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Pivot hole thickness optimization and material design for functional requirement of front axle support

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Abstract
The tractor front axle support should be designed to a factor of safety ranging from 5.5 to 6.5. Design optimization of the component was done to meet this functional requirement with pivot hole thickness as the variable. The optimum result gave a factor of safety of 6.2 with reasonable weight increase of 14.433Kg. The weight increase is useful for vehicular weight balance. Cast iron that possesses the required mechanical properties for front axle support was designed with CES Edupack.

Keywords
Tractor, Front Axle, Factor of Safety, Optimization, Material Design

1. Introduction

Agricultural tractors are in the class of mobile machines and the main components of an agricultural tractor are axles, front axle support, chassis, transmission, rollover protection, and hitch systems. In the agricultural tractor industry, the design of tractor components and systems is done according to pre-determined specifications and requirements. The most critical design criteria for the components were determined regarding the strength requirements, since these components experience high loads in the application areas of agricultural tractors. Among the main components, the most critical loading conditions occur on the front axle and front axle support [1].

Späth [2] investigated the loads, which acts on a tractor chassis. For this purpose, an instrument wheel was designed and built which allows the wheel load, the draft and lateral force at a tractor rear wheel to be measured reliably and with sufficient precision. Experiments were carried out including driving over a ramp and axle loads were recorded.

The Institute of Agricultural Machinery of Technical University Munich [3] in the year 1999 did some studies to investigate the loads on the tractor body. The goal was to calculate the fatigue life of the tractor components. A tractor was equipped to measure the loads on the tractor axles and the loads on the three point hitch. The loads while working on the field and driving on the ISO-tracks were measured. A load spectrum was processed from the load time history by using rainfall cycle method. Finally, the total fatigue damage for the tractor components was calculated, considering damage accumulation hypothesis defined by Miner [4].

Yahya [5] developed an instrument and sensor system for an agricultural tractor. The system was constructed on the tractor and was capable of recording information for drawbar pull force, drive wheel torque and both vertical and horizontal forces at the 3-point hitches of the tractor implement. The data acquisition system utilized a designed draw bar pull transducer to measure horizontal pull at tractor drawbar point, wheel torque transducers to measure the torque at both tractor rear wheels, and a 3-point auto hitch dynamometer to measure the horizontal and vertical forces on the implement behind the tractor.

Al–Janobi et al. [6] developed a data acquisition system to measure various tractor performance parameters such as wheel forces, three-point linkage forces, drawbar force, PTO torque and ground speed. An electronic circuit was designed and fabricated to provide exact angular position measurement of the clevis bolts in the tractor wheels at any travel speed and scanning rate of the data logger used. This measurement was found to be more accurate and reliable as compared to the measurement by the marker pulse of the optical shaft encoder, which is dependent on the data logger scanning time. The force measurement from the clevis bolts combined with the angular position measurement gives the total horizontal and the vertical components of forces on the revolving wheel. An onboard data logger was used to sample signals from the various transducers as well as the angular position measurement circuit in the system. The system was field tested for its performance and found to be accurate and reliable in measurement of tractor performance parameters.

Balasubramanian et al. [7] developed a data acquisition system to measure vibration data from an agricultural tractor. Accelerometers were mounted on the front and rear axle and on the driver's seat. An ultra sound ground speed sensor was used to monitor velocity. These sensors were connected to a National Instruments Modular Signal Conditioning Carrier (MSCC). LABVIEW was employed to provide Graphical User Interface (GUI) to the data acquisition system; manage data acquisition and store ground speed and accelerometer signals. An obstacle course was constructed to stimulate rough field terrain. The tractor was driven through the course at prescribed velocities while data was created to mark the obstacles and provide a ground of old obstacles. Correlations could then be made between the known obstacle of varying magnitude and the measured shock and vibration events as a function of ground speed.

Redkar [8] did a study to prove that a good correlation exists between virtual simulation and physical behaviour of machine components. A nonlinear behaviour of tractor front axle was simulated using Abacus CAE. Non linearity was simulated by putting the material nonlinear data in the material stress-strain curve.

Mohanty et al. [9] in their study at Tata Industries employed CAE approach to analyze a new design of the front axle of an agricultural tractor. The geometric models for the existing design and proposed designs were created and imported into ANSYS. The proposed designs were evaluated for selected worst case scenarios of the tractor. Based on the finite element analysis results, re-design was carried out for the front axle.

Koyuncu [10] in his study did analysis of the FE model of the front axle support. He implemented for the load cases that are considered during the design of the front axle support. A set of load cases for the agricultural tractor front axle supports was selected by surveying the literature and consulting the designers of Erkunt Agricultural Machinery.

Aduloju et al [11] have performed a structural analysis on 105.84 kg GG cast iron URSUS tractor front axle support to obtain the maximum stress on the component as 88 N/mm^2 and the maximum displacement as 0.01370mm. The factor of safety recorded as the result of the analysis was 2.84 which were lower than the recommended safety factor of 5.5 to 6.5.

This paper is centered on the design optimization of the tractor front axle support to meet its functional requirement with the pivot hole thickness as the variable. The optimum value of the factor of safety and weight increase were evaluated. The weight increase is useful for vehicular weight balance. Cast irons that have the required mechanical properties for Front Axle support were designed with CES Edupack.

2. Methodology

Virtual analysis of the component was performed using Pro-Engineer software version 4.0. Solid modelling and structural integrity of the component was simulated in the Pro-Mechanica environment. Pro Engineer is a registered trademark of Parametric Technology Corporation, Needham, MA, USA. Technical Specifications of the tractor are shown in table 1. The front axle support design was manufactured from GG-25, gray cast iron. The material properties needed for the virtual structural simulation as obtained from previous work [10] on the material is as shown in table 2.

Table 1. *Technical Specifications of Tractor*

Parameter	Value
Engine volume	3.3 litres
Maximum Power	60HP
Maximum Torque	222Nm
Weight	3010 Kg

The tractor front axle support dimensions were measured and recorded. The component was modeled as a .prt file in the solid subtype environment of the Pro Engineer software. These dimensions were used to virtually model the component. Pro-mechanica was used to simulate the stress variation, displacement, strains across the component. The software uses a finite element method in finding solution to problems. The software made provisions for specifying the material properties of the component, virtual component constraint and load application.

Table 2. *Mechanical properties of GG-25 Cast iron*

Property	Value
Modulus of Elasticity	120000
Poisson's Ratio	0.23
Ultimate Tensile Strength	250MPa

The design stress is inversely proportional to the contact area and increased factor of safety could be achieved by increase in contact area of the component. The increase in the contact area can be achieved by increasing the pivot thickness of the front axle support. The pivot thicknesses were varied with the necessary constraint. The constraint considered mainly were the point of attachment to the tractor, position and thickness of the Front axle.

Structural Analysis was performed on the re-designed component with varying thicknesses. Nine cases were considered and the new design stress and weight were recorded. The factor of safety for each case was calculated.

The best case that was recommended after the completion of analysis was therefore picked for component re-modeling. The pivot thicknesses were considered in the component re-modeling. The component was dimensioned to aid in the fabrication of the component.

The Ultimate tensile strength of material influences the behavior of the component under service. Material with tensile strength that could withstand the stress during service was designed for front Axle support. The material design for this component was done with EduPack version 2011.2 v 7. Edupack is a trademark of Granta Design Limited, Cambridge, United Kingdom. The desired mechanical properties were fed to the material property box to generate Cast iron types, compositions and other mechanical properties for the tractor front axle support.

3. Results and Discussion

Stress analyses were performed for tractor front axle support for pivot thickness of PT 30-72.5. PT 30-72.5 could be interpreted as pivot thickness A of 30mm and Pivot thickness B of 72.5. This results in stress variation across the re-designed component of PT 30-72.5 with maximum stress of 67.79N/mm^2 and displacement variation across the component with the maximum displacement of 0.0098mm.

The local displacement and strain energy occurs at a polynomial order of 7. This is below the set limit of convergence for the critical measures which is at the polynomial order of 9. The convergence of other measures occurs below the set limit of 10%. These prove that the results are accurate.

The mass of the component after the first optimization was increased to 113.12 kg and the design stress reduced to 67.79N/mm^2 to obtain the factor of safety for the component design using GG-cast iron (250MPa) of 3.69. The factor of safety obtained for the first optimization is lower than the recommended value of 5.5 to 6.5.

Table 3 shows the Pivot hole thickness optimization results for the tractor front axle support. Pivot hole A was increased from 26mm to 58mm and pivot hole B was increased from 70mm to 90mm. The pivot hole A thickness could not be increased beyond 58mm and pivot hole B could not be increased beyond 90mm because of the restriction created by the axle position and size.

Table 3. *The Pivot hole thickness optimization results for the tractor front axle support.*

Thickness (mm)		Total Weight (kg)	Added Weight (kg)	Added Cost ($)	Ultimate Stress (N/mm^2)	Design Stress (N/mm^2)	Factor of Safety
Pivot hole A	Pivot hole B						
26	70	105.847	0	0	250	88.0428	2.8395
30	72.5	113.118	7.2717	35.26	250	67.7869	3.6880
34	75	114.094	8.2474	40	250	64.0384	3.9039
38	77.5	115.070	9.2231	44.72	250	60.2899	4.1466
42	80	116.045	10.199	49.45	250	56.5414	4.4215
46	82.5	117.021	11.175	54.18	250	52.7929	4.7355
50	85	118.162	12.316	60	250	48.4078	5.1645
54	87.5	119.304	13.457	65.25	250	44.0231	5.6788
58	90	120.279	14.433	70	250	40.2746	6.2074

There was a consistent decrease of Design Stress from 88.0428N/mm^2 to 40.2746 N/mm^2 and steady increase of the factor of safety from 2.8395 to 6.2075. There was a sharp weight increase 7.2717 for pivot hole A thickness of 30 and pivot hole B thickness of 72.5 this is because there is more material addition for same step thickness addition for this optimization case than the other cases. This could be attributed to the initial shape of the pivot hole A and pivot hole B.

Figure 1 presents the stress analysis performed for tractor front axle support for pivot thickness of PT 58-90. The PT 58-90 could be interpreted as pivot thickness A of 58mm and Pivot thickness B of 90mm. It was observed that the maximum stress on the component was 67.79N/mm^2 and the component was analyzed for the set limit of convergence for the critical measures at the polynomial order of 9. Figure 2 shows that the maximum stress has convergence at polynomial order of 8 and Figure 3 shows that maximum displacement has convergence at polynomial order of 8. Figure 4 shows that the maximum strain energy has convergence at polynomial order of 8.These are below the set limit.

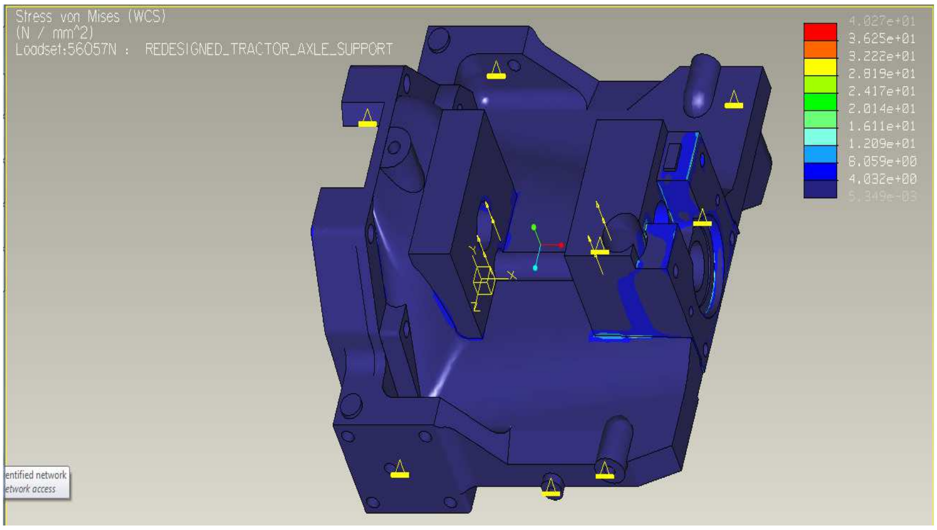

Figure 1. *Stress Variation across the re-designed component PT 58-90*

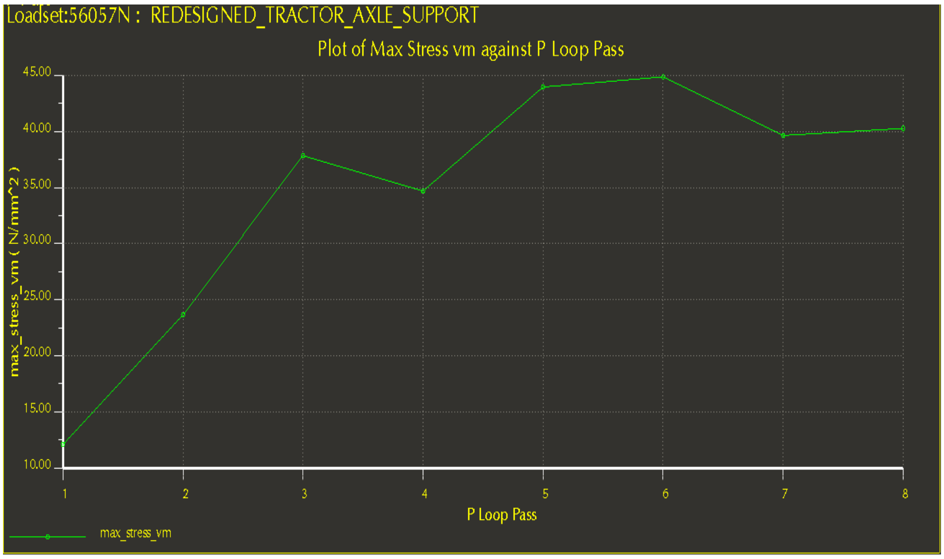

Figure 2. *Plot of Maximum Stress against P Loop Pass for the Re-designed component TH 58 90*

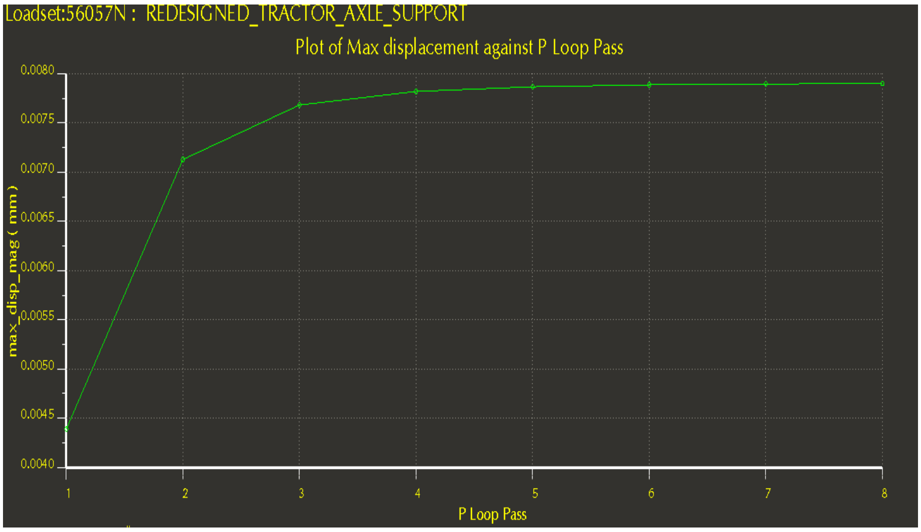

Figure 3. *Plot of Maximum displacements against P Loop Pass for the Re-designed Component PT 58-90*

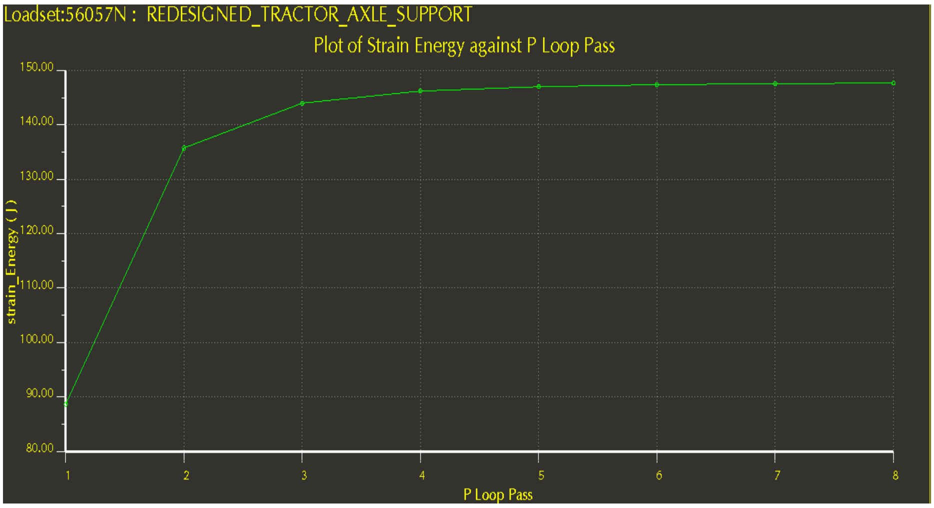

Figure 4. *Plot of strain Energy against P Loop passes for Redesigned component TH 58-90*

The convergences of other measures occur below the set limit of 10% as shown in table 4. These prove that the results are accurate. The mass of the component was 120.28 kg. The added weight was 14.43kg.The design stress was 40.27N/mm^2. The factor of safety for the component design using GG-cast iron (250MPa) is 6.21. The factor of safety lies between the recommended values of 5.5 to 6.5. This design could be said to be very good.

Table 4. *Percentage convergence for re-designed Component TH 58-90*

Name	Value	Convergence (%)
max_disp_mag:	7.900777e-03	0.1
max_disp_x:	3.258665e-03	0.2
max_disp_y:	7.765568e-03	0.1
max_disp_z:	-1.708281e-03	0.1
max_stress_prin*:	4.954479e+01	2.0
max_stress_vm*:	4.027465e+01	1.5
max_stress_xx*:	3.523916e+01	0.1
max_stress_xy*:	-1.422626e+01	0.1
max_stress_xz*:	2.090998e+01	0.3
max_stress_yy*:	3.866405e+01	9.1
max_stress_yz*:	1.557077e+01	9.9
max_stress_zz*:	2.557664e+01	9.7
min_stress_prin*:	-2.431618e+01	0.3
Strain_energy:	1.476729e+02	0.1

Figure 5 shows the new Tractor front axle support that was re-modeled as a result of the optimization of the pivot hole thickness. Modifications were not made to the points of attachment to the tractor. This is to ensure that the new front axle can easily replace the existing one without much effort.

Table 5 shows the new materials designed for Tractor front axle support. These materials with the elemental composition were designed to withstand the stress on the component during service. Five materials have been designed with minimum % Fe content of 92.815% and maximum % Fe content of 95.78%. The five materials are cast iron types which besides meeting the strength characteristics requirement also have good vibration absorbing and fatigue strength characteristics. Table 6 shows the mechanical properties of the designed cast irons. The most important material criterion for the design was the minimum allowable stress of 440N/mm^2.

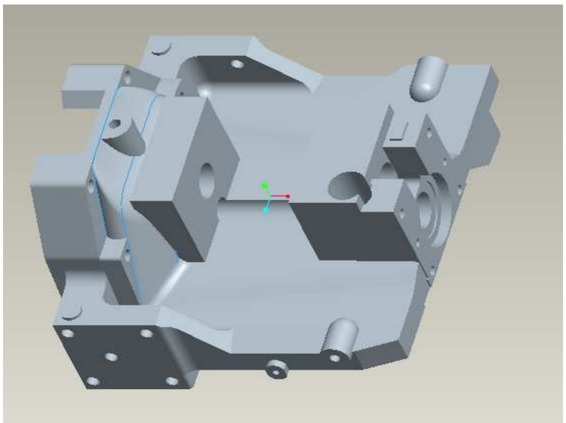

Figure 5. *The Re-designed Tractor Front Axle Support*

Table 5. *Materials selected for new design criterion with composition*

S/N	Material name	Composition
1	Pearlitic malleable cast iron (BS grade p 45-06)	95.465%Fe, 2.33%C, 1.275%Si, 0.75%Mn, 0.11%S, 0.07%P
2	Pearlitic malleable cast iron (former BS P 440/7-AQ)	95.78%Fe, 2.18%C, 1.147%Si, 0.62%Mn, 0.13%S, 0.143%P
3	Pearlitic malleable cast iron (former BS P 440/7-N)	96.116%Fe, 2.38%C, 1.118%Si,0.136%Mn, 0.13%S,0.12%P
4	Nodular graphite cast iron (BS grade 420/12)	92.815%Fe, 3.64%C, 0.045%Mg, 0.4%Mn, 0.66%Ni, 2.44%Si
5	Nodular graphite cast iron (BS grade 450/10)	93.752%Fe, 3.47%C, 0.32%Mn, 0.072%P, 0.015%S, 2.37%Si

Table 6. *Mechanical properties of the designed materials*

S/N	Material name	Tensile Strength (Pa)	Young's modulus (Pa)	Elongation (%)	Fatigue strength at 10^7 cycles (Pa)	Fracture toughness (Pa.m^1/2)
1	Pearlitic malleable cast iron (BS grade P 45-06)	4.75e8	1.654e11	11	2.462e8	4.52e7
2	Pearlitic malleable cast iron (former BS P 440/7-AQ)	4.6e8	1.627e11	9	2.45e8	4.48e7
3	Pearlitic malleable cast iron (former BS P 440/7-N)	4.52e8	1.584e11	9	2.382e8	4.2e7
4	Nodular graphite cast iron(BS grade 420/12)	4.48e8	1.691e11	17	2.07e8	3.92e7
5	Nodular graphite cast iron (BS grade 450/10)	4.41e8	1.547e11	14	2.17e8	3.61e7

4. Conclusion

The following conclusions were drawn from this study:

1. Two solutions have been provided to meet the functional requirement of the tractor front axle support during service. The first approach was the pivot hole thicknesses optimization to increase the area of contact of the pivot to the front axle support. We have observed that there was sharp weight increase for the first pivot thickness increase followed by gradual weight increase as the pivot thickness increases. The sharp weight increase has been attributed to initial shape of the pivot hole face. The optimization result of tractor front axle support for pivot thickness of PT 58-90 gave the best safety of factor.
2. The Computer Aided Material design has been performed to suggest five cast irons for the tractor front axle support. The elemental composition and the mechanical properties of materials have been presented.
3. Although it was observed that the re-modeled piece will have more weight and subsequently cost more, the overall benefit will be more in terms of long run evaluation. The weight addition could also help in vehicular weight balancing. The general downtime experienced with tractors in the agricultural industry can be solved. This will save both government and individual a lot of money and other scarce resources. Our farm yard will be less littered with junks and many of our youths will be put to work. Similar Analysis should be applied to other parts of the Agricultural tractor like axles, chassis components and transmission components

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