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A study on the significance of exhaust manifold's bending angle to the brake torque of 115cc SI engine

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Abstract. The exhaust manifold is a crucial component of the exhaust system in any SI engine, responsible for efficiently expelling combustion products. However, when the exhaust manifold's design is suboptimal, it leads to negative consequences for the engine's performance due to the presence of backpressure. Backpressure refers to the difference between maximum exhaust pressure and atmospheric pressure. An increase in backpressure decreases the overall performance and fuel efficiency of an SI engine. This study aimed to investigate the bending angle characteristics of the exhaust manifold and the brake torque of the 115cc SI engine using 1D engine analysis. The relationship between the exhaust manifold's bending angle characteristics and the brake torque was analysed using Analysis of Variance (ANOVA) with a p-value of less than 0.05, while the validation with experimental data showed a maximum error of 6.62. In the previous research, it was noted that a lower bending angle leads to better performance. However, the current results indicate that out of the three bending angles considered, having one of them yields the most substantial enhancement in brake torque. The optimized bending angle configuration obtained from the analysis increased the mean brake torque by 0.011 Nm (0.14%). Consequently, this study enhances the average brake torque through the optimal bending angle characteristics of the exhaust manifold. The study's objective aligns with Sustainable Development Goal (SDG) 9: Industry, Innovation, and Infrastructure, as the improved performance achieved through an optimal exhaust manifold design configuration is expected to promote domestic technology development.

1. Introduction
The automotive industry is one of the most important revenue-generating businesses, and its technology is improving over time. All production engineering of motorised vehicles and main parts such as engines and body pieces, except fuels and batteries are regarded to be part of the automotive industry. The most significant elements in the automobile business are performance and fuel consumption efficiency. Reciprocating engines, commonly known as piston engines, employ rotating motion to build pressure at high temperatures to generate energy for the engine. The exhaust system is one of the most significant components of a SI engine. The design characteristics of the exhaust system are particularly essential since they impact the performance of the SI engine [1], [2]. The silencer and the manifold are the two primary components of the exhaust system as shown in Figure 1.

Figure 1. Components of an exhaust system

Exhaust back pressure is the significant thermodynamic condition that affects the engine's performance which is described as the pressure differential between a location on an exhaust system and ambient pressure[3]. In previous studies, higher exhaust backpressure reduced engine power and torque while increasing fuel consumption. Several studies have been conducted to discover a strong correlation between exhaust backpressure[4]and IC engine performance (power, torque, and fuel consumption). Bhure et al. (2018) documented that there is a 2 % increase in fuel consumption at 87.5% valve opening, brake-specific fuel consumption (BSFC) increases by 10% at 75% valve opening, 42% of Hydro Carbon (HC) Emission, HC decrease at 75% Back Pressure Control Valve, BPCV opening[2]. Krishna et al. (2018) state that the inclination angle in the manifold pipe causes a pressure drop transversely to the outlet exhaust pipe, which leads to an increase in volumetric efficiency across the manifold and reduces the flow resistance of the fluid causing an increase in the engine power and ultimately the engine performance would be improved [5]. Kumar et al. (2022) stated that in the conjugate heat transfer analysis, CHT, the initial velocity is 7 m/sec. The result shows that the fluid attains the max velocity at the exhaust pipe, reaching up to 54.0338 m/sec, and the Exit Temperature of the exhaust is 1089.15K[6]. Sankar et al. (2018) mention that Pressure Maintainer Valve helps maintain reduced back pressure. At 1500rpm, pressure decreases for 1.95×10^5 Pa at a 0-degree retainer valve; at 75000rpm, pressure decreases for 2.118e+05 Pa at a 90-degree retainer valve[7]. Therefore, it is concluded that exhaust backpressure can negatively impact IC engine performance, increasing fuel consumption and reducing efficiency. However, it can be controlled using several methods: pressure maintainer valve, larger exhaust pipe, and free-flowing exhaust system.

The bending angle of an exhaust manifold is defined as the deflection angle of the distal tip segment. It is measured between the bent flange and its original position[8]. The bending angle and radius have a large impact on the engine backpressure. According to Sachin et al. (2017), the long bend model facilitates an easy flow of exhaust gases and low backpressure at the exhaust outlet compared to the sharp and short bend. The minimum backpressure and higher exhaust velocities are achieved using a long bend Exhaust manifold. Also, the velocity at the outlet of the long bend model is higher, reducing the backpressure considerably[9]. Mondol et al. (2018) state that pipes with fewer than 90-degree bends lose pressure in significant amounts in the exhaust manifold (108.87 Pa) the pipe's bend angle-related pressure losses. Due to a change in flow direction or laminar flow, momentum must be exchanged at the pipe bending section. There is a greater pressure drop when the pipe bending angle is less than 90-degree bend pipes[10]. Kamal et al. (2021) state that the larger distance between perforations at 20 mm for exhaust muffler leads to considerable disparities in the results, with a 15% difference in pressure drop, as opposed to the smaller distance between perforations, which results in less than 1% difference in pressure drop for perforated pipes with 6mm and 7mm diameters. The perforation diameter of 5mm in exhaust muffler resulted in a pressure decrease of up to 44.66%[11]. From the study, it can be observed that the bending angle and radius of an exhaust pipe have a significant impact on engine backpressure. A long bend with a large radius will result in lower backpressure than a sharp bend with a small radius which results in engine's performance increment.

This study aims to correlate the exhaust manifold's bending angle and the torque of a 115cc SI engine at low-end engine speed (2500-6000 rpm) through 1D engine analysis. Moreover, this study also evaluates the significance of bending angle to the engine's torque when it comes to designing the entire exhaust system. The MODENAS CT115S engine served as a platform for obtaining boundary conditions for 1D engine analysis. Hence, the outcome of this study helps engineers to consider the degree of significance of the exhaust manifold's bending angle when it comes to designing the exhaust system. Moreover, the optimal exhaust manifold's bending angle configuration was also obtained that enhances the engine's torque.

2. Methodology

Figure 2 shows the flow chart for this study where the research started with an in-depth literature review before defining the objective which is to enhance the engine's brake torque and to evaluate the significance of the exhaust manifold's bending angle to the engine's performance. Next, the Design of Experiment (DOE) was constructed to conduct a 1D engine simulation. The results from the 1D engine simulation were validated with an actual experiment using an engine dyno in MODENAS Research and Development (R&D) department. Analysis of variance (ANOVA) was conducted to obtain the reliability of the simulation results from 1D engine analysis and also to establish the most significant variable that affects the engine's brake torque. Finally, a regression model was constructed that predicts the average brake torque based on variable bending angle configuration.

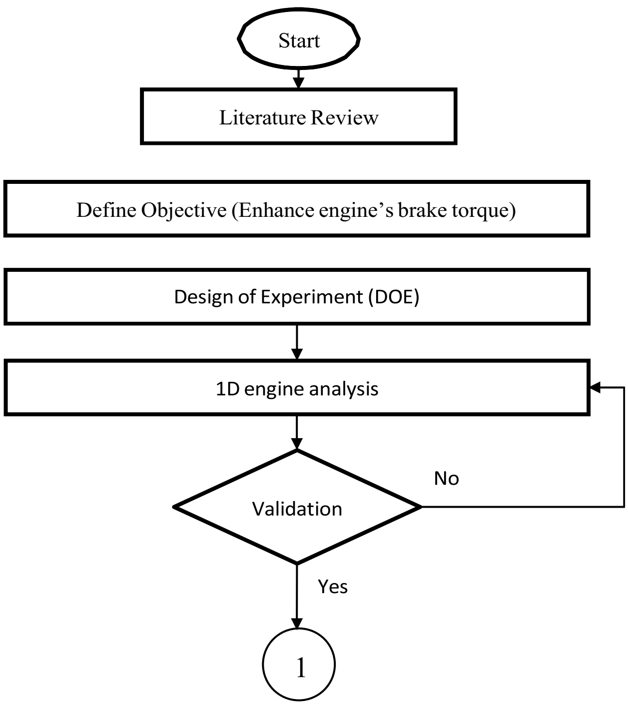


Figure 2. Research Flow Chart

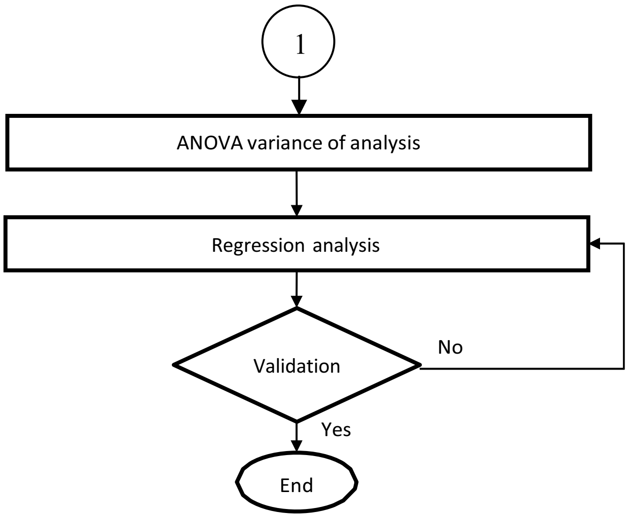


Figure 3. Research Flow Chart (Continue)

2.1. Design of Experiment

Figure 3 shows the design of the stock or existing exhaust manifold for MODENAS CT115s and Table 1 shows the scope of variables for this study. Three (3) different variables which are BA1, BA2 and BA3 with 3-level studies in this research. The existing or stock bending angles for the exhaust manifold were fixed in level 3 and reduced until level 1 was equal to each other. Table 2 shows the constructed DOE for this research that gives the maximum combination of 27 samples for the variables with 3 levels.

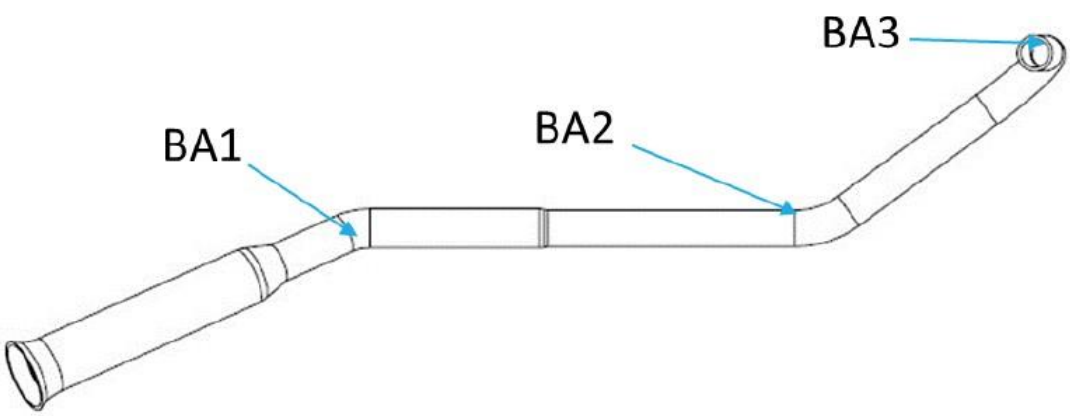


Figure 4. Exhaust manifold's bending angle selection (MODENAS CT115S)

Table 1. Scope of variables

Variables	Symbol	Level 1	Level 2	Level 3
Bending Angle 1	BA1	0	76.5	153
Bending Angle 2	BA2	0	74	148
Bending Angle 3	BA3	0	40	80

Table 2. Design of Experiment (DOE)

Sample	BA1	BA2	BA3
1	0	0	0
2	0	0	40
3	0	0	80
4	0	74	0
5	0	74	40
6	0	74	80
7	0	148	0
8	0	148	40
9	0	148	80
10	76.5	0	0
11	76.5	0	40
12	76.5	0	80
13	76.5	74	0
14	76.5	74	40
15	76.5	74	80
16	76.5	148	0
17	76.5	148	40
18	76.5	148	80
19	153	0	0
20	153	0	40
21	153	0	80
22	153	74	0
23	153	74	40
24	153	74	80
25	153	148	0
26	153	148	40
27	153	148	80

2.2. 1D engine analysis

Ricardo Wave software was utilized to conduct a 1D engine simulation to correlate the exhaust manifold's bending angle configuration and the brake torque of the 115cc SI engine. It has already been demonstrated in the past that 3D simulation is more accurate than 1D simulation. However, 1D simulation is effective in terms of time consumption and is often used to determine the effect of changing a specific design, such as the design of an intake or exhaust manifold, on engine performance [12], [13]. Hence, 1D engine analysis is a fast, convenient and accurate tool if it is validated via experimental analysis. The scope of performance for this study is brake torque. The SI- Wiebe combustion model was used for this research because it is extensively utilised to predict the performance of a SI engine [12]. The equation that represents the model is shown in Equation (1) where W_n is the cumulative burnt rate, θ_0 is the crank angle during the start of the combustion, θ_i is the specified crank angle, B is the combustion mode parameter and A is the scaling factor. The combustion model parameter defines the combustion profile's shape with respect to time.

$$W_n = 1 - exp[-A(\theta_i - \theta_0)^{B+1}] \quad (1)$$

The scaling factor, A is represented by Equation 8 where $x_{B,EOC}$ is the mass fraction burned.

$$A = -\ln(1 - x_{B,EOC}) \quad (2)$$

2.3. Analysis of Variance (ANOVA)

ANOVA was conducted in this research to evaluate the significance of the exhaust manifold's bending angle to the brake torque as well as the contribution of each variable (bending angle) with 95 percent confidence. Equation (3) shows the method of obtaining the contribution of each variable where C_f is the contribution of each factor in percentage, SS_{fi} is the sum of the square of factor i and $\sum SS$ is the total sum of squares for all factors

$$C_f = \frac{SS_{fi}}{\sum SS} \quad (3)$$

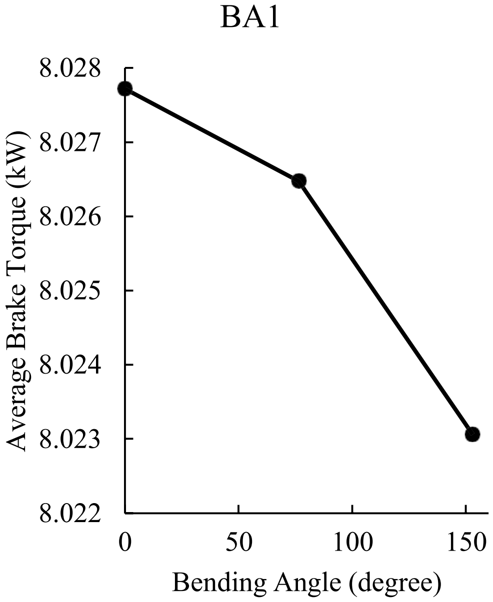
3. Results and Discussion

Table 3 shows the results (brake torque) obtained from 1D engine analysis for 27 samples from DOE using full factorial method in the Minitab software. From the results, it can be observed that sample 4 shows the highest brake torque compared to all 27 samples where it enhances the brake torque by 0.011 Nm (0.14%) compared to the existing or stock exhaust manifold's design.

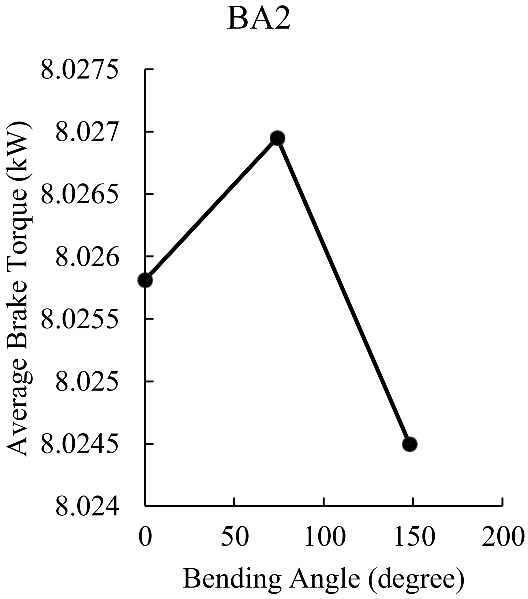
Table 3. Brake torque of DOE samples

Sample	Brake Torque at each engine speed (Nm)								Average brake torque (Nm)
	2500	3000	3500	4000	4500	5000	5500	6000	
1	7.916	8.197	7.928	7.875	8.166	8.268	8.093	7.777	8.028
2	7.919	8.195	7.932	7.881	8.163	8.259	8.09	7.778	8.027
3	7.923	8.192	7.938	7.885	8.162	8.251	8.089	7.778	8.027
4	7.929	8.186	7.946	7.897	8.165	8.239	8.089	7.786	8.03
5	7.931	8.182	7.951	7.899	8.163	8.234	8.088	7.785	8.029
6	7.936	8.177	7.954	7.904	8.159	8.226	8.085	7.783	8.028
7	7.95	8.158	7.969	7.925	8.161	8.2	8.076	7.792	8.029
8	7.953	8.154	7.97	7.927	8.157	8.192	8.074	7.788	8.027
9	7.956	8.148	7.972	7.93	8.153	8.184	8.07	7.787	8.025
10	7.917	8.192	7.931	7.881	8.165	8.262	8.092	7.777	8.027
11	7.921	8.191	7.936	7.882	8.163	8.255	8.089	7.775	8.027
12	7.925	8.186	7.94	7.887	8.16	8.246	8.086	7.776	8.026
13	7.929	8.179	7.947	7.899	8.165	8.237	8.086	7.783	8.028
14	7.934	8.176	7.95	7.9	8.163	8.229	8.084	7.783	8.027
15	7.937	8.172	7.954	7.907	8.158	8.223	8.082	7.781	8.027
16	7.953	8.152	7.969	7.927	8.157	8.197	8.073	7.787	8.027
17	7.954	8.149	7.971	7.929	8.157	8.192	8.07	7.785	8.026
18	7.956	8.144	7.971	7.933	8.152	8.184	8.067	7.782	8.024
19	7.925	8.175	7.941	7.889	8.16	8.247	8.084	7.772	8.024
20	7.929	8.172	7.943	7.892	8.158	8.241	8.082	7.773	8.024
21	7.931	8.168	7.947	7.896	8.155	8.234	8.082	7.773	8.023
22	7.936	8.161	7.953	7.907	8.158	8.224	8.079	7.779	8.025
23	7.94	8.16	7.956	7.909	8.156	8.22	8.078	7.778	8.025
24	7.944	8.154	7.96	7.914	8.154	8.212	8.075	7.777	8.024
25	7.956	8.136	7.969	7.931	8.154	8.187	8.066	7.784	8.023
26	7.958	8.134	7.969	7.935	8.152	8.182	8.062	7.781	8.021
27	7.96	8.128	7.971	7.938	8.147	8.173	8.058	7.778	8.019

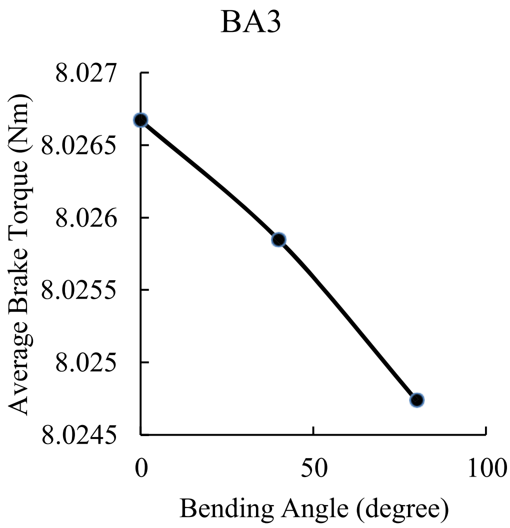
Figure 3 shows the means of brake torque for each variable and it can be observed that having no bending angle (0 degrees) enhances the brake torque for BA1 and BA3 by 0.06% and 0.02% respectively. However, for BA2, having a bending angle of 74 degrees enhances the brake torque by 0.03%. From past studies, it was documented that having a lower bending angle reduces the coefficient of friction and the backpressure which increases torque. However, in most of the past studies, the effect of a single bending angle on the backpressure and the engine's performance was focused. In this research, the effect of multiple bending angles on the brake torque is studied and shows that there is an optimal value for bending angles that enhances the engine's performance. Moreover, the overall bending angles show that 0 degrees (no bending angle – sample 1) do enhance the brake torque by 0.009 Nm (0.11%). This shows that the difference in brake torque increment between 1 and sample 4 is just 0.03% which is insignificant. 1D engine simulation tool is best known for its time efficiency (faster compared to 3D simulation). However, 1D engine simulation tool has a lower accuracy compared to 3D simulation tool which could be the reason for a small error (difference of 0.03% between sample 1 and sample 4). Hence, it can be considered that a bending angle of 0 degrees for all variables is also optimal in enhancing the brake torque affirming the results obtained from past studies [14].



(a)



(b)



(c)

Figure 5. Means of Brake Torque for each bending angle

3.1. Experimental Validation

An experimental study was conducted in the MODENAS facility to obtain the brake torque using the engine dyno where Table 4 and Figure 4 show the comparison between experimental and simulation results for the stock exhaust manifold's design configuration. From the table below, it can be observed that the maximum percentage of error is around 6.62% which is significantly lower than 10% which validates the 1D engine analysis model utilized for this study[15][16].

Table 4. Brake Torque comparison between experimental and simulation results for stock exhaust manifold's design configuration

SPEED (rpm)	Brake Torque (Nm)		Error (%)
	Experimental	Simulation	
2500	7.61	7.9598	4.394583
3000	7.59	8.12828	6.622311
3500	7.95	7.97084	0.261453
4000	8.32	7.93778	4.8152
4500	8.52	8.14654	4.58428
5000	8.61	8.17349	5.34056
5500	8.33	8.05792	3.37655
6000	8.18	7.77819	5.16585

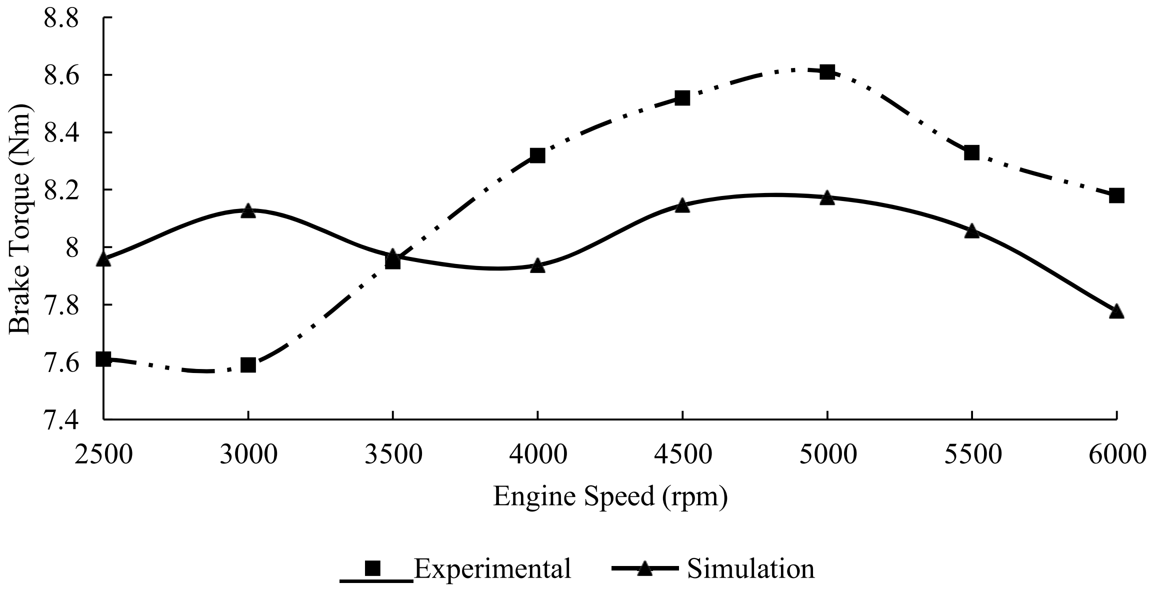


Figure 6. Experimental and simulation brake torque comparison for stock exhaust manifold's design configuration

3.2. Analysis of Variance (ANOVA)

Analysis of variance was conducted to further verify the simulation data and also to evaluate the significance of bending angles to the brake torque. From Table 5 it can be observed that the p-value for each variable (BA1, BA2 and BA3) is lower than 0.05 [17] [18]affirming the reliability of the data from 1D engine analysis. It can be also observed that BA1 has the highest contribution of 59.76% in enhancing the brake torque of the engine. This shows that the first bending angle is the critical variable that affects the engine's torque. Once the exhaust gas exists in the combustion chamber, it first passes the first bending before going through the next bending or other form of fluid restrictions. Hence, the losses or backpressure that is built would be greater at the first bending that causes it to be the significant or critical variable.

Table 5. Analysis of Variance (ANOVA)

Source	DF	Adj SS	Adj MS	F-Value	P-Value	Contribution (%)
Regression	3	0.000124	0.000041	23.72	0.000	

BA1	1	0.000098	0.000098	56.25	0.000	59.76
BA2	1	0.000008	0.000008	4.59	0.043	4.88
BA3	1	0.000018	0.000018	10.33	0.004	10.98
Error	23	0.000040	0.000002			
Total	26	0.000164				

A regression model was constructed as shown in Equation (4) with a percentage of error of 0.034% affirming the reliability of the formula. This model predicts the average brake torque (T_{avg}) with variable bending angles as the subject which could be utilized by engineers to successfully obtain and evaluate the losses that will occur due to the bendings of the exhaust manifold during the designing stage. Figure 5 shows the residual plot of average brake torque for the regression model. From the figure, it can be observed that the residuals are equally distributed on the centre line further affirming the reliability of the regression model.

$$T_{avg}: 8.02981 - 0.000031\,BA1 - 0.000009\,BA - 0.000025\,BA3 \quad (4)$$

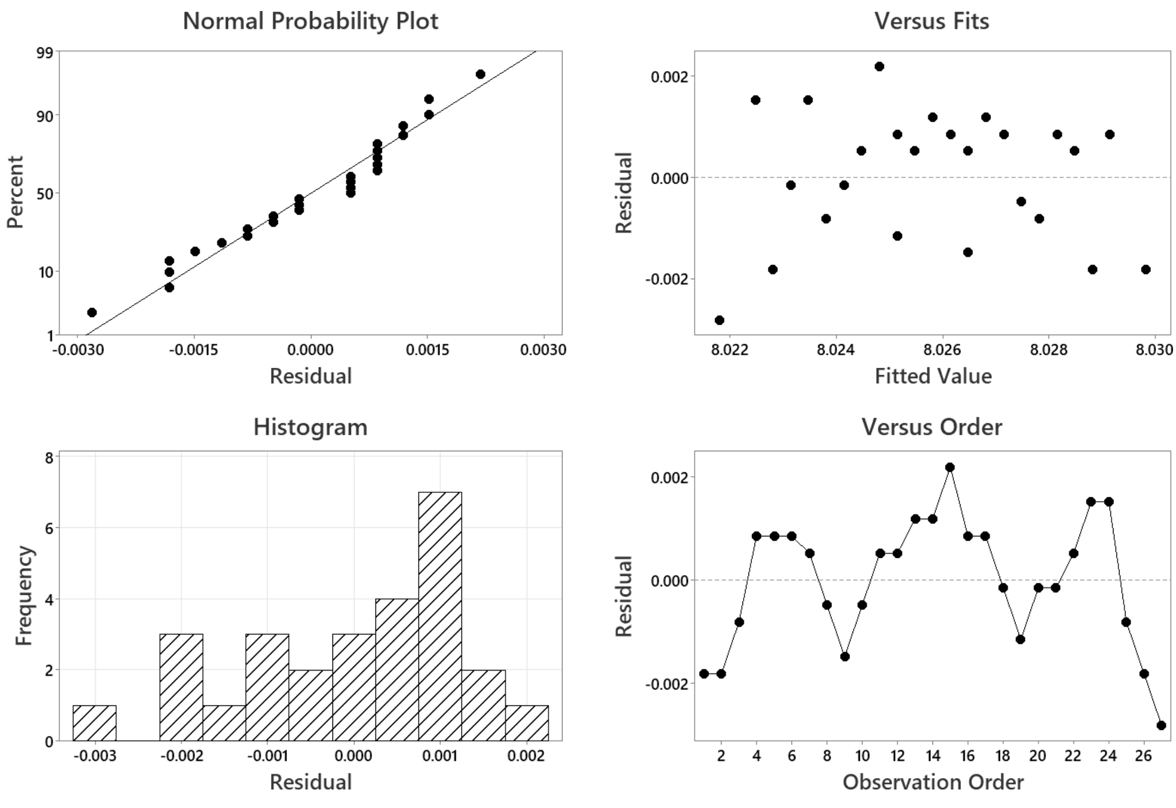


Figure 7. Residual Plot of Brake Torque

4. Conclusion

In conclusion, the significance of the bending angle to the engine's torque for the 115cc SI engine was evaluated. It is found by having a straight pipe with no bending angles does only improve the engine's torque by 0.11% which is significantly lower compared to the other form of possible performance enhancement through the elimination of the engine's losses. The simulation result was validated with experimental data where the maximum percentage of error is 6.62%. Results from analysis of variance show bending angle affects the engine's torque with a p-value<0.05 further affirming the reliability of the 1D engine analysis model. Moreover, a regression model was constructed where it is useful for engineers to successfully obtain and evaluate the losses that will occur due to the bendings of the exhaust manifold during the designing stage.

5. Acknowledgement

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