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Failure Analysis and Redesign of Dozer Silencer for Noise Reduction

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ABSTRACT: Exhaust noise of the internal combustion engine is a pollutant of concern to the mankind. A suitable design and development of muffler / silencer will reduce noise levels and at the same time performance of engine will not be affected by back pressure caused by muffler. The present work aims to study failure analysis and redesign of silencer. The present silencer fitted on the D9H dozer machines, are failing. The approximate life of 1.5 to 2 years is observed. The reasons for cracks in the silencer were improper design, pressure of pulsating flow of gas, vibrations etc. Particular attention was given to gas force which will induce vibrations. The exhaust noise and vibrations produced by silencer of D9H dozer are measured. The existing and new designed mufflers were tested for vibrations and fatigue in software. We have designed and fabricated a new muffler and compared its noise, vibrations with existing muffler. The new designed muffler is able to reduce the noise from 120 dB to 95 dB. The expected life would be 2 to 2.5 years.

KEYWORDS: -Exhaust Silencer, natural frequency, vibration, sound, Insertion loss

I. INTRODUCTION

Sound is physical phenomenon and also sensation of hearing. Noise is unwanted sound and can only exist in presence of listener. Noise may be intermittent, erratic or continuous depending upon its source [Cummins, 1993]. Today the world is facing very serious problem regarding noise and its pollution. Each and every part of globe is suffering this problem. Due to high industrialization and globalization, the equipments related to industries are increased and most of them are producing noise having very high intensity. Existence of such high intensity noise is very harmful for human being and also for environment. The effect of persistently high noise levels on health should not be underestimated. Noise issues are generally classified as residential, commercial, and industrial. There are many ways of moderating or reducing the effects of excessive noise levels. They depend greatly on the type of noise source; the magnitude of noise level and the pattern of occurrence. Noise may be reduced at source, in its path, and at point of reception. With rapid development of city construction, the removal and building of city buildings construction machinery is causing increase in noise. This noise is adversely affecting physiology and psychology of workers. The high level noise can damage person’s hearing and nervous system. This may lead into insomnia, dreaminess. Diesel engine of bulldozer discharge a large amount of noise during working, for example inlet noise, exhaust noise, noise radiated from machine body, gear noise. Among all above noises the exhaust noise from engine is one of the most important, which could severely affect machine performance. Muffler or silencer is the apparatus which is fixed on machine to reduce the noise. [Fang Jian-Hau, Zhou Yi-Qi 2004]. Measuring and analyzing exhaust noise through silencer of heavy earth moving equipments such as bulldozer is very important for protecting environment and improving performance. So there is requirement to design a silencer which would reduce the noise levels and have a good life span.

II. WORKING OF EXHAUST SILENCER

The automobile petrol or diesel engine produces pulsating flow of gases from each cylinder's exhaust and sets up pressure waves in the exhaust system. The exhaust port and the manifold having average pressure levels higher than the atmospheric. This varies with the engine speed and load. At higher speeds and loads the exhaust manifold is at pressure substantially above atmospheric pressure. These pressure waves propagate at speed of the sound relative to the moving exhaust gas, which escapes with a high velocity producing an objectionable exhaust boom or noise. A suitably designed exhaust muffler or silencer accomplishes the muffling of this exhaust noise. The velocity of sound in the gas at a given

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temperature is directly proportional to the square root of the product of the pressure and the ratio of the specific heats (at constant pressure to that at constant volume), and inversely to the square root of the density of the gas. As the temperature varies, the velocity also varies directly as the temperature by another square root law involving the product of the coefficient of thermal expansion of the gas and the temperature.

The exhaust noise can be reduced appreciably by providing resonance chambers to offset the noise wave effects. This is accomplished by the principle of the Helmholtz resonator. In principle, it comprises the exhaust pipe, which goes through the large volume of a chamber. The axial holes in the exhaust pipe enclosed by the chamber allow the gases to vibrate with the large mass of the gases in the chamber and generate the sound of the same frequency but in opposite phase to that which has to be nullified (called anti-sound). To achieve this silencer volume should be proportioned to the engine piston displacement, and inversely proportioned to the engine speed and the square root of the number of engine cylinders. The usual length to diameter (l/d) ratio of the resonator is about 4:1 to 8:1. A small l/d ratio silencer attenuates the sound well for a narrow frequency band, where as the large l/d silencer attenuates the sound to a lesser degree but over a wider frequency band.

Silencing of heavy earth moving equipments such as D9H dozer is more concerned. These machines are producing very high frequency sound causing disturbance and annoyance in daily life. After some time period, silencer start to fail and noise is increased. There may be cracking, corrosion or many other problems which are affecting life of the silencer. Analysing and developing the new silencer would be useful.

III. PROBLEM DEFINITION

The present silencer fitted on the D9H dozer machines are failing due to cracking. The approximate life of 1.5 to 2 years is observed. The reasons for cracks in the silencer may be improper material used for manufacturing of silencer. There may be less thickness material used. Due to welding or heating work hardening at specific locations is observed. Welding of internal parts with baffles or inlet /outlet pipes with outer casing is not done properly. Improper workmanship may be found in different manufacturing operations. Vibration of engine is transformed to the silencer which may cause periodic loads on silencer. Pulsating flow of gases is impinging on internal parts which may cause fatigue at some locations. Thermal stresses due to hot gases coming out from engine manifold may affect life of silencer.
It would be essential to analyze and redesign the silencer of dozer. So we would be benefited by the findings and suggestions in design of silencer. The failed silencer is as shown in below figure.

Figure No. 1 Actual cracked silencer end

IV. PURPOSED WORK AND METHODOLOGY

1. Study of existing D9H dozer silencer for design, material and its thickness and manufacturing processes.
2. Geometry modeling of old silencer using CATIA V5. Analysis of silencer for different areas like vibration or fatigue failures. This is done with software like MSC-NASTRAN.
3. Modify the design with different alternatives like change in geometry or internal supportive structure or rearrangement of parts. Modeling and analysis of new silencer design.

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V. SCOPE OF WORK

Here an effort is made to analyze and redesign the existing silencer. The silencer is required only for D9H type dozer having capacity of 500 HP. Scope of is limited to silencer of D9H dozer. Silencers of other automobiles or any other stationary equipment are not considered.

VI. THEORY

The exhaust system is an often–ignored part of a vehicle, which is in fact a complex assembly of various components performing important tasks in harsh environments. The system conveys hot toxic gases, produced in the combustion chamber, from the engine exhaust ports and discharges them into the atmosphere through the tailpipe. It reduces the noise produced by the engine inside and outside of the vehicle, reduces gas emissions and affects the performance of the engine. The exhaust system can be divided into two main parts, namely the hot (or front) end consisting of the manifold connected with a flexible front end pipe to the catalytic converter, and the cold (or rear) end with a down or centre piece of pipe leading from the catalytic converter to the silencer with an attached tail pipe. The hot end components usually function at temperatures in excess of 600 ºC, while temperature in cold end ones is below 600 ºC.

The purpose of an automotive silencer is to reduce engine noise emission. If we hear a car running without a silencer we will have an appreciation for the significant difference in noise level a silencer can make. If vehicles did not have a silencer there would be an unbearable amount of engine exhaust noise in our environment. In an automotive engine, pressure waves are generated when the exhaust valve repeatedly opens and lets high-pressure gas into the exhaust system. These pressure pulses are the sound we hear. As the engine rpm increases so do the pressure fluctuations and therefore the sound emitted is of a higher frequency. All noise emitted by an automobile does not come from the exhaust system. Other contributors to vehicle noise emission include intake noise, mechanical noise and vibration induced noise from the engine body and transmission. The automotive silencer has to be able to allow the passage of exhaust gasses whilst restricting the transmission of sound.

The use of an exhaust silencer is prompted by the need to reduce the engine exhaust noise. In most applications the final selection of an exhaust silencer is based on a compromise between the predicted acoustical, aerodynamic, mechanical and structural performance in conjunction with the cost of the resulting system.

VII. SILENCER DESIGN

There are numerous variations of the two main types of silencer designs commonly used, namely absorptive and reactive. Generally automotive silencers will have both reactive and absorptive properties. The reactive or reflective silencers use the phenomenon of destructive interference to reduce noise. This means that they are designed so that the sound waves produced by an engine partially cancel themselves out in the silencer. For complete destructive interference to occur a reflected pressure wave of equal amplitude and 180 degrees out of phase needs to collide with the transmitted pressure wave. Reflections occur where there is a change in geometry or an area discontinuity. A reactive silencer generally consists of a series of resonating and expansion chambers that are designed to reduce the sound pressure level at certain frequencies. The inlet and outlet tubes are generally offset and have perforations that allow sound pulses to scatter out in numerous directions inside a chamber resulting in destructive interference.

Reactive silencers are used widely in car exhaust systems where the exhaust gas flow and hence noise emission varies with time. They have the ability to reduce noise at various frequencies due to the numerous chambers and changes in geometry that the exhaust gasses are forced to pass through. The down side to reactive silencers is that larger backpressures are created, however for passenger cars where noise emission and passenger comfort are highly valued reactive silencers are ideal and can be seen on most passenger vehicles on our roads today.

Sound waves are reduced as their energy is converted into heat in the absorptive material. A typical absorptive silencer consists of a straight, circular and perforated pipe that is encased in a larger steel housing. Between the perforated pipe and the casing is a layer of sound absorptive material that absorbs some of the pressure pulses. Absorptive silencers create less backpressure than reactive silencers; however they do not reduce noise as well. Generally reactive silencers use resonating chambers that target specific frequencies to control noise whereas an absorptive silencer reduces noise considerably over the entire spectrum and more so at higher frequencies. It is good practice to design a silencer to work best in the frequency range where the engine has the highest sound energy. In practice the sound spectrum of an engine exhaust is continually changing, as it is dependent on the engine speed that is continually varying when the automobile is being driven. It is impossible to design a silencer that achieves complete destructive interference, however some will always occur. Noise spectrum variation makes silencer design quite difficult and testing is the only sure way to determine whether the silencer performs well at all engine speeds. However, as a general rule of thumb, exhaust noise is generally limited to the fundamental frequency and the first few harmonics, which can be calculated; therefore these frequencies should be used as a starting point for preliminary silencer design. There are numerous functional requirements that should be considered when designing a silencer for a specific application. Such functional requirements may include adequate insertion loss, backpressure, size, durability, desired sound, cost, shape and style.

VIII. LITERATURE REVIEW

Vibration characteristics of exhaust system were investigated using FEM and simulated mode shapes. The exhaust pipe is subjected to several stresses, most of which are due to vibration. Particular attention is given to gas forces which will induce vibration. These vibrations will then induce a fatigue life to the system. So it is necessary to study the fatigue behavior of the exhaust pipe by analyzing the vibration modes and the response of vibrations by its sources. Exhaust gas mass is forced through the pipe after leaving the engine. Its momentum forces the change in direction of motion in expansion or contraction of end pipe. This gas produces some resonance in such frequency range that might cause fatigue failure of exhaust pipe when resonance exists continuously. Engine vibrations transmitted to exhaust pipe are divided into two categories, longitudinal and bending vibration. Both categories must be taken into account for noise and vibration analysis. Dynamic characteristics of exhaust system are modeled by MSC / NASTRAN of FEM software. [Abu A.]

Mechanical criterion is important in case of silencers involving high temperature gases carrying solid particles which might deposit on inner surface of silencer reducing its effectiveness. Diameter of inlet pipe is taken same as diameter of exhaust port of engine. Ratio of cross sectional area of expansion chamber to the cross sectional area of circular pipe is taken as 10. Length of expansion chamber is taken 10 to 12 times diameter of inlet pipe. Diameter of outlet pipe (or tail pipe) is taken same as inlet pipe. Sound level meter was placed at a distance of one meter away form outlet of silencer and at an angle of 45^{O}. Metallic bulb thermocouple was inserted in outlet pipe of silencer to measure temperature. Tube filled manometer was attached to inlet and outlet pipe of silencer to measure pressure drop across silencer. This will help to find back pressure on engine. [Bhattacharya P., Pauna R.]

Long time noise exposure would harm physiologically and psychologically. It could also damage person's hearing. Diesel engine of excavator discharges large amount of noise consisting of exhaust noise, noise from machine and gear noise. Among which exhaust noise is important. Transmission loss and insertion loss were main performance evaluation standards for silencers. Transmission loss is difference between entrance energy and exit energy of silencer. Insertion loss is difference of sound power level from sound source and before and after installing silencer. Perforated pipe silencer has good noise elimination characteristics for high frequency. [Fang Jian-Hau, Zhou Yi-Qi]

Exhaust manifold is exposed to high temperature so oxidation and creep consideration becomes critical. These manifolds failed due to phenomenon called thermo-mechanical low cycle fatigue. For structural and flow analysis CFD and FEA are used. [Londhe A., Yadav V.]

Generally an exhaust silencer should satisfy some basic requirements such as adequate insertion loss, low back pressure, and ideal silencer sizing reducing cost. Parameters governing silencer are silencer chamber design, restrictions of flow of exhaust gases and material of the silencer. The relationship between noise and back pressure is inversely proportional. Lowering the noise will result in increase in back pressure. The design of resonance chamber inside a silencer reflects the sound wave which is 180^{O} out of phase. The sound waves reflected back from the wall collide with exhaust sound waves and they cancel each other. Higher the back pressure less is net power available at crank shaft. Silencers with extended tube chamber are better than those of simple expansion chamber. If number of chambers are more (with corresponding increase in total length), better will be the insertion loss. If area ratio of chambers is more, greater will be the insertion loss. Perforated pipes play significant role in silencer design. Holes in pipe should be placed close together with one inlet pipe and two exhaust pipes. Silencer design consists of four chambers with 3rd chamber being biggest. [Mohiuddin A.K.M., Ideres M. R.]

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The exhaust silencer designed so that silencer exhaust noise is at least 5dB lower than combustion induced engine body noise or other predominant sources like transmission noise in earth-moving equipments. Most of the un-muffled noise is limited to firing frequency and its first few harmonics. Back pressure should be kept low. As it would affect brake power, volumetric efficiency and hence specific fuel consumption. A large size silencer would cause problems in accommodation support and price. A uniform wall temperature is required to avoid thermal cracking of walls. The silencer must be made from corrosion resistive material. Flow generated noise within silencer element and at tail pipe exit should be sufficiently low, particularly for silencers with large insertion loss.[Munjal]
Silencers with extended tube are better than open chamber. If number of chambers are more (with corresponding increase in total length), better will be the insertion loss If ratio of chambers is large greater will be the insertion loss. The resistance through perforated pipe is directly proportional to square of mean flow velocity through the holes and inversely proportional to square of total area of each perforated hole. A broadband of transmission loss can be achieved by introducing unequal partitions along the length of concentric tube resonator. The shell noise (secondary radiation sound from exposed surface of the shell of the silencer) is controlled by using double wall sandwich construction for the shells of commercial silencers. Higher order effect at sudden area changes can be controlled by offsetting inlet and outlet tubes. Expansion chambers with offset inlet and outlet demonstrate plane wave behavior to relatively high frequencies. The designer has to compromise between transmission loss, back pressure and size (and hence weight and cost). In this context, choice of concentric resonator with portioned lengths gains merit. For such a resonator, value of back pressure & size are small and transmission loss can be improved by unequal partitions. [Munjal]
A well designed silencer would have adequate insertion loss, minimum or optimum restriction, moderate volume, weight and cost, high durability and would easy to manufacture and maintain. It has been observed in practice that total volume silencer V_m is proportional to the total piston displacement V_p and the insertion loss increases with increase in V_m / V_p. Typical values of volume ratio for about 20 dB of insertion loss may vary from about 3.5 for low specific output engines and to about 12.5 for high specific engine output. Material used for fabrication of silencers is generally mild steel or aluminized steel for low exhaust gas temperatures (up to about 500 ^{O}C). Type 409- stainless steel for the temperatures of up to 700 ^{O}C and true stainless steel type 321 for still higher temperatures. Surface coating is necessary for weather protection and aesthetic appeal. Normally suitable paint is used. Thickness and type of shell have a bearing on shell noise and durability. Standard 22 gauge plate is minimum requirement.
For large shells or for reduction of noise one may use increased body thickness, double wrapped bodies and insulted body. For easy removal the silencer is connected to the manifold with a slotted tube, threaded connection or mounting flange with bolts. The silencer configuration should be such designed that its constituting parts can be easily separated and reassembled. [Munjal]

The recent progress in the development of thermo-mechanical fatigue design tools using FEA related to the design of stainless steel exhaust manifold. A numerical method was proposed for the design and the lifetime prediction of stainless steel exhaust manifold under thermal fatigue load. The use of a virtual thermo-mechanical fatigue design approach permits to optimize the design of the manifold, reducing the risk of failure. Decreasing fuel consumption leads to hotter exhaust fumes. So durability of exhaust system especially for corrosion and thermo-mechanical fatigue resistance need to be improved significantly. Use of virtual thermo-mechanical fatigue design approach permits to optimize design of exhaust system.[SIMON C., SANTACREU P. O.]

Smaller the holes better is the damping. The holes should be stabbed outwards instead of plain drill. This will result in nozzle effect facilitating flow outward. The degree of silencing obtained from a single chamber is quite small. Brook lands silencers specifications insisted on addition of fishtail at outlet to diminish sound. Chamber volume should be kept at least 10 to 15 times swept volume of cylinder. It is evident that a reduction in silencer outlet pipe area is relied on for silencing effect to a large effect. Absorption silencers may be used to reduce musical hum. Flat surfaces should be avoided because of their tendency to drum. Some construction have in-corporate double wall container with walls separated by a small space, the idea being to damp out damping. Reduction in outer diameter sets up increased resistance, but its effect encourages wave motion, along with this smaller bore outlet, reduce noise. Noise reduction can be achieved by; reduction in exit area, placing chambers in series which is far more effective than single box, tapering passages or fishtails in outlet area, interference by flow reversal of gases etc. Pressure pulse from engine has to reflect back as early as possible, also volume of first chamber should be kept small. Sound wave entering into the silencer should not direct impinge on outer casing whatever may be their frequency, unless much of heavier metal is used.[Smith P. H.,Morrison J. C.]

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The cause of significant failure of silencer was low cycle thermal fatigue and fracture. A failure analysis was performed and design modification was made to avoid further failures. The failed silencer was subjected to fluctuating mechanical stress by flow induced vibration thermal cycles and thermal gradients. Cyclic thermal stresses produce low cycle fatigue damage on steel structure. The strength of weldments was reduced due to heat affected heat zones during welding process. Thermal stress result in plastic deformation and / or creep deformation and also produce crack at welds. [SOON-BOK LEE**]**

The velocity of sound in a gas at a given temperature is directly proportional to the square root of product of pressure and the ratio of specific heats (at constant pressure and at constant volume) and inversely proportional to square root of density of gas. The exhaust noise can be reduced appreciably by providing resonance chamber to offset noise effects. The silencer volume is directly proportional to piston displacement volume. The usual length to diameter ratio of resonator is 4:1 or 8:1. Effectiveness in silencing also depends upon the relative lengths of exhaust pipes (from exhaust manifold to silencer) and tail pipe. A ratio of 1:2 is better than 4:1. To produce friction and reduce sound resonator silencer may be provided with baffles at end or at centre, or with four chambers.

IX. CONCLUSIONS FROM REVIEWS OF LITERATURES

Material thickness should be increased. Minimum material thickness can be as 1.6 mm or 2 mm could be best. A silencer with uniform wall temperature is required to avoid cracking of walls. [Munjal] Number of perforations should be increased. With increase in no of perforations transmission loss is increased.[Vasile O., Fang Jian-Hau]. Effective utilization of volume should be done. First chamber should be small and third being largest. Silencer design should consists of four chambers with first chamber smaller and third chamber being biggest. Length of expansion chamber should be taken as 10 to 12 times inlet pipe diameter. [Bhattachrya P., Mohiuddin A.K.M., Munjal]. Ferritic steel can be used for manufacturing of silencer with higher percentage of Si and Mo. [Stephon M.]. Reverse flow technique should be used instead of straight through type. Sound wave should not directly impinge on outer casing. It may cause increase in noise and vibrations. Smaller holes give better dampening. Holes with stabbed outwards give nozzle effect facilitating less noise. Pressure pulse should be reflected back as early as possible by keeping volume of first chamber smaller. [Smith P.H.]. Flat surfaces should be avoided because of their tendency to drum. Sound waves reflected from hemispherical region may be used. [Smith P.H., Munjal]

X. ACTUAL ANALYSIS

Following assumptions were made in the analysis
1. For fatigue analysis material properties are taken from S-N curve library of the software.
2. Road conditions for vibration analysis are considered in only 1G analysis.
Following figure shows cross section of old silencer.

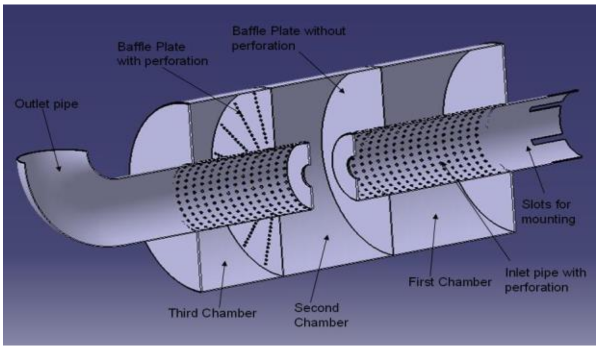

Figure No. 2 Old Silencer cross section

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This silencer has given boundary conditions as shown. As silencer is mounted on engine exhaust with help of clips its inlet end is given fixed conditions.

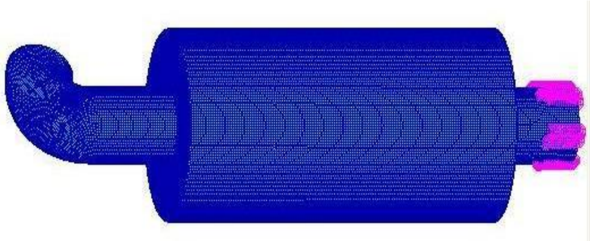

Figure No. 3 Old Silencer with boundary Conditions

The following figure shows frequency response of silencer.

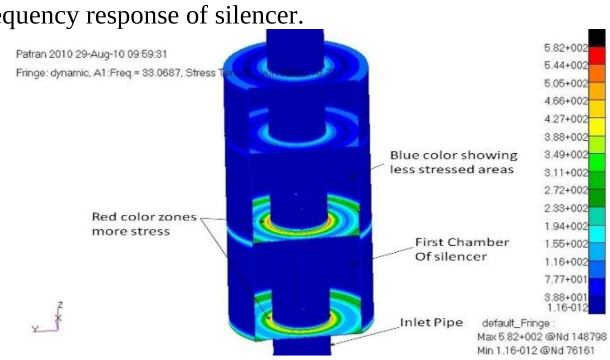

Figure No.4 Old Silencer frequency response

Following figure shows areas of more stress occurring at baffle plate and inlet pipe joints. These areas are matching with actual cracks of silencer.

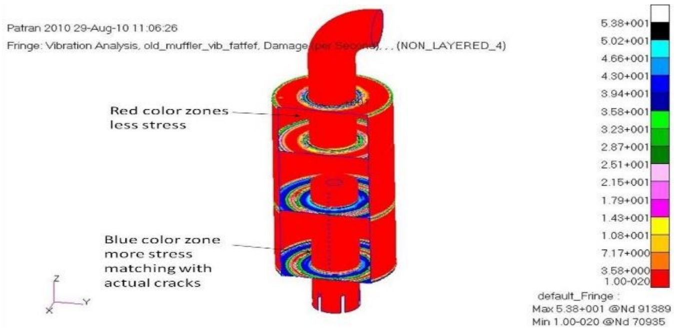

Figure No.5 Vibration Analysis of Old Silencer**.**

The new designed silencer is as shown in following figure. Inlet, outlet pipes and various chambers are shown below.

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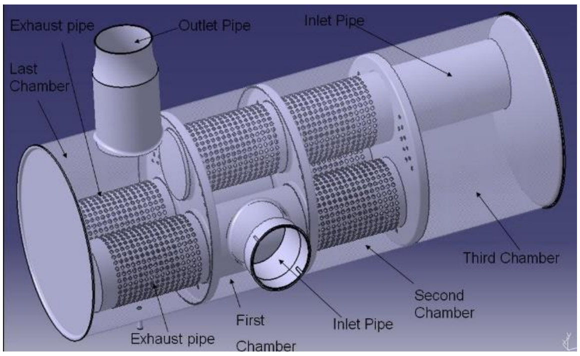

Figure No. 6 CAD Model of New silencer

This new designed silencer is meshed and given boundary conditions as shown below.

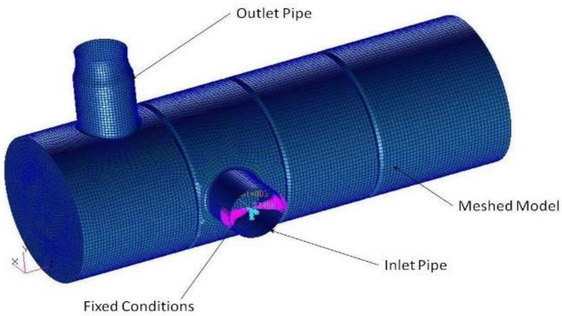

Figure No. 7 Meshed Model of New Silencer with Boundary Conditions

This silencer is analyzed for various natural frequencies and their frequency response were considered

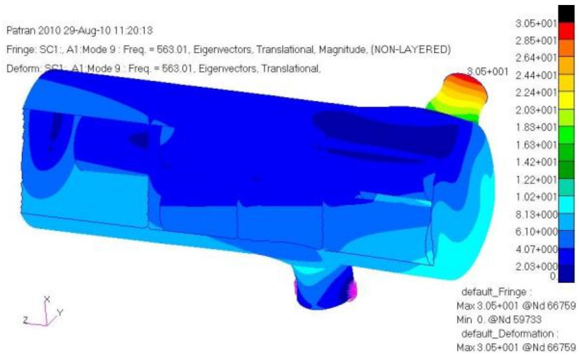

Figure No. 8 New Silencer with Natural Frequency

The analysis shows displacements of new silencer are less as compared with old silencer. For new silencer maximum displacements are occurring at end caps rather than inlet baffle plate and inlet pipe joints.

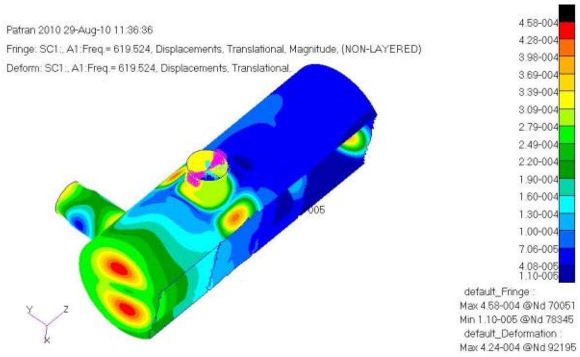

Figure No. 9 Displacement at Frequency

XI. MANUFACTURING AND TESTING OF SILENCER.

For manufacturing of silencer Low Carbon Steel Sheets are used. Material properties of these sheets are as per IS 513:1994. The sheets used are of deep drawing (DD) capacity. The material is CRCA and is of 2 mm thickness. This material is having carbon 0.1%, Manganese 0.45%, Sulphur 0.035%, and Phosphorus 0.035%. The sheets are having Tensile strength of 270 – 370 M Pa, Yield strength 250 M Pa, Hardness 55 HR. For designing of new silencer various points were considered from literature review. Following figure shows finished silencer.

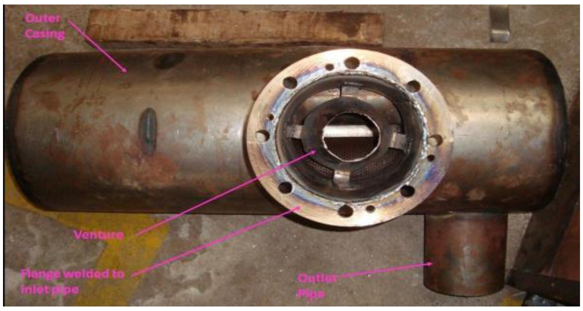

Figure No. 10 Finished silencer

XII. ACTUAL TESTING OF SILENCER

Sound is measured with sound meter and vibrations with accelerometer. With help of SPL meter and vibration level meter following readings are obtained while carrying out tests.

Table No. 1 Vibrations and Sound pressure levels

Silencer type	Speed range	Sound pressure level(dB)	Vibration level (mm/s)
Old	Slow	99.6	0.18
	Medium	104.1	0.06
	High	111.9	0.06
New	Slow	95.5	0.07
	Medium	104.1	0.06
	High	105.7	0.06

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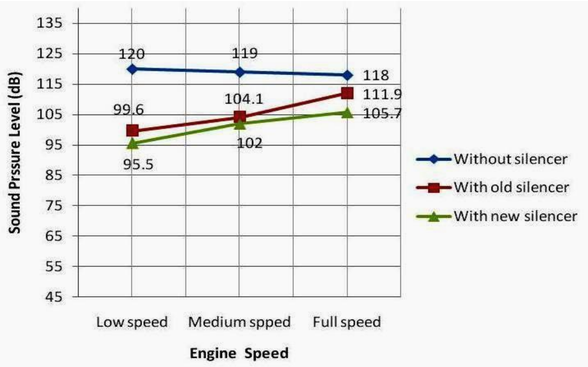

Figure No. 11 Graph of Sound pressure level against Engine Speed

XII. CONCLUSION

Study of existing silencer was carried out to understand the design, material and manufacturing process of existing silencer. This type silencer is typically used for heavy earth moving equipments such as D9H dozer. After studying the silencer geometry was created in CATIA V5. Analysis of model was carried out for structural vibration, fatigue. Figures are indicating the area of failure of silencer. Recommendations for new design of silencer provided to manufacturer. New silencer was manufactured and analyzed for vibration, fatigue etc. the results are satisfactory. The noise level is considerably reduced to the acceptable level.

The reduction in noise is up to from 120 dB (without silencer) to 95 dB (with new silencer). For low speed sound reduction is 4.11%. For medium speed sound reduction is 2.01%. For high speed sound reduction is 5.54%. The expected life of silencer would be 2 to 2.5 years

XIV. SCOPE TO FUTURE WORKS

1. This study is applied to only D9H dozer silencer which are heavy earth moving equipments. This study can be further extended for other automobile vehicles, gas turbines, blowers, centrifugal fans, DC generators where noise reduction is more required.
2. Parametric modeling of silencers for different engine horse powers can be done. This will give information about actual silencer size, volume, area etc. prior to manufacturing.

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