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ORIGINAL RESEARCH

Design and simulation of an exhaust muffler for a single cylinder diesel engine for the Wuzheng tricycle model 7YPJ-1750PD

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Abstract
Exhaust muffler systems are mechanical devices used to absorb and attenuate the noise level of exhaust gases as they enter the atmosphere. This work was aimed at designing and simulating the performance of an exhaust muffler system for the Wuzheng tricycle model 7YPJ-1750PD using its simple expansion chamber as a benchmark to lower the engine exhaust noise by minimising the backpressure. A combination muffler was designed alongside a simple expansion chamber. The two were assembled using solid Edge CAD software. The system was made to undergo CFD and harmonic acoustic simulations using the ANSYS FLUENT software to check its working conditions and performances. It was observed that the assembled muffler system reduced the noise level of the original muffler by 15 dB with a minimal effect on the engine. The assembled muffler system also had a lower average backpressure (911.3 Pa) as compared to that of the original muffler (1151.6 Pa). From the simulation results, the combination muffler was found to be more efficient in attenuating engine exhaust noise levels as compared to the original muffler.

Keywords: Exhaust, Muffler, Backpressure, Transmission, Loss, Simulation

Introduction
In developing countries such as Ghana, tricycles are highly utilized for commercial and agricultural activities due to their affordability, mobility and ruggedness. The Wuzheng cargo diesel tricycle with a model of 7YPJ-1750PD is not an exception. However, one limitation it has is the high exhaust noise it produces as a result of the wave front generated by the exhaust gases that exits the two-stroke diesel engine. The tricycle would be highly efficient if the engine noise levels are reduced to moderate levels (Wall, 2003). A reduction in the noise levels will also protect the health of users (Zhang, 2016). In this work, simulation is performed to give a predicted model of reducing the noise levels. A combination of an absorber-type and a straight-through type muffler is used to decrease the noise generated by the exhaust gases, while keeping to the barest minimum power losses generated by the engine as compared to the tuned pipe. The specific objectives of this research are to design an efficient exhaust muffler system using the Solid Edge CAD software, evaluate the working performance of the designed muffler system using an Ansys fluent simulation and optimize the engine exhaust noise levels generated while minimizing the backpressure produced. According to Shinde *et al*. (2017) the original purpose of an exhaust system is to perfectly course the fume gases from the engine so that they can enter the surroundings, while providing constriction for ignition clamour. In recent times, the major research procedure for quantifying the acoustic efficiency of the exhaust muffler according to Gen *et al.* (2012) involves transfer matrix technique, finite element technique and boundary element technique. The finite element technique has become the most popular three-dimensional analysis technique due to its good adaptability (Zhongxu *et al*., 2011).

Finite element technique can be used to simulate different categories of mufflers; for instance, it is the one that is suitable for analyzing the muffler that possesses a complex geometry and cross-sectional structure; (Jianguo *et al*., 2011, Jung Fu *et al.,* 2015). Craggs (1973) first endeavored to investigate the muffling properties of noise reduction units by utilizing the finite element technique, which laid a consolidating foundation for the finite element technique employed in acoustics. Young and Crocker (1976; 1977) employed the finite element two-dimensional analysis technique for computation of the muffler's transmission loss (TL) for the first time, which advanced the knowledge on the application of finite element technique for the muffler. Ross (1981) utilized finite element technique to investigate muffler's muffling properties which had a perforated structure. Mechel (2008) explained the finite element technique utilized in various structures of mufflers in relation to their acoustics properties in his monograph. Rong *et al*. (2014) and Jing (2012) employed the acoustic finite element technique, used complex muffler for his research work, and tailored his research towards the acoustic properties analysis technique. Jun Fu *et al*. (2015) adopted the automatic matched layer method of finite element on the basis of LMS Virtual to improve the acoustic attenuation performance of an exhaust muffler of a 175 series of agricultural diesel engine. Lei (2012) evaluated various categories of perforated pipe muffler's TL by using the finite element technique and, also, investigated the different parameters influencing the acoustic efficiency of perforated pipe frame of the muffler. Mohumuddin *et al*. (2005) conducted some experiments to study the noise and back pressure for silencer design features. The primary goal of the research was to obtain a relation between the noise level and the back pressure and concluded that the relation between the noise and the back pressure is inversely proportional. Wang and Dong-Peng (2010) conducted some analysis on a specific model of an automobile exhaust muffler using PRO/E and ANSYS to enhance the design efficiency. The solid model was generated by PRO/E and model analysis was also performed by ANSYS to analyze the vibration of the muffler, in order to differentiate the working frequency from natural frequency and eliminate resonating. Data exchange between PRO/E and ANSYS was done by employing IGES (Elementary graphics exchange specification) format. Muffler natural frequencies modal shapes were computed using the Finite Element Method. The software employed in this regard was ANSYS. The muffler vibration was investigated intuitively. The natural frequencies and mode geometry were taken into consideration during the design of the muffler to eliminate resonance in the exhaust system. Chen and Shi (2011) investigated the CFD

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numerical simulation of exhaust muffler using the information obtained from the physical numerical modelling of the flow field of the muffler. For this work, the researcher simulated the field through a numerical technique with Fluent and studied the influence which the flow field of the internal structure of the muffler has on the efficiency of the muffler.

Rajasekhar Reddy and Madhava Reddy (2012) explained the design and optimization of exhaust muffler in automobiles by studying the muffler dimensions which are obtained through the Benchmarking to generate CAD models. The CAD models were generated in CATIA V5 R19 and were later sent to HYPER MESH for pre-processing. Free analysis was performed on this muffler by FEA technique utilizing NASTRAN Software. The stress and stiffness of the model was investigated from the results generated from the analysis to verify the design. Yasuda *et al*. (2013) performed some research on an automobile muffler with the acoustic feature of low-pass filter and Helmholtz resonator. With respect to the standard structure, a muffler with an interconnecting hole on the tail pipe was proposed to enhance its acoustic efficiency. Acoustic efficiencies of the proposed muffler were analyzed experimentally and theoretically in frequency and time domains. The results portrayed that the specimen muffler had attenuation performances of low-pass filter and Helmholtz resonator when an interconnecting hole was created on the tail pipe. According to Sherekar and Dhamangaonkar (2014) the performance of an exhaust muffler can be expressed in terms of the transmission loss, insertion loss, back pressure and sound emitted at the tail pipe. The performance of an exhaust muffler is an expression of its attenuating capability. The transmission loss is the distinction between the sound power at the entry of the muffler to that at the exit of the muffler. This can be said to be the net sound power lost in its flow through the muffler. The transmission loss is measured in decibels (dB) and can be expressed mathematically as:

$$\text{Transmission Loss} = 10\log_{10}\frac{W_i}{W_t} \quad (1)$$

Where W_i = Incident sound power and
W_t = Transmitted sound power

Backpressure is the extra static pressure generated by the muffler on the engine through the restriction on the flow of the exhaust gases (Sherekar and Dhamangaonkar, 2014). Backpressure is generated when the exhaust gases are compelled to change direction. Whenever backpressure is generated, it decreases the power output and torque of the engine and this can lead to an increase in fuel consumption, emissions and exhaust temperatures. These variables must be kept at minimum to reduce the power loss of the engine (Raj *et al*., 2021). Apparently, most mufflers have complex internal and external shape. This is to help increase the efficiency of the muffler. The shape of an exhaust muffler affects its performance, as a muffler with a larger volume would have a minimal backpressure. Also, as compared to a single expansion chamber a double chamber muffler produces a better performance (Raj *et al*., 2021)

Materials and Methods

Design of simple expansion chamber attached to a combination exhaust muffler

A conceptual 3D design of the simple expansion chamber attached to a combination exhaust muffler was made using Solid Edge Software. In this design concept stainless steel 410 is used to make a muffler which is then attached to a simple expansion chamber of similar material. This combination muffler is formed from the merging of resonance and absorptive muffler concepts. It entails large number of ports with resonators. These ports are arranged in series with the pipe which discharges the exhaust gases. Enclosed in the chamber is a layer of stainless steel 420 for the absorption of the sound of the exhaust gases. It also has a resonance chamber at one end of the muffler. This concept seeks to capitalize on the advantages of the absorptive and wave cancellation muffler which have more airflow and less sound. Figures 1 and 2 show the 3D design model of the muffler and its views.

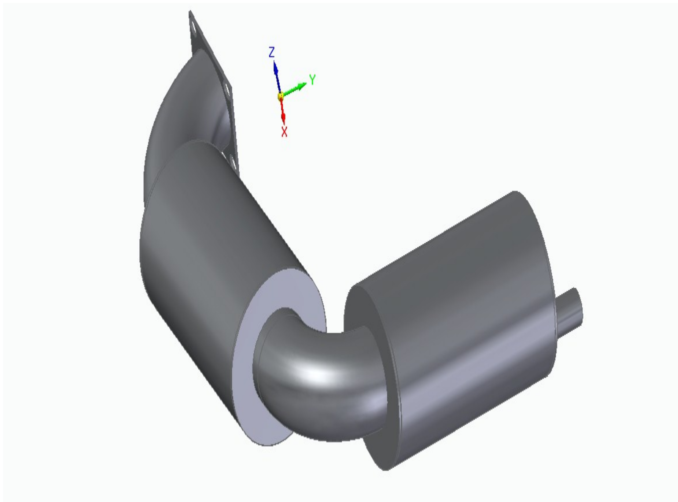

Figure 1 Design model of a simple expansion chamber attached to a combination muffler

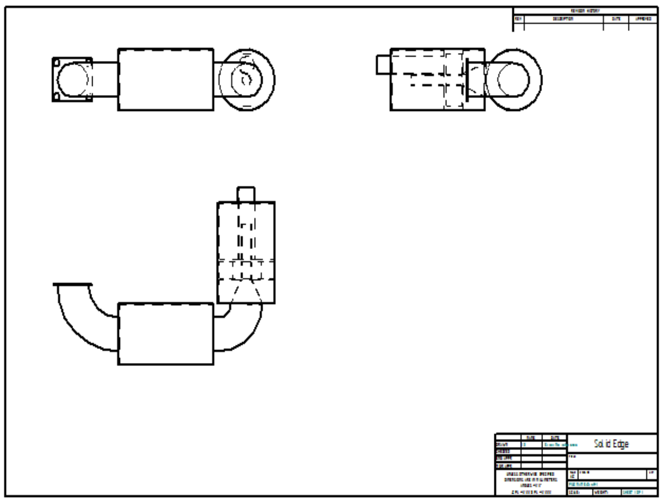

Figure 2 Orthographic views of a simple expansion chamber attached to a combination muffler

Working principle of expansion chamber attached to a combination exhaust muffler

Mufflers exist in different models and designs consisting of absorptive, turbo, straight-through and even the simple expansion chamber. The analysis used in this work is based on a design concept which is the assembly of a simple expansion chamber and a combination muffler. The simple expansion chamber is a tuned-pipe exhaust system which enhances the power output of an engine through enhancing its volumetric efficiency. This type of combination muffler works on the principle of attenuation occurrences where the medium through which sound passes lengthens in distance and sound absorption capacity is thus, increased. Here, engine noise enters the simple expansion chamber from the exhaust manifold to expand to lose energy with a low backpressure and then enters the combination muffler. In the combination muffler, the noise is channelled into ports with resonators thus, causing a wave cancellation effect. The steel wool lining of the walls absorbs the noise from the ports. The ports are arranged in series with the pipes which discharges the exhaust gases through the tail pipe into the environment at a reduced noise as compared to that which would come out directly from the simple expansion chamber.

Design methodology

According to Kakade and Sayyad (2017), the design of a muffler should basically satisfy at least the following five conditions simultaneously:

(i) The acoustic requirement, which gives the minimum noise reduction, that should be generated from the muffler as a function of frequency. The operating parameters must be known because huge steady-flow velocities or huge alternating velocities may change the ability of the muffler to produce the acceptable exhaust sounds.

(ii) The aerodynamic requirement which specifies the maximum allowable average pressure difference through the muffler at a specific temperature and mass flow.

(iii) The geometrical requirement which provides the maximum acceptable volume and restrictions on shape and size of the muffler.

(iv) The mechanical requirement which basically specifies materials which are durable and require little maintenance to increase the lifespan of the muffler.

(v) The economical requirement which is crucial in the marketplace as it fundamentally affects how the design would be accepted and utilized.

The design methodology of a muffler for an engine involves the following procedures:

Benchmarking

This process involves setting a target by going through a benchmarking exercise of the same type of models to set a goal with respect to the transmission loss of the same engine power models. However, due to the unavailability of experimental data, the exhaust muffler of the Wuzheng tricycle model 7YPJ-1750PD was used as a benchmark for the design with the same engine exhaust parameters. Based on this, the concept was designed and carried forward for virtual simulations. The benchmarked muffler was basically a simple expansion chamber. Figures 3 and 4 show a 3D model of a benchmark muffler and an orthographic view of a benchmark muffler respectively.

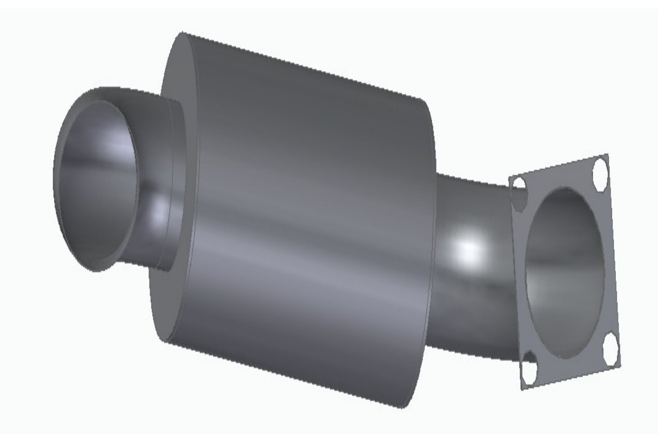

Figure 3 Design model of benchmark muffler

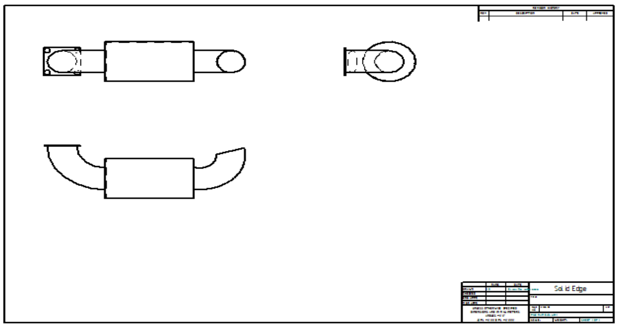

Figure 4 Orthographic views of benchmark muffler

Simulation

In light of previously mentioned approach, various techniques were shown up with desired combinations of various components inside the volume of the muffler. The designed concepts were verified virtually using a CAE simulation software (ANSYS) so as to achieve the transmission loss and backpressure satisfactory for the optimum performance of the engine against the benchmark of the performance of the chosen muffler. A fluid flow (fluent) and harmonic acoustic analysis simulation were carried out on the muffler designs. The inlet conditions in Table 1 were used. The medium used for the exhaust gas was Carbon oxide nitride (NCO).

Table 1 Inlet conditions for the ANSYS simulations

Parameter	Inlet conditions
Exhaust gas velocity (m/s)	44.464 – 45.1682
Temperature (K)	660
Pressure (Pa)	1147.169 - 1190.18

Mesh generation

Mesh generation is the discretization of the domain into little volumes where equations are solved with the assistance of iterative techniques. In other to carry out the simulations, meshes were generated on the muffler designs as shown in Figures 5 and 6.

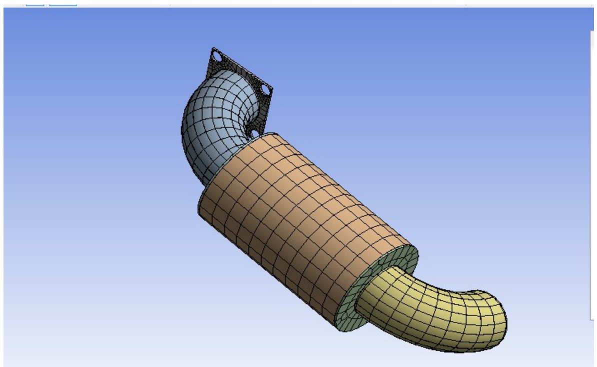

Figure 5 Design model of benchmark muffler

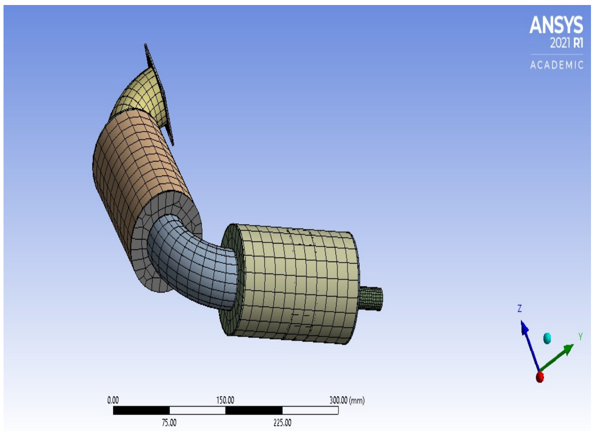

Figure 6 Orthographic views of benchmark muffler.

Computational fluid dynamics analysis

When a steady air flow travels through mufflers, the pressure difference is proportional to the flow and geometry of the air passageways. The pressure difference in an exhaust muffler is significant for muffler design and improvement. The ability to predict pressure decrease will be extremely helpful in the design and development of mufflers. Predicting the pressure decrease would enable us to quantify the performance of the muffler. This analysis begins with the specification of the inlet and boundary conditions for the domain of each model leading to the modelling of the entire system.

Harmonic acoustic analysis

In acoustics, when a vibrating body like a string is set in motion, it vibrates as a whole with a fundamental frequency and with a lower intensity. If these smaller lengths are integer fractions (1/2, 1/3, 1/4, etc. of the entire length of the string, their frequencies are called harmonics and are integer multiples of the fundamental frequency. Other resonating frequencies which are not whole multiples of the fundamental can also be present and are known as Partials. Bells as an example have numerous partials in their spectra more than strings or pipes. It is the presence and relative strengths of harmonics and partials in a spectrum which are mostly liable for the tone quality (timbre) of any sound producing object (Jones, 1978). A cavity type resonator is constructed so as to vibrate at a specific frequency giving off little energy to the outer medium and thus, resonating for a substantial length of time. Measurements of transmission losses from the simulations were used to analyse the acoustic performance of the exhaust muffler. Predicting transmission loss is a crucial analysis for the creation of a muffler at the early design stage since it indicates the muffler's performance. This analysis begins with the outline of the boundary conditions including the radiation boundary and the inlet condition which is the surface velocity. For this work, the surface velocity used is equal to the velocity of the exhaust gases. The velocity of the exhaust gases was computed as:

$$V = \left(\frac{2\pi N}{60}\right) r \qquad (2)$$

Where r is the radius of the flywheel attached to the crankshaft and N is the engine speed in revolutions per minute (RPM).

The circumference of the flywheel (C) was given as:

$$C = 2\pi r \qquad (3)$$

The circumference was measured as 133.4 cm;

$$\text{hence, } r = \frac{133.4}{2\pi} = 21.23 \text{ cm} = 0.2123 \text{ m}$$

From the Operator's manual for the Wuzheng tricycle model 7YPJ – 1750PD, the normal operating speed of the tricycle's engine is 2000 RPM. Therefore, for an engine speed of 2000 RPM, the velocity of the exhaust gases (V) is:

$$V = \frac{2\pi\,(2000)}{60}(0.2123) = 44.464 \text{ m/s.}$$

This was used as the inlet velocity for the simulations.

Results and Discussion

The results of the fluid flow (fluent) and harmonic acoustic analysis on the original muffler and the simple expansion chamber attached to a combination muffler (conceptual design model) are shown in Figures 7, 8, 9 10, 11 and 12. The other results for the simulation are shown in Tables 2, 3, 4 and 5. A graph for back pressure and transmission loss results are also shown in Figures 13 and 14 respectively. Table 4 is obtained from the CFD fluid flow (fluent) and harmonic acoustic simulations.

Table 2 shows the simulation results for the original muffler model. The average pressure for the inlet for the muffler model is 1171.837 Pa and that of the outlet is 2897.475 Pa. The average velocity for the inlet for the original muffler model is 45.1682 m/s and that of the outlet is 77.2251 m/s. The average backpressure for the original muffler model is 1151.6320 Pa and the average transmission loss is 2.883 dB. In the case of the conceptual design model as shown in Table 3, the average pressure for the inlet for the original muffler model is 1171.837 Pa and that of the outlet is 1114.288 Pa. The average velocity for the inlet for the original muffler model is 45.1682 m/s and that of the outlet is 391.8305 m/s. The average backpressure for the conceptual design muffler model is 911.3056 Pa and the average transmission loss is 17.971 dB. The average pressure for the inlet of both the original and conceptual design muffler is the same. The average pressure (2897.475 Pa) of the outlet of the original muffler is higher than that of the conceptual design (1114. 288 Pa).

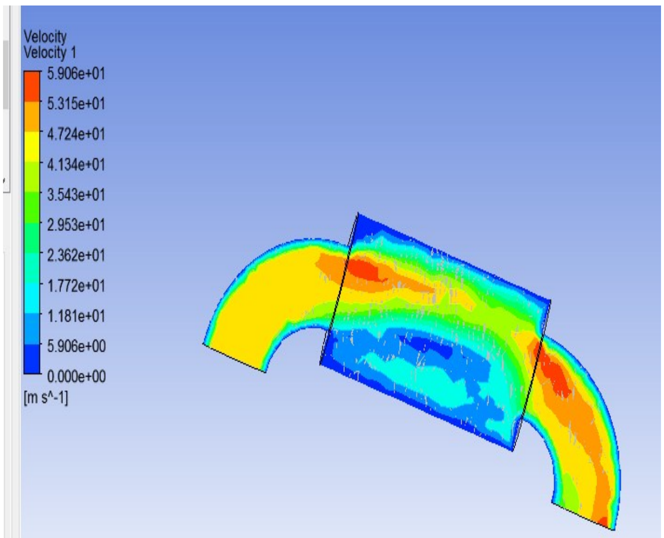

Figure 7 Velocity contour of original muffler

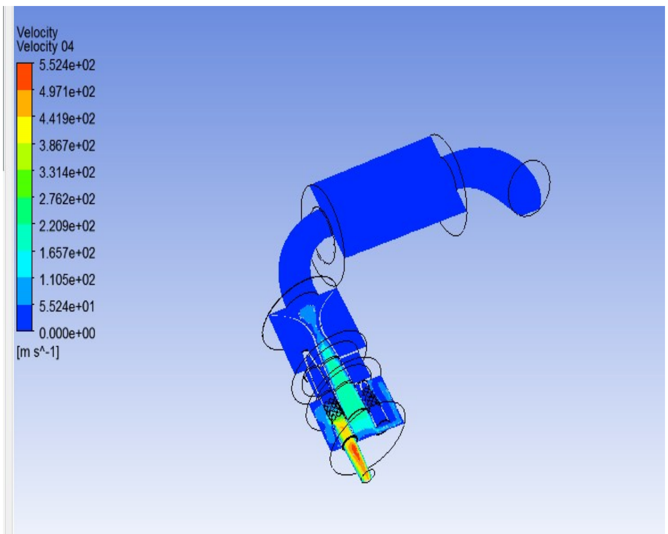

Figure 8 Velocity contour of the conceptual design

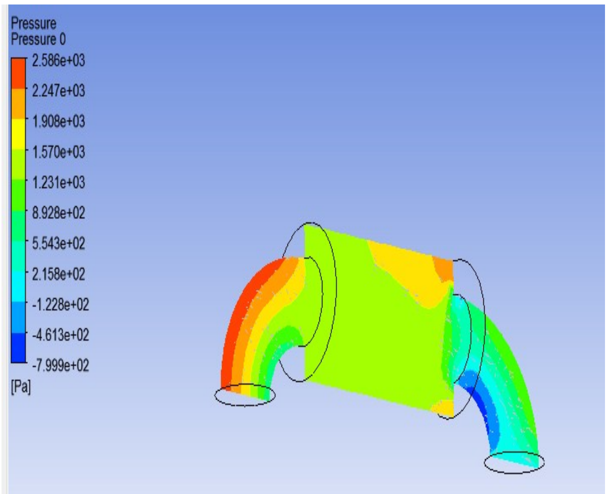

Figure 9 Pressure contour of the original muffler

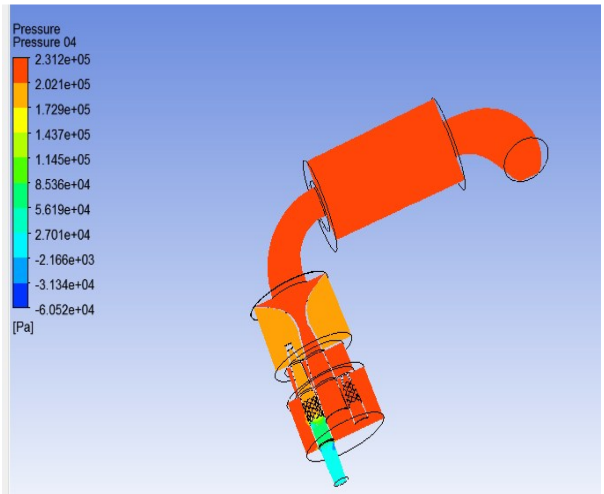

Figure 10 Pressure contour of the conceptual model

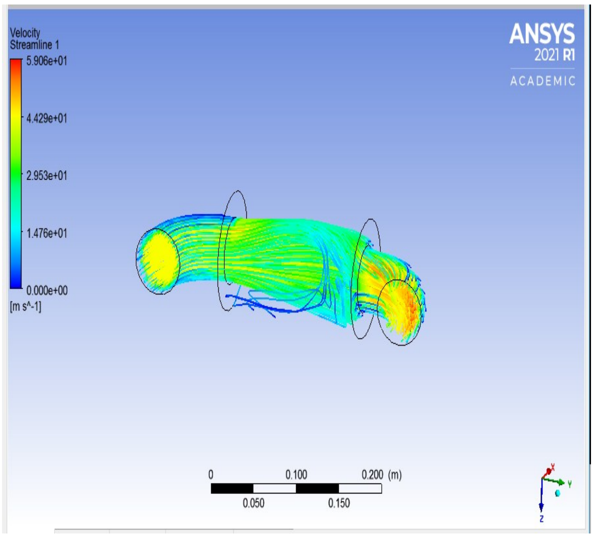

Figure 11 Streamlines in original muffler design model

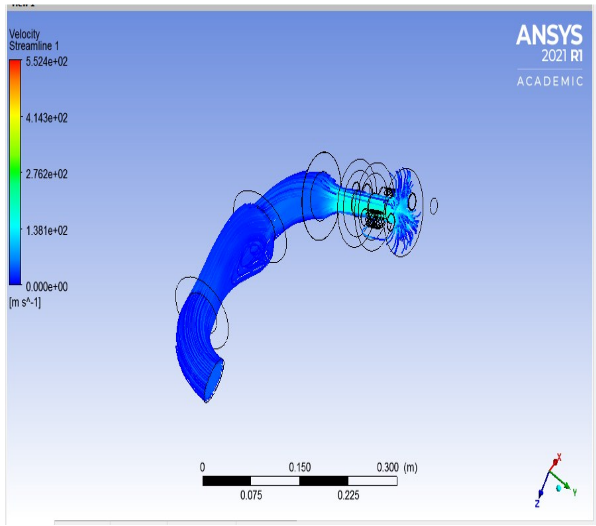

Figure 12 Streamlines in conceptual design model

Table 2 Simulation results for original muffler model

Design	S/N	Pressure (Pa)		Velocity (m/s)		Back pressure (Pa)	Transmission loss (dB)
		Inlet	Outlet	Inlet	Outlet		
Conceptual design model	A	1190.18	3104.9799	44.4640	71.8176	1116.1356	2.884
	B	1175.49	2929.3902	45.0198	76.1224	1144.0571	2.884
	C	1174.509	2917.2036	45.0576	76.4404	1145.4780	2.882
	D	1147.169	2638.3273	46.1314	84.5203	1200.8571	2.882
Average		1171.837	2897.475	45.1682	77.2251	1151.6320	2.883

Table 3 Simulation results for the Conceptual design model

Design	S/N	Pressure (Pa)		Velocity (m/s)		Back pressure (Pa)	Transmission loss (dB)
		Inlet	Outlet	Inlet	Outlet		
Conceptual design model	A	1190.18	2491.428	44.4640	93.0772	872.9085	14.911
	B	1175.49	1079.589	45.0198	214.7994	915.2457	18.989
	C	1174.509	625.1375	45.0576	370.9506	916.3824	18.992
	D	1147.169	260.9977	46.1314	888.4948	940.6857	18.990
Average		1171.837	1114.288	45.1682	391.8305	911.3056	17.971

Table 4 Numerical parameters between the original muffler and the Chosen design mode

SR No	Parameter	Original muffler	Conceptual design model
01	Average pressure difference between inlet and outlet of muffler (Pa)	1725.64	57.549
02	Average velocity difference between inlet and outlet (m/s)	32.06	346.662

Table 5 Performance parameters of both mufflers

SR No	Exhaust muffler type	Number of iterations	Average exhaust backpressure (Pa)	Exhaust temperature (K)	Average Transmission loss (dB)	Remark speed variation (RPM)
01	Original muffler	100	1151.6320	660	2.883	2000 - 2075
02	Chosen muffler	100	911.3056	660	17.971	2000 - 2075

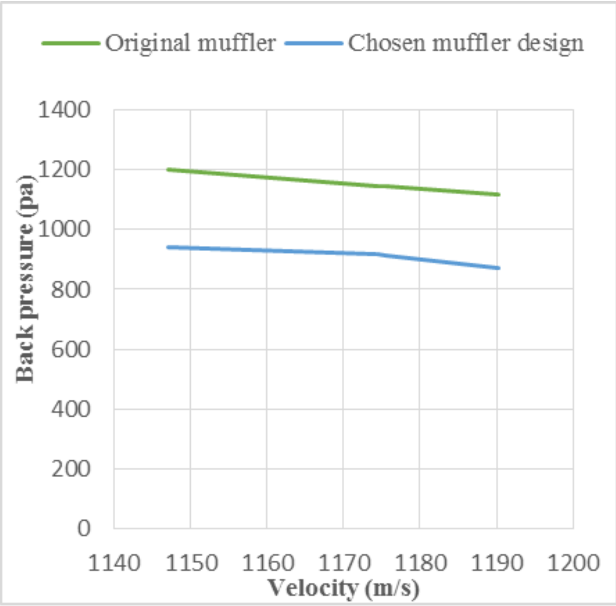

Figure 13 Backpressure against exhaust gas velocity simulation results for original and conceptual muffler design models

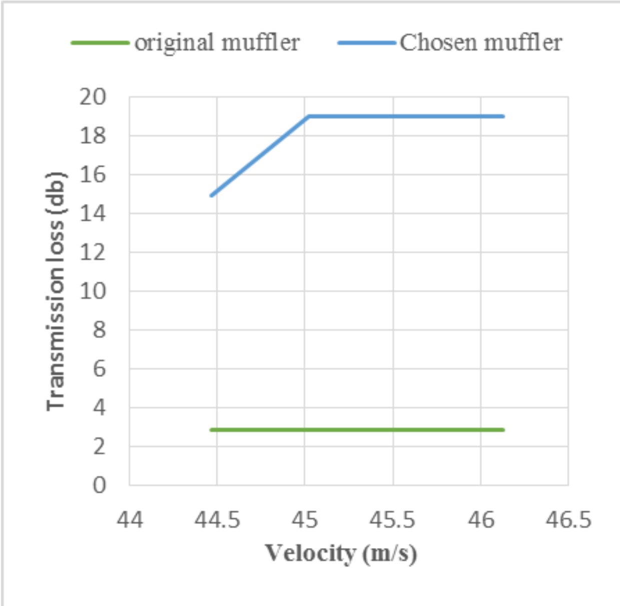

Figure 14 Transmission loss against exhaust gas velocity simulation results for original and conceptual muffler sign models

The average velocities for the inlet of both the original and conceptual design muffler are the same. The average velocity (77.2251 m/s) of the outlet of the original muffler is lower than that of the conceptual design model (391.8305 m/s). The average backpressure (1151.6320 Pa) for the original muffler model is higher than that of the conceptual design model (911.3056 Pa). The transmission loss (2.883 dB) for the original muffler model is lower than that of the conceptual design model (17.971 dB).

Table 4 shows the numerical parameters between the original muffler and the chosen design model. The Average pressure difference between inlet and outlet of muffler (Pa) for the original muffler model is 1725.64 Pa which is higher than that of the conceptual design model (57.549 m/s). The average velocity difference between inlet and outlet of the original muffler model is 32.06 Pa which is lower than that of the conceptual design model (346.662 Pa).

Table 5 shows the performance parameters of both mufflers. Both the original and conceptual design models have the same number (100) of iterations, the same exhaust temperature (660 K) and the same remark speed variation (2000 – 2075 rpm). The parameters which differ are the average exhaust backpressure and the average transmission loss which are selected based on the previous results.

Figure 13 shows a graph of backpressure against exhaust gas velocity simulation results for original and conceptual muffler design models. The backpressure (1200.8571 Pa) for the original muffler design model declines from a velocity of 1147.169 m/s until it gets to 1116.1356 Pa at a velocity of 1190.18 m/s. The backpressure (940.6857 Pa) for the conceptual design model declines from a velocity of 1147.169 m/s until it gets to 915.2457 Pa at a velocity of 1175.49 m/s. The backpressure for the conceptual design declines sharply from this point until it gets to 872.9085 Pa at a velocity of 1190.18 m/s. It can be found that the backpressure for both the original muffler design model and the conceptual muffler design model decreases with increasing velocity.

Figure 14 shows a graph of transmission loss against exhaust gas velocity simulation results for original and conceptual muffler design models. The transmission loss (2.884 dB) remains constant at a velocity of 44.464 m/s until it gets to a velocity of 45.01198 m/s where it declines slightly to 2.882 dB at a velocity of 45.0576 m/s. The transmission loss remains constant from this point onward. On the other hand, the transmission loss for the conceptual design model (14.464 dB) at a velocity of 44.464 increases sharply until it gets to 18.989 dB at a velocity of 45.0198 m/s. The transmission loss for the conceptual design model becomes constant as the velocity increases from this point.

Conclusions

A muffler design concept has been developed and studied. The exhaust backpressure, transmission loss and the fluid flow were simulated using ANSYS FLUENT. The design concept was also studied in comparison to the original muffler of the Wuzheng tricycle model 7YPJ – 1750PD, which is a simple expansion chamber. The conceptual design model was a combination muffler attached to a simple expansion chamber. The average inlet velocity of the original muffler is 45.1682 m/s and its average outlet velocity is 77.2251 m/s. Also, the average inlet velocity of the conceptual design model is 45.1682 m/s and its average outlet velocity is 391.8305 m/s. The average inlet pressure for the original muffler is 1117.837 Pa and its outlet pressure is 2894.475 Pa. Also, the average inlet pressure for the conceptual design model is 1117.837 Pa and its outlet pressure is 1114.288 Pa. As such, the pressure loss in the Conceptual design model is greater as compared to the original muffler.

The average backpressure for the original muffler is 1151.6320 Pa and for the conceptual design model is 911.3056 Pa. The backpressure produced by the conceptual design model is lower than that of the original muffler. The average transmission loss (TL) for the original muffler is 2.883 dB and for the conceptual design model it is 17.97 dB. As such, the chosen muffler design has a higher transmission loss as compared to the original muffler and thus, it would be better in attenuating the exhaust noise levels.

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Conflict of Interest Declaration

The authors declare that there is no conflict of interest.

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