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Design and Analysis of the Support System for the Exhaust Gas Aftertreatment Unit in Stage V Emission Tractors

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Abstract

In line with the increasing global environmental awareness, the goals of improving air quality and protecting public health necessitate the reduction of harmful pollutants emitted by diesel engines. In this context, the implementation of Stage 5 emission standards requires the integration of advanced exhaust gas aftertreatment systems into exhaust assemblies, such as Diesel Oxidation Catalyst (DOC), Diesel Particulate Filter (DPF), and Selective Catalytic Reduction (SCR). These systems play a critical role in reducing the environmental impact of internal combustion engines and contribute significantly to the goal of a more sustainable world. However, the mass of these systems and the vibrational loads to which they are subjected - particularly due to the severe excitation experienced during off-road agricultural operations - make the structural integrity of the supporting brackets critical. The structural durability of these components is of great importance to ensure safe, long-lasting, and trouble-free operation. In this study, the structural durability and vibrational behavior of a bracket designed to carry the exhaust gas aftertreatment system for a diesel engine used in tractors were investigated. A design optimization study was also conducted to achieve a safer and more efficient configuration. The structural performance of the bracket under static and dynamic loading was evaluated using Finite Element Analysis (FEA), considering vibration conditions arising from field operations. Additionally, modal analysis was performed to identify possible resonance conditions resulting from engine and chassis-induced vibrations. The findings indicate that the optimized bracket design enhances durability and service life, significantly reducing the risk of field failures. The improved design supports clean and efficient engine operation in compliance with Stage 5 emission standards, contributing positively to environmental performance.

Keywords: Bracket design, Exhaust aftertreatment systems, Emission, Finite element analysis, Structural analysis
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1. Introduction

In line with the developing environmental awareness and the goals of improving air quality, the reduction of nitrogen oxides (NO_x), particulate matter (PM), and other harmful exhaust emissions originating from diesel engines have great importance. The advantages of diesel engines, such as low fuel consumption, have led to their widespread preference, especially in off-road agricultural vehicles; however, these engines pose serious environmental risks due to their high NO_x and PM emissions. In this context, the implementation of Stage V emission standards aims to significantly reduce these pollutants, making it mandatory to integrate advanced exhaust gas aftertreatment systems such as Diesel Oxidation Catalyst (DOC), Diesel Particulate Filter (DPF), Selective Catalytic Reduction (SCR), and EGR into diesel engines. These systems contribute to controlling emissions from vehicles by pro-viding cleaner combustion without reducing engine performance [1, 2].

Due to the emission standards required in tractors, the exhaust gas aftertreatment systems and their sizes and weights have increased. The mounting brackets that attach these systems to the engine body or chassis are exposed to vibrations and impacts; therefore, their structural durability is of critical importance. For this reason, to ensure the reliability of exhaust aftertreatment system brackets used in tractors, static, fatigue, and vibration analyses are performed by means of finite element analysis. In this way, design optimization is achieved, reducing production costs and development times. In addition, fatigue damage and vibration effects occurring in the connection regions of exhaust systems are analyzed to minimize the risk of failures that may occur in the field. These approaches are important to increase the durability of the exhaust system under the harsh working conditions of tractors and to ensure compliance with environmental standards [3–14]. As a result of recent research and development studies, two main strategies have been widely adopted for reducing emissions in commercial diesel engines. In both strategies, an exhaust gas aftertreatment system that includes a Diesel Oxidation Catalyst (DOC) directly connected to a Diesel Particulate Filter (DPF), in addition to the existing SCR catalyst, is used (Figure 1) [14].

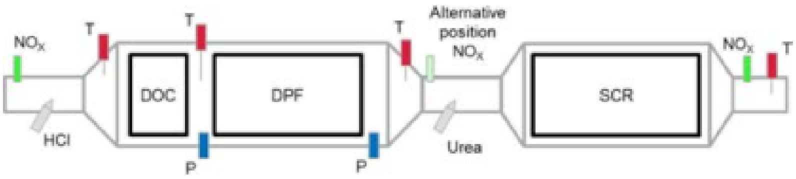

Figure 1. Exhaust aftertreatment system

In this study, the structural performance of the brackets supporting the exhaust aftertreatment system integrated into the tractor chassis was investigated under the stringent emission standards applied to commercial diesel engines. Considering the high mass of the aftertreatment components and the vibrational loads during operation, the structural integrity of these brackets is critically important. The analyses included determining the natural frequencies, evaluating resonance risk, and performing random vibration analyses. Structural strength limits were also assessed under specific dynamic loads. The results demonstrate that the optimized bracket design improves durability and service life, minimizes potential failures in the field, and supports clean, efficient engine operation compliant with Stage V emission standards. The examined tractor is shown in Figure 2, and the engine specifications are given in Table 1.

Table 1. Specifications of the Tumosan common rail diesel engine

Number of Cylinder	4
Engine Displacement	3.9L
Bore x Stroke	104 mm x 115 mm
Rated Power @ 2200 rpm	125 Hp
Rated Torque @ 1400 – 1600 rpm	530 Nm
Specific Fuel Consumption	235 g/kWh
Compression Ratio	17:1
Emission Level	Stage V

Figure 2. Tumosan tractor with Stage V certification

2. Exhaust Aftertreatment System

In the tractor on which the design and analysis study was carried out, DOC (Diesel Oxidation Catalyst), DPF (Diesel Particulate Filter), and SCR (Selective Catalytic Reduction) systems are used in an integrated manner to reduce exhaust emissions. This combined exhaust aftertreatment system has a total weight of approximately 45 kg. A detailed illustration and component layout of the exhaust aftertreatment system used are presented in Figure 3. The mentioned system not only ensures compliance with environmental standards but also has critical importance in terms of the tractor's performance and durability criteria.

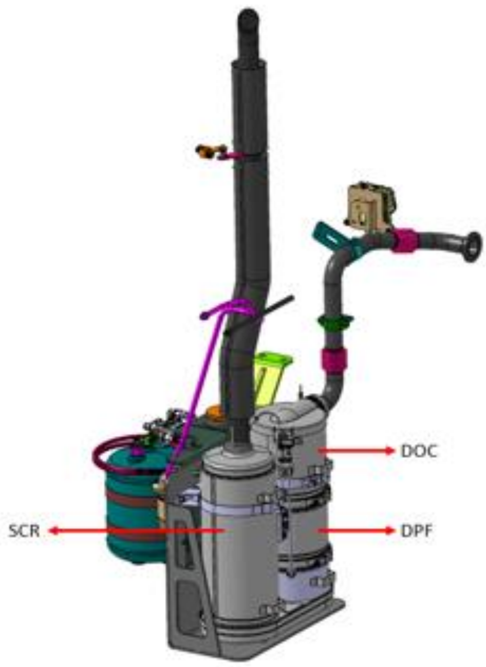

Figure 3. Configuration of the exhaust aftertreatment system

2.1. Design and Analysis of the Supporting Bracket for the Exhaust Gas Aftertreatment System

2.1.1. Design Study

During the design of the bracket carrying the exhaust gas aftertreatment system, the aim was to develop a structure capable of safely supporting the static weight of the system while also providing sufficient strength against vibrations and dynamic loads occurring during operation. In the design process carried out in this context, not only structural strength but also weight optimization was taken into consideration. Since the exhaust aftertreatment system has a significant mass, it is important to ensure adequate strength in the supporting bracket without introducing additional weight. Therefore, the bracket was designed to be as light as possible while maintaining sufficient rigidity. In material selection, criteria such as manufacturability and cost were also considered. Consequently, an optimum design was achieved by evaluating structural durability, manufacturability, and economic efficiency together.

For the manufacturing of the bracket carrying the exhaust gas aftertreatment system, St37 (S235JR) steel was selected as the material. The mechanical properties of this material are given in Table 2.

Table 2. Mechanical properties of St37 (S235JR) steel

Young's modulus	200 GPa
Poisson's ratio	0.3
Density	7850 kg/mm^3
Tensile Yield Strength	235 MPa
Ultimate Tensile Strength	360 MPa

The image of the initial design of the bracket intended to carry the exhaust gas aftertreatment system is presented in Figure 4. This design was evaluated in terms of both structural strength and manufacturability, forming the basis for the subsequent analysis stages. Static strength, modal, and random vibration analyses were applied to the supporting bracket designed in this study. Through these analyses, the structural behavior of the bracket under applied loads was evaluated, and vibration-induced risks were assessed.

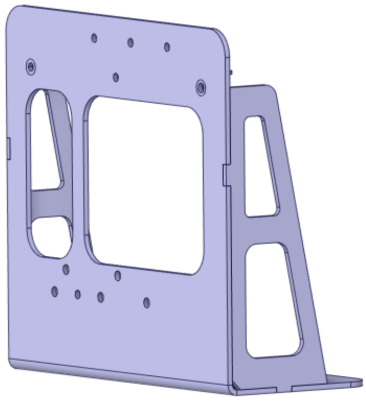

Figure 4. Support bracket for the exhaust aftertreatment system

2.1.2. Analysis Studies

In the analysis studies of the support bracket, a modal analysis was first performed to evaluate the possible over-lap between the operating frequencies of the tractor engine and the natural frequencies of the bracket, thereby preventing potential resonance risks. Considering the engine's operating frequencies at rated power, rated torque, and idle speed, the analysis results were used to optimize the bracket design to minimize the likelihood of resonance.

After determining the most optimum design, a random vibration analysis was conducted on the support bracket system to examine its structural behavior across different frequency ranges. Finally, the static strength of the optimized bracket was evaluated; under specific acceleration conditions, the structural safety of the bracket was analyzed against the loads it may encounter during operation.

This comprehensive analysis process demonstrated both the vibration resistance and static strength of the bracket, ensuring a reliable and optimized design for real operating conditions.

2.1.2.1. Modal Analysis

Within the scope of the modal analysis study, the possible overlap between the natural frequencies of the sup-porting bracket and the operating frequencies of the engine was thoroughly evaluated, and potential resonance risks were investigated. During this assessment, the system's behavior under critical operating conditions was analyzed by considering the engine speeds corresponding to rated power, torque, and idle. Accordingly, the engine operating speeds of 750, 1400, 1500, 1600, 2200, and 2550 rpm were examined as critical cases.

Since the engine used in the analyzed tractor is a four-cylinder engine, the 2nd, 4th, and 8th order harmonics play a significant role in the structural vibration response. Overlaps occurring at these harmonic orders may cause resonance effects, thereby increasing the fatigue risk on the bracket.

The natural frequencies obtained from the initial design of the support bracket are presented in Table 3, while the possible overlaps with the engine operating frequencies were analyzed using a Campbell Diagram to identify critical frequency ranges (Figure 5).

Table 3. Natural frequencies of the initial design version

1st mode	19,6 Hz
2nd mode	41,7 Hz
3rd mode	53,7 Hz
4th mode	71,1 Hz
5th mode	149,0 Hz
6th mode	173,9 Hz

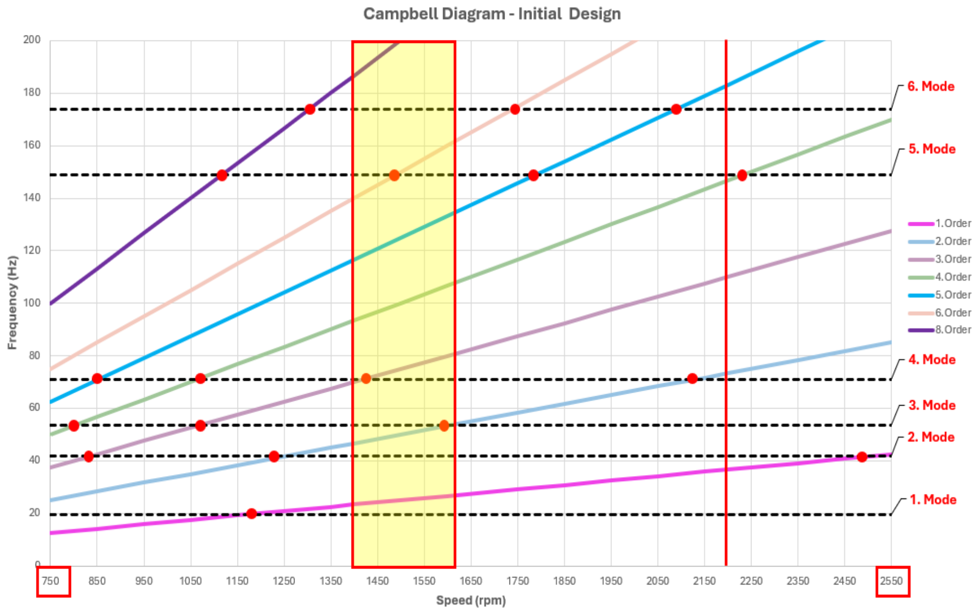

Figure 5. Campbell diagram of the initial design

In the initial design, a natural frequency overlap was observed within the rated torque speed range and near the maximum idle speed. Since these overlaps occurred particularly at the 2nd order harmonic, which corresponds to the engine's combustion order, design modifications were implemented. In the second design version, the mass of the supporting bracket was increased. The supporting bracket of the second version is shown in Figure 6.

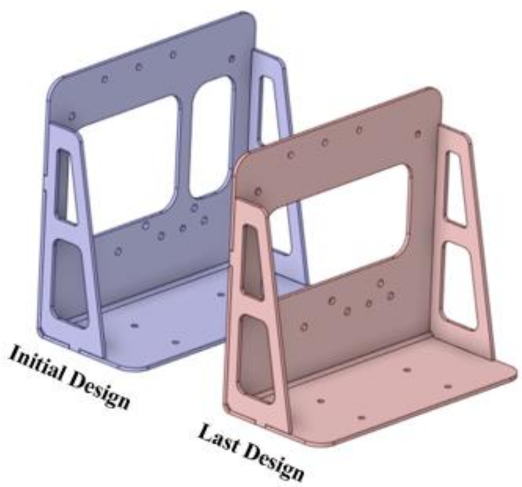

Figure 6. Comparison of the initial and last designs

The natural frequencies of the last design version of the supporting bracket are presented in Table 4, and the possible overlaps with the engine operating frequencies were analyzed using a Campbell Diagram to identify critical frequency ranges (Figure 7).

Table 4. Natural frequencies of the last design version

1st mode	19,5 Hz
2nd mode	30,1 Hz
3rd mode	54,0 Hz
4th mode	67,9 Hz
5th mode	146,0 Hz
6th mode	166,4 Hz

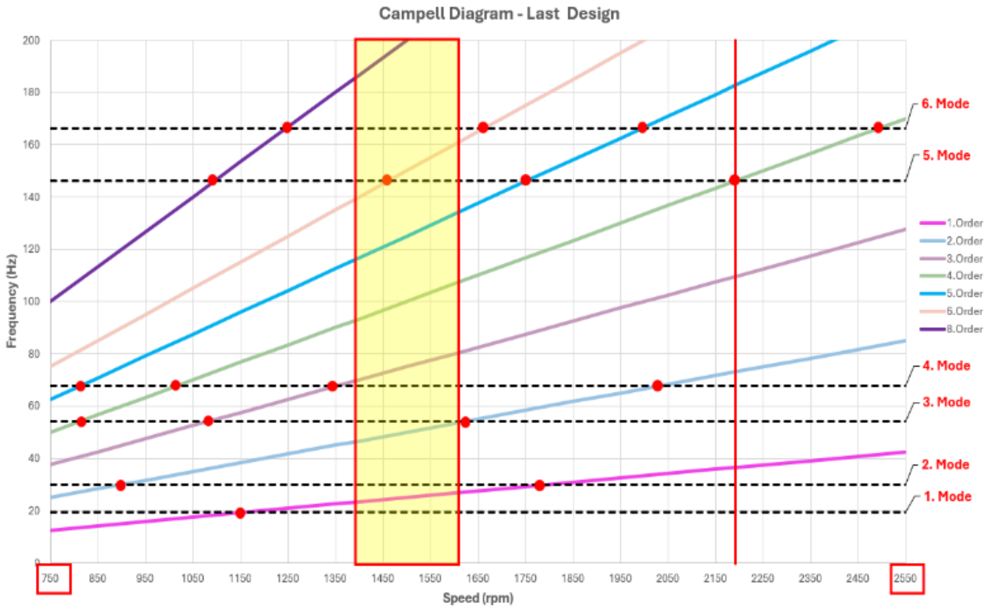

Figure 7. Campbell diagram of the last design

Since the engine's rated torque speed range of 1400–1600 rpm represents the most frequently used operating range of the tractor, resonance risks in this region are critically important for the system's durability. In the last de-sign version developed through optimization, the mode frequencies in this critical range were rearranged, the number of overlaps was reduced, and the resonance risk was minimized. Thus, the vibration resistance of the bracket carrying the exhaust aftertreatment system was improved, and structural reliability was ensured, particularly within the engine's commonly used operating range.

2.1.2.2. Random Vibration Analysis

In the last version selected as the optimum design, a random vibration analysis was conducted to evaluate the structural performance of the supporting brackets at specific frequencies. Random vibration refers to vibrations with unpredictable frequency and amplitude variations over time. This analysis is critical for predicting the effects of irregular vibrations originating from the engine and the road, as well as for preventing potential fatigue failures. The power spectral density ($(m/s^2)^2/Hz$) data used in the analysis are shown in Figure 8.

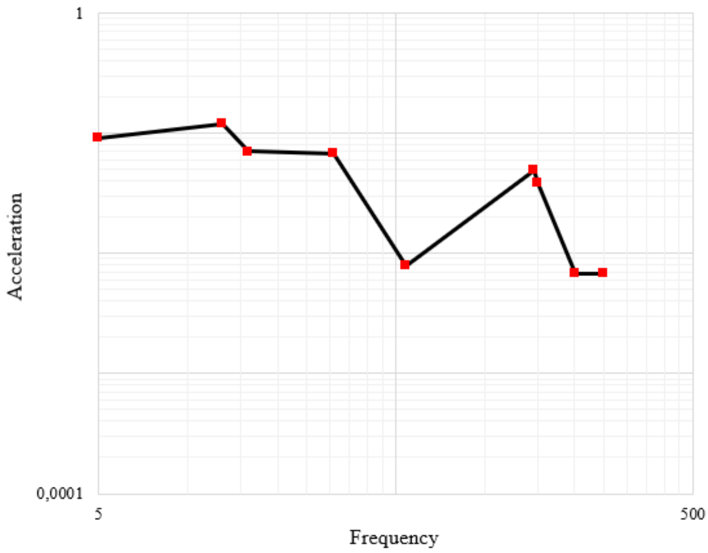

Figure 8. Power Spectral Density (PSD) Graph

In the random vibration analysis, the irregular vibrations originating from the engine and the road, which the system may be exposed to under real operating conditions, were evaluated using a 3-sigma scaling factor. High sigma excitations simulate rare extreme conditions. According to the results, no structural damage risk was predicted in the supporting bracket or connected components. The material yield limits were not exceeded, and the maximum deformation value was limited to only 0.09 mm. These results demonstrate that the optimum bracket design is sufficient in terms of both structural reliability and long-term durability. The analysis results are presented in Figures 9 and 10.

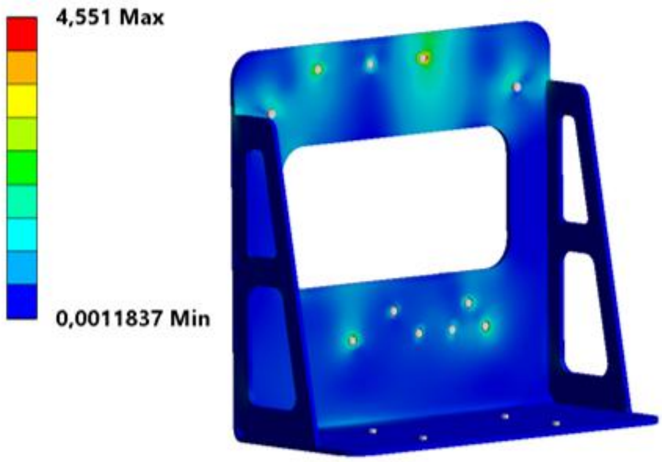

Figure 9. Equivalent stress results of the random vibration analysis

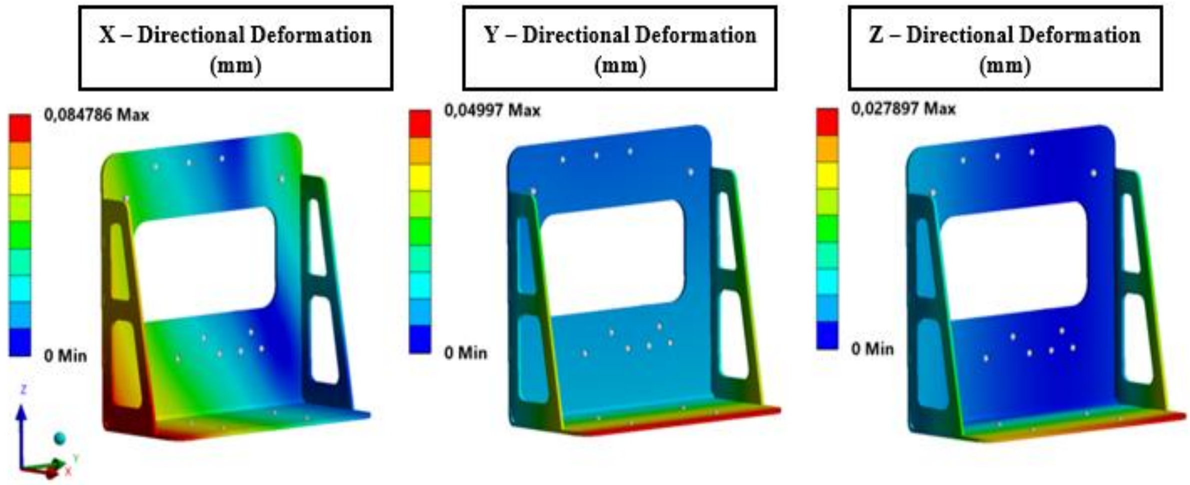

Figure 10. Directional deformation results of the random vibration analysis

2.1.2.3. Static Durability Analysis

In the static analysis of the supporting bracket, accelerations of 5g were applied in the x, y, and z directions to rep-resent the operating conditions of the system. Within the scope of this analysis, the maximum principal stresses and total deformations under these accelerations were evaluated, and the forces transmitted to the bolts connecting the brackets were examined. Based on the maximum force obtained, appropriate bolt selection was made to ensure connection safety. This study covers both the structural strength of the bracket and the reliability of the fastening elements.

Under the boundary conditions applied in the static strength analysis, the bolt subjected to the highest axial force in the supporting bracket connections was identified. The calculations revealed that the axial force transmitted to this bolt was approximately 5200 N. To safely withstand this load, the fastener was selected in accordance with the VDI 2230 standard, and an M12–8.8 grade bolt was chosen as the most suitable option. Thus, both structural integrity and long-term connection reliability were ensured. The analysis model and the location of the related bolt are shown in Figure 11.

As a result of the static strength analysis, the maximum principal stresses on the supporting bracket were thoroughly examined, and it was determined that these stresses did not exceed the yield strength of the selected material. This indicates that there is no risk of plastic deformation or structural damage in the part. The results obtained demonstrate that the bracket can operate safely under the given loading conditions and is structurally sufficient in terms of strength.

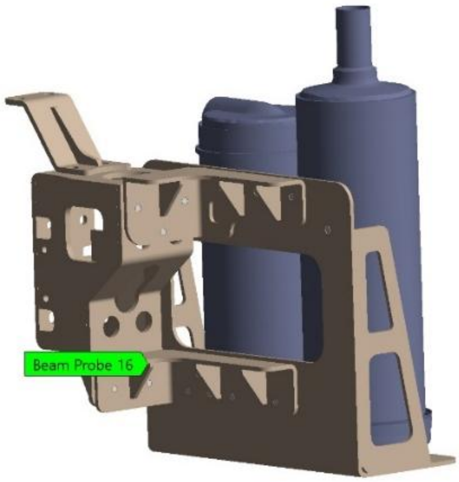

Figure 11. Static durability analysis model

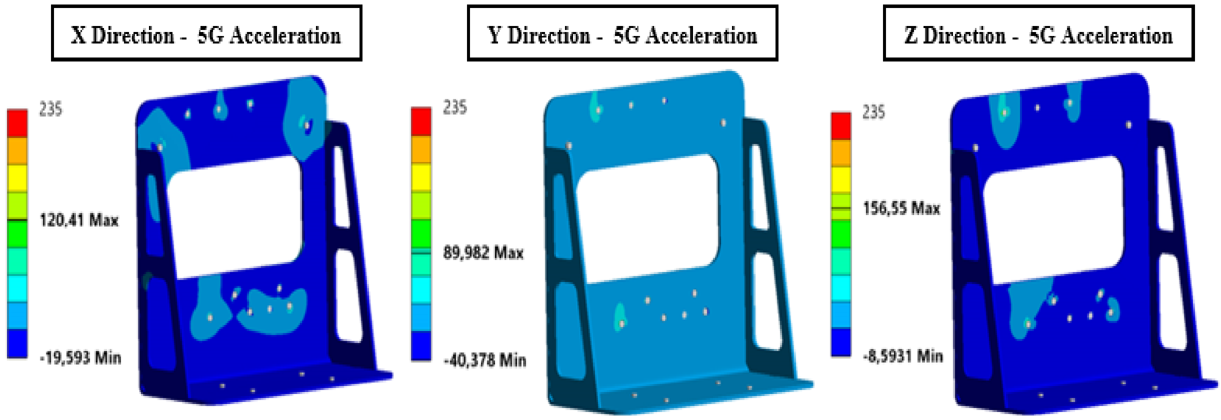

Figure 12. Static durability analysis results

3. Conclusion

As a result, since the exhaust gas aftertreatment system is critically important for protecting the environment and hu-man health in commercial diesel engines, it is essential that the brackets supporting this system are durable and long-lasting. In vehicles operating under harsh conditions, such as tractors, these brackets are expected to withstand high vibrations originating from both the engine and the terrain.

According to the analysis results obtained in this study, a resonance risk was identified in the initial bracket design at the tractor's frequently used rated torque speeds. To eliminate this risk, a new design was developed, and with the last version of the bracket, the likelihood of resonance at critical operating frequencies was significantly reduced. In the random vibration analysis conducted on the optimum design, the structural reliability of the supporting components was evaluated under irregular road- and engine-induced vibrations, and no structural damage risk was predicted for the bracket or connected components.

Finally, in the static durability analysis, the structural performance of the supporting bracket was thoroughly evaluated under accelerations applied in the x, y, and z directions. The results demonstrated that the bracket can safely operate under these multi-directional loads. In addition, the bolts connecting the brackets were examined, and appropriate fasteners were selected based on the forces at the connection points, ensuring the overall structural safety of the system.

Based on all these analyses and evaluations, a safe, durable, and long-lasting supporting structure for the exhaust gas aftertreatment system was designed for tractor applications, thereby enhancing the overall reliability of the system.

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References

[1] Gökçe E. Investigation of Performance and Emission Characteristics of a Domestic Tractor Engine for the Stage III-B Standard. Kocaeli University; 2022.

[2] Özcan E. Theoretical Investigation and Application Regarding to 4 Valved Cylinder Head Design of a Turbo Diesel Tractor Engine Suited for Stage IIIB Emission Standart. Istanbul Technical University; 2009. http://dx.doi.org/10.29228/

[3] Chakraborty A, Polisetti S, Jayaseelan J, Upadhyay R. Application of Reliability Technique for Developing a Test Methodology to Validate the Engine Mounted Components for Off-Road Applications Under Vibration. SAE Technical Paper Series. 2017 Sept 29. https://doi.org/10.4271/2017-01-7004

[4] Perumal S, Kumar A, Mahajan A, Redkar D, Balakrishnan S. Field Failure Resolution of a Tractor Engine Exhaust System Using Constrained Single Objective Optimization and Stochastic Analysis. SAE International Journal of Commercial Vehicles. 2017 Jan 10;10(1):411–22. https://doi.org/10.4271/2017-26-0233.

[5] DU Dong-hui, CAO Liu-jian, HE Ming-fei. Finite Element Analysis of After Treatment Mounting Bracket Based on Creo Simulation Software. Tractor & Farm Transporter. 2022;49(2):43-46.

[6] XU Zhi-liang, LI Jing, ZHANG Lie-ming. Finite Element Analysis of Fixed Support for Tractor Compressor. Tractor & Farm Transporter, 2023;50(3):64-67.

[7] Nareddiwar S, Dey T, Sunilkumar R. Packaging Design, Weld Fatigue Analysis and Validation of Diesel Exhaust After-treatment System. Mechanical Engineering Research. 2018 Nov 30;8(2):36. https://doi.org/10.5539/mer.v8n2p36

[8] Mohapatra DP, Kangde S, Londhe A, Srikanth NN, Singh P. Powertrain Mounted Exhaust System Failure Correlation and Methodology Development in CAE. SAE Technical Paper Series. 2017 Jan 10. https://doi.org/10.4271/2017-26-0267

[9] Gupta B, Li J, Singaravel V. Simulation Methodology for Failure Analysis of Catalytic Converter Mounting on Commercial Vehicles. SAE Technical Paper Series. 2024 Apr 9. https://doi.org/10.4271/2024-01-2247

[10] Rahman S, Chakraborty A, Perumal S, Redkar D, Usulamarthi R, Singh R. Structural Development and Improvement of SCR Assembly Design for Exhaust After Treatment System of a Construction Equipment Off Highway Vehicle. SAE Technical Paper Series. 2024 Jan 16. https://doi.org/10.4271/2024-26-0091

[11] Solanki AS, Jaju YR. Test Correlation of an Exhaust System Durability Failure Using Enhanced CAE Approach. SAE Technical Paper Series. 2019 Jan 9. https://doi.org/10.4271/2019-26-0293

[12] P S, Sujatha C, K. C. Transient Fatigue Analysis of Exhaust System Mounting Brackets for Commercial Vehicle - Correlation. SAE Technical Paper Series. 2017 Mar 28. https://doi.org/10.4271/2017-01-1333

[13] LI De-zhi, LIU Zhao-bin, YANG Yin, XIAO Yong, XING Shou-chen, ZHANG Lu-yun. Finite Element Analysis and Optimization of Mounting Bracket of Engine After-treatment System. Tractor & Farm Transporter. 2021;48(1):32-34.

[14] Heuser P, Ghetti S, Rathod D, Petri S, Schoenfeld S. Bharat Stage VI Solutions for Commercial Engines for the India Market. SAE Technical Paper Series. 2017 Jan 10;1. https://doi.org/10.4271/2017-26-0043