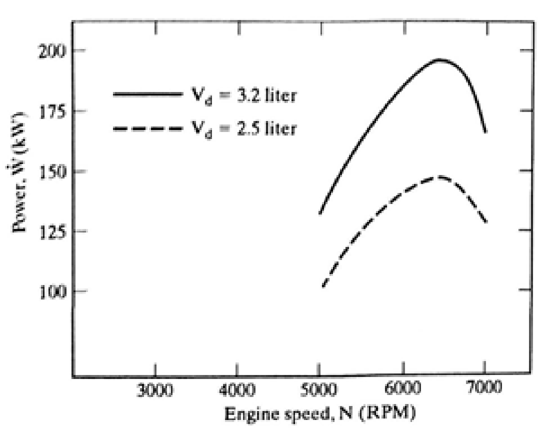


Figure 2 a) Brake power - performance curve of a typical automobile reciprocating engine [2]

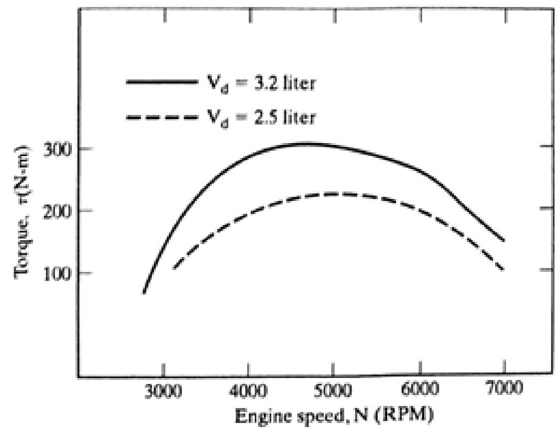


Figure 2 (b) Brake torque - performance curve of a typical automobile reciprocating engine [2]

2.3 Engine Performance Testing

The performance test has been conducted at Proton Dyno Cell #3 located at the Engine and Transmission Plant, Shah Alam, Selangor. The facility is equipped with an APICOM Eddy Current Dynamometer able to produce maximum power of 250Hp or 186kW runs with Cadet V12 CP Engineering system. The torque specification for the dynamometer is 800 Nm with maximum speed of 12,000 revolution per minutes according to the manufacturer. To explain on dynamometer principle, eddy current dynamometer is an electromagnetic load device consists of a disk placed inside its housing which produces a torque between the housing and disc resulted from a resistive magnetic fields called 'eddy current' against the rotation [4].

2.4 Engine Experiment and Dynamometer Setup

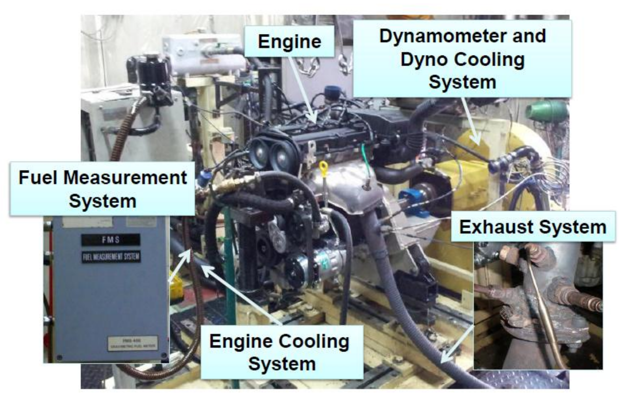


Figure 3 The engine sample mounted on a test bed [5]

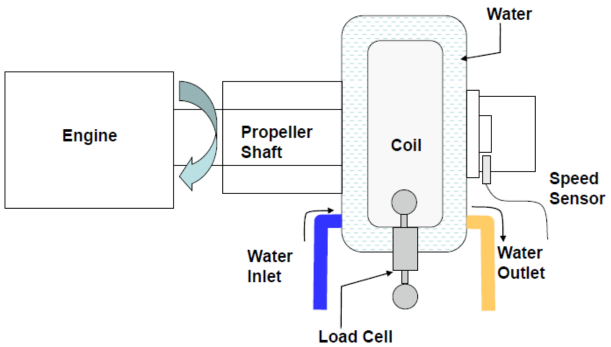


Figure 4 Schematic diagram of the engine the dynamometer setting [6]

The engine is mounted on a test bed and connected with a propeller shaft secured by the couplings which directed to the dynamometer and equipped with sensors and encoder as shown in Fig. 3 and Fig. 4. The engine is installed with sensors such as coolant temperature, oil temperature, oil pressure, vacuum pressure and air intake pressure sensor for the purpose of data collection. The engine torque is measured with a load cell readily installed on the dynamometer.

2.5 Test Conditions

The testing is conducted in ambient conditions around 16 °C ~ 24 °C for 11 hours which is measured by a K-Type thermocouple set to the air intake manifold connected by a transducer. The engine is operated in Speed Control mode at Wide Open Throttle (WOT). A standard RON 95 fuel is used throughout the testing along with PETRONAS Mach 5 SL 10W-30 engine oil.

3.0 RESULTS AND DISCUSSION

3.1 Brake Power and Torque Results for Optimal Valvetrain

As shown in Fig. 5, the engine produces maximum brake power at 5000 rpm to 5500 rpm with 105.4 kW and 105.6 kW respectively which exceed minimum brake power of 97.9 kW. Meanwhile, the maximum brake torque is produced at 2000 rpm to 4000 rpm with ranging from 206 Nm to 225 Nm which exceed the minimum brake torque of 194.8 Nm as being designed for the engine. In terms of functionality, the engine is comparable with typical reciprocating engine as the brake power curve shows the increases to maximum around 5000 rpm to 5500 rpm, about one and a half times the speed of maximum torque. The curve then decreases at higher speed due to the friction losses which will increase with speed.

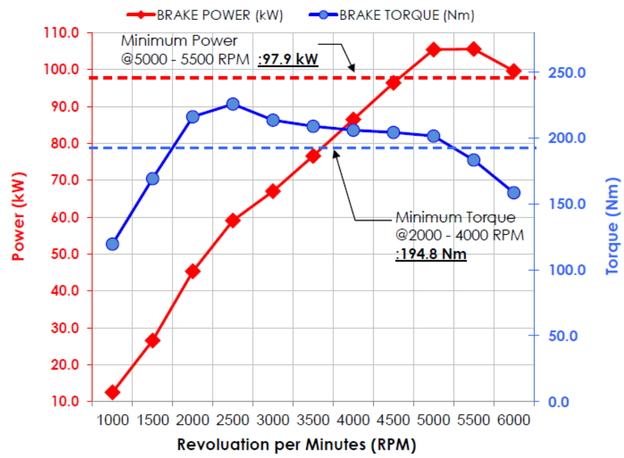


Figure 5 Optimal (Doe) engine performance test result

3.2 Performance Comparison Optimal Against Baseline

The result is compared against the baseline valvetrain to verify the similarities or any changes that could be produced with the settings. Based on Fig. 6(a) and 6(b), there are no unusual trends for both brake power and torque curve patterns for optimal valvetrain as compared to baseline valvetrain except the overall curves are slightly higher. The optimal brake power and torque are approximately 6.9% above the baseline performance which are more dominant at 2500 rpm.

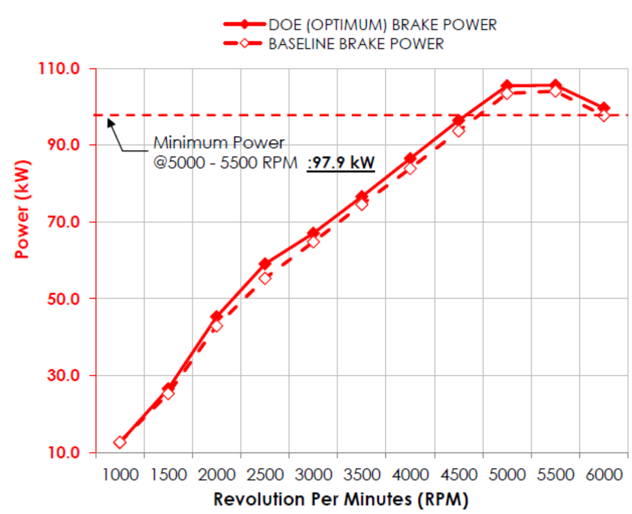


Figure 6 a) Brake power curve performance comparison optimal against baseline engine

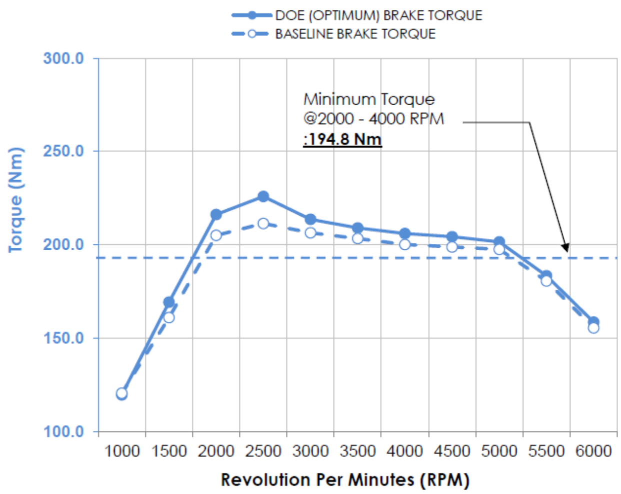


Figure 6 b) Brake torque curve -performance comparison optimal against baseline engine

In order to have more confidence, follow-up tests have been done for two improved engine samples. As recommended by Taguchi experimental result, these engines were built with the minimum level of camshaft waviness for both exhaust and intake (1.5µm and 0.5µm respectively) and remain other parameters. From previous test, the camshaft waviness was the most significant factor that affects the valvetrain noise level. According to S. Hwang et. al [7], the tappet impact noise between camshaft lobe and tappet surface is one of four classifications in mechanical type (MLA) noise. Thus, the selection of camshaft parameter used in improved valvetrain is highly important towards the verification of engine performance. Similar pattern of outputs are produced in Fig. 7 with after improvement valvetrain for both samples show slightly above the baseline result. This findings continue to convince that the optimal valvetrain results are reliable and repeatable.

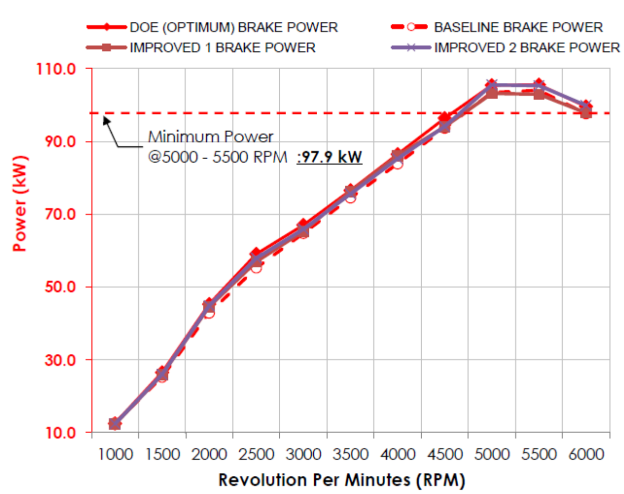


Figure 7 a) Brake power curve performance comparison optimal and after improvement against baseline valvetrain

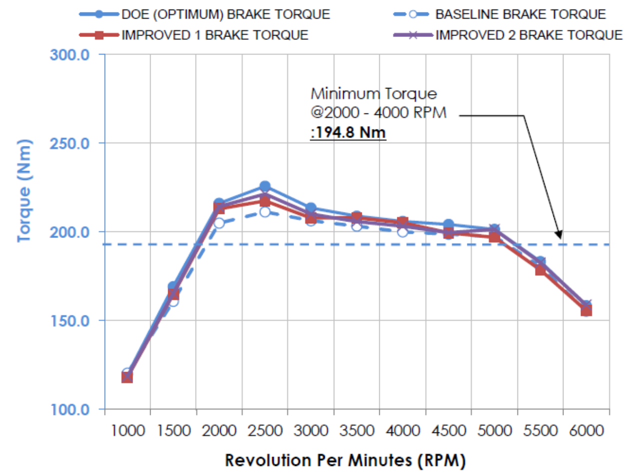


Figure 7 b) Brake torque curve- performance comparison optimal and after improvement against baseline valvetrain

3.3 Brake Specific Fuel Consumption (BSFC) and Emission Level.

In this final part, BSFC and Emission level for the optimal valvetrain are verified to address the overall engine output. Based on the results, the average BSFC (308 g/kWh) of the optimal valvetrain is within the design target (<393 g/kWh) at 2000rpm 2bar BMEP. In terms of Emission level, the results shown in Table 3 are within the Mass Target (g/km) for Euro 3 standard with condition to the total mileage of the test car (Model: Proton Preve, Total Mileage: 151,830 km)

Table 3 Emission test result for optimal engine

Emissions	Mass Target (g/km) <Euro 3>	Final Mass (g/km)	Judgment
Carbon Monoxide (CO)	<2.30	1.84	OK
Hydro Carbon (HC)	<0.2	0.07	OK
Natrium Oxide (NOX)	<0.15	0.03	OK
Carbon Dioxide (CO2)	NIL	229.35	OK

4.0 CONCLUSION

A performance validation test of an optimal valvetrain parameters has been presented in this paper. Results indicate that the optimal setting can achieve the minimum target designated by the OEM (Original Engine Manufacturer) and have approximately 6.9% above than the baseline performance. Further follow-up test made for 'after improvement' valvetrain samples has also confirmed that the optimal result is repeatable by implementing the recommended parameter setting of minimum camshaft waviness for exhaust and intake side. Finally, the BSFC and Emission level results shown that the optimal valvetrain is comparable to the engine design target.

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