Optimization of Power and Torque with lower Exhaust Noise for FSAE Vehicle

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Abstract. The exhaust noise is considered to contribute disturbance to large extent in any vehicle. The sound wave cancellation device is used for better noise attenuation without much compromise on engine efficiency. This paper aims to design an advanced muffler which gives considerably lower back pressure in exhaust system line, thereby optimizing the power and torque of an engine. Study includes close monitoring of parameters such as power, torque, and transmission loss within the given boundary conditions. The limiting condition laid by Formula Society of Automotive Engineer (FSAE) is satisfied using Ricardo Wave Build software.

1. Introduction

Engine is the main power source of automotive vehicle and it requires some device to reduce the continuous generated noise emitted by a vehicle. Muffler is an important component in the combustion engine as it plays a vital role in exhaust system of the vehicle. Its basic function is to reduce noise generated by the flowing burnt gases in the exhaust pipe and hence they can be considered as an acoustic noise reducer. The dampening of the pulsation in the exhaust gases are slowly allowed to expand in the muffler. Acoustic noise reduction is mostly achieved by introducing series of baffle which performs the obstruction to the sound pressure waves [1,2]. This design of baffles harmonically cancels the sound waves. This method proved to have significant noise quieting but principally due to increase in the back pressure of the gases in the exhaust system results in reduction of overall efficiency of the system. This compound path of gases in exhaust line is the major area of study. Also, effect on length variation of exhaust line on noise transmission loss needs to be observed.

Performance of engine system is characterized by analyzing its behavior with respect to speed and load parameters as discussed in [3]. Fuel consumption, exhaust noise, emissions, etc. could be considered in muffler design for optimization of torque and power. Mufflers are designed with various configurations, like Baffle type muffler which consist of baffle plates in the path of gas thereby creating obstruction to the natural flow. The main purpose of this muffler is to avoid straight path of gas and potentially reduce the noise, but power loss is very high. Whereas the principle of wave cancellation type of muffler is cancellation of flowing gas waves. This is designed to split the exhaust gases in number of paths. The overlap of crests and troughs of the flowing gas waves is used to calculate the length of path travelled, the process significantly reduces the noise level but only one frequency is attenuated. Resonance type muffler when connected to the exhaust line, due to Helmholtz principle the resistance to the gas flow is minimum hence compensation of engine power is reduced. Absorber type muffler uses sound absorbing material. This material absorbs sound of any frequencies. Backpressure due to this muffler is comparatively low but not very capable of noise reduction for range of frequencies. Resonance and absorber type muffler gives advantage of both mufflers resulting high noise attenuation with lower backpressure.
2. Problem Formulations:

This work preliminary aims to design an advanced muffler which has a feature to absorb and quietens the noise within the prescribed norms with minimal loss of brake power. For simulation, the engine is modeled in Ricardo Wave Built software with preprocessor as Wave Built, solver as Wave and postprocessor as Wave Post.

Kenneth, et al. discussed in [4] about exhaust pipe system design and effect of back pressure on engine performance. Exhaust pipe system design is driven by parameters like specific power, sound, and emission, etc. An ideal length of exhaust pipe is necessary to control reflected pressure wave which arrives back at the exhaust port during the time of the valve overlap period. The dynamic speed of sound is the result due to chance in exhaust gas temperature for entire range of engine speed. However, the combine effect of complex scavenging phenomenon and the changes in the dynamic geometry within the exhaust line makes the length selection a critical task. The two equations namely Smith and Bell give the estimation for the length of exhaust pipe under the given specified parameters.

\[ P = \frac{ASD^2}{1400 \times d^2} \text{feets} \]  
\[ P = \left( \frac{850(180 + D)}{R} - 3 \right) \text{inches} \]

where pipe length is represented by \( P \), \( A \) stands for exhaust open period in degrees, whereas \( S \) denotes stroke length in inches, \( D \) represents cylinder bore in inches, \( d \) stands for exhaust valve port diameter all in inches, \( B \) is exhaust opens before BDC, and target rpm by \( R \). The pipe length from Equation (1) and equation (2) comes to be 533 and 763 mm from the above equation. So, for better result 615 mm length of exhaust pipe is selected considering the calculated two values and space availability [3]. Throttle response can be improved with high exhaust gas velocities at low engine speeds to achieve quick throttle response. By the law of conservation of mass, higher gas velocity can be achieved from a small diameter exhaust pipe, conducive to throttle response for acceleration. The problem associated with pipes having smaller cross section area, which restricts the mass flow rate of exhaust gas at higher rpm. A pipe diameter of 1.6 inch is selected using Bell equation, which is found sufficient for higher range of engine speed around 8000 – 10000 rpm.

\[ D^2 = \frac{cc}{(P + 3) \times 25} \]  

Where, \( D \) stands for diameter of exhaust tail pipe, \( P \) denotes is the length of exhaust tail pipe and \( cc \) represents the volume of cylinder. Table 1 shows the dimensions selected for overall muffler design.

**Table 1. Muffler Dimensions.**

| Parameters         | Description   |
|--------------------|--------------|
| Shape              | Cylindrical  |
| Diameter           | 100 mm       |
| Length             | 350 mm       |
| Absorptive Material| Glass Wool   |

2.1 Designing of WaveBuild Models

In Ricardo Wave software the engine system design also acoustic and noise simulation environment are the essential part of designing. The mentioned designs are done for testing related to engine power and
the later for sound measurement. For simulating any system related to the engine, its model must be built in Wave Build. Wave Build is used as pre-processor for WAVE analysis. All the parameters are accurately given as input to simulate the required scenario. The operating condition parameters required to define the engine system are like exhaust system (exhaust header lengths, muffler), intake system (throttle body, plenum, runner, fuel injector), engine parameters (bore, stroke, valve timings, port lengths, etc.) In this way, the entire model is prepared for analysis in WAVE solver.

Several advantages of using the software especially where controlled experiments are not possible. Large number of iterations in minimum time is possible, various parameters can be easily monitored and altered like temperature, pressure, flow velocity, noise level with comparatively less cost which would have required in actual manufacturing

Procedure to create engine models in Ricardo Wave Build software is explained in the proceeding section. Firstly, defining simulation controls and duration – 100 cycles fuel – Indolone. Secondly defining the ambient condition i.e., 303 K with ambient pressure of 1 atmosphere and then defining the below given engine parameters. The engine parameters and their values are given in Table 2.

| Parameters             | Description |
|------------------------|-------------|
| Total Cylinders        | One         |
| Engine Type            | Spark Ignition |
| Strokes/ cylinder      | Four        |
| Engine speed           | 1000 to 10000 rpm |
| Combustion Duration    | 250 to 350 |
| Location of 50% burnt point | 100 TDC    |

Table 3 illustrates the values of cylinder geometry considered for simulation. Further, cylinder initial conditions are depicted in Table 4. Exhaust valve properties with their simulation values considered are shown in Table 5.

| Parameters            | Description |
|-----------------------|-------------|
| Bore                  | 89 mm       |
| Stroke                | 60 mm       |
| Clearance Height      | 3.6167 mm   |
| Connecting Rod length | 105 mm      |
| Head Surface Area multiplier | 1.2 (to make 7465.37 mm) |
| Piston Surface Area multiplier | 1.0 (flat top piston) |
| Compression ratio     | 12.88       |
| Wrist pin offset      | 0.0 mm      |

| Parameters                  | Description |
|-----------------------------|-------------|
| Cylinder Head Temperature   | 503         |
| Cylinder Liner Temperature  | 433         |
| Swirl Ratio                 | 0           |
| Intake/Exhaust Valve Temp.  | 453         |
| Piston Top Temp             | 503         |
Table 5. Exhaust Valve Properties.

| Parameters             | Description |
|------------------------|-------------|
| Valve type             | Generic Lift|
| Reference Diameter     | 29 mm       |
| Fuel/Air Ratio         | 0.0714      |
| Mixture Temp.          | 30          |
| Nozzle Diameter        | 0.2 mm      |
| Sprat spread angle     | 30          |
| Fuel Index             | 1: fuel 1   |
| Crank Timing           | 2500        |
| Open Duration          | 2260        |

2.1.1 Muffler simulation for engine brake power

The muffler model is designed considering the basic calculations [4]; also, CATIA V5 software is used for modelling of cylindrical plenum with volume of 2000 cc and is meshed in Ricardo Wave Mesh. Further the procedure includes the engine modelling and considering the parameters which are given above in Wave Build canvas. Ambient values of temperature of 303 K and pressure 1.01325 bar is taken into consideration. The bore diameter of 46.3 mm of throttle body is added, a shaft diameter of 5mm and a minimum plate angle of 6.67 ° is considered as per the data given in table.

As per the decided, the plenum, engine, muffler and exhaust are placed in appropriate in the WaveBuild3D. Here the ambient temperature of 303 K and a pressure of 1.01325 bar values are given. The careful placement of injector is done on the duct before the intake port and on the runner at a length of 146 mm from intake valve. All the above-mentioned parts like runner, exhaust pipe etc., are internally connected by circular ducts of appropriate diameters. Fig. 1 depicts the input to the Ricardo Wave Pre-processor.

Figure 1. Final Engine system in Ricardo Wave.
2.1.2 Muffler Simulation for Noise Transmission Loss
The procedure includes the acoustic piston which is a noise source is added to Wave Build canvas also along with the acoustic piston a terminal is added. The placement of muffler is placed in between them and are connected via the circular ducts’ internal diameter according to the muffler start and end diameter. Fig. 2 shows model of a muffler built in modelling software.

![Muffler modelled in Catia V5.](image)

3. Results and Discussions

The parameters assumed for simulation are depicted in Table 6. Simulation is carried out for three different values of inlet pipe, perforated holes, and tail pipe diameter. Muffler diameter and length are kept constant also absorption material and baffle thickness values are kept fixed.

| Parameter               | Value 1(mm) | Value 2(mm) | Value 3(mm) |
|-------------------------|-------------|-------------|-------------|
| Inlet pipe dia.         | 25          | 20          | 15          |
| Inside pipe dia.        | 30          | 30          | 30          |
| Perforated holes diameter | 5           | 7           | 6           |
| Holes spacing           | 3           | 3           | 3           |
| Muffler dia.            | 80          | 80          | 80          |
| Muffler length          | 300         | 300         | 300         |
| Tail pipe dia.          | 15          | 20          | 15          |
| Absorption material thickness | 125       | 125         | 125         |
| Baffle thickness        | 2           | 2           | 2           |

The system analysis is carried out by varying the engine speed in rpm and its effect on power and torque is observed. Also, the effect of transmission loss is studied with respect to frequency.
Figure 3. Engine speed v/s Brake Power analysis for designed muffler.

Figure 4. Engine speed v/s Brake Torque analysis of designed muffler.
The results in Fig. 3 and 4 shows that the new designed muffler as per stated in value 2 is found superior in terms of both acoustic and engine performance. With the new muffler of 5 mm perforated hole size and inlet pipe diameter of 15 mm the following observations were made. The brake power and the brake torque obtained are sufficient for the speed range of 5000 rpm. The value obtained from the performance curved for the brake power is approximately 17 Kw and for brake torque is 33 Nm. Also, the transmission losses as depicted in Fig.5 for the given speed are well below the norms of 110 db. Hence the values obtained for the parameters namely brake power, brake torque and transmission loss are proved to be within the limits specified by FSAE. The present work thus experimentally shown that results from analysis can be used as an alternative design of vehicle.

![Figure 5. Engine transmission loss v/s frequency analysis of designed muffler.](image)

### 4. Conclusion:

The effect on the output of the engine performances by varying the various parameters have been simulated and observed. Ricardo Wave software is used to carry out the simulation. The change in muffler design showed the improved effect on power and torque of the engine. Parameters like inlet pipe diameter, perforated hole size and tail pipe diameter are altered on the new designed muffler. This resulted in optimum values of power and torque with reduction of noise level is obtained at the given 5000 rpm of engine speed.

Further work can be carried out in addition to the present work like pressure drop can be evaluated and scientifically optimized to obtain adequate backpressure. Also, various pressure drop reduction in noise level using Design of Experiments software to find exact matrices for all the possible parameters. Variable muffler or active muffler is possible in parameters like diameter, volume which can be varied according to operating conditions.

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