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Design, Modelling, Simulation and Fabrication of an Improved Manual Tyre-Changer Machine

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ABSTRACT

This study seeks to design, analyze, model, simulate and fabricate improved manual tyre changer machine. The conceptual designs for the manual tyre-changer machine (MTCM) was generated, detail design of the MTCM as well as proper material selection for the MTCM was carried for fabrication, and ultimately, the performance of the designed and fabricated MTCM was modeled and simulated. Analytical machine design methods was employed for MTCM design using the design input data comprising of the data of the type of material with its mechanical-physical properties as well as its geometric data required to design the machine and its components. This research utilized mild steel, cast steel. The 3-D model of the MTCM was generated through Solid Works Computer Aided Design (CAD) Tool using the data of its design characteristics while ANSYS 16.0 workbench and Solidworks 2022 was used to simulate the MTCM performance. The results from the analysis showed that the design of improved manual tyre changer machine has mechanical advantage of bead breaker arm of 8.67, wall thickness of bead breaker arm of 4.8738mm, allowable bending stress of 80 N/mm^2, allowable shear stress 40 N/mm^2, shank diameter of bolt at A 10.84949mm, shank diameter of bolt at B 11.3743mm, height/thickness of nut at A and B 9.6mm, length of a side of the outer square section of insertion/extraction arm based on bending stress is 46.296mm, length of a side of the inner square section of mount/demount arm based on bending stress 38.58mm, angle of twist of a 60mm × 60mm × 5mm insertion/extraction arm while inserting/extracting a tyre on 16” × 7” rim was selected due to its lower angle of twist of 3.6848×10^{-9} rad. The circular pitch for the pinion gear was determined as 9.426mm.The circular pitch for the driven gear is determined as 6.284mm.The module for the pinion gear was determined as 3mm.The module for the driven gear was determined as 2.4mm.The number of teeth for pinion gear is determined as 20.The number of teeth for driven gear was determined as 30. The torque on driven gear is 4340.02N-mm and the force acting on gear teeth was determined as 144. 67N. Theoretically the bending strength of bevel pinion gear was determined as 13.74 N/ mm. Theoretically, the bending strength of bevel driven gear was determined as 17.169 N/ mm^2.The contact stress for the pinion gear was determined as 3.65N/m^2. The contact stress for the pinion gear was determined as 4.00N/m^2. The ANSYS simulation results showed that the maximum value of equivalent stress for the MTCM bevel gear was 4.8699×10^8 Pa, the maximum value of equivalent elastic strain for the MTCM bevel gear was 0.0022615m/m. and the maximum value of total deformation for the MTCM bevel gear was 9.654 x 10-5m. The ANSYS simulation results showed that the maximum value of equivalent stress for the MTCM shaft for pry bar was 34950Pa, the maximum principal elastic strain for the MTCM shaft was 1.4946×10^{-7} m/m and the maximum value of total deformation for the MTCM shaft for pry bar was 9.3091×10^{-8}m. The ANSYS simulation results also showed that the maximum value of equivalent stress for the MTCM roller bearing was 3.2406Pa, the maximum value of equivalent elastic strain for the MTCM roller bearing was 7.8388×10^{-10}m/m and the maximum value of total deformation for the MTCM roller bearing was 5.7215×10^{-8}m. Conclusion and recommendations were made that ANSYS simulation tool applied in this study have shown that it is possible to predict how the machine components will behave in a real case and allows the engineer to see where the stresses, strains and total deformations will be the greatest and how the machine will behave with such occurrence to provide better reference for redesign of the machine. Finally, the manual tyre changer machine was fabricated and performance evaluation was carried out to test the functioning and the time it takes to carryout tyre replacement. It was seen that the total average time required to carry out tyre replacement was 156s for rim size 381mm, 187s for rim size 406.4mm, and 215s for 431.8mm rim size. The operator is experienced lesser effort while carrying out the performance testing.

1. INTRODUCTION

1.1 Background of the Study

The process of removing the tyre beads from the rim involves exerting stress on the sidewall of the tyre, close to where the wheel rim flange is located. This is known as tyre bead-breaking. The vast majority of tyre technicians in Nigeria and the vast majority of other developing or underdeveloped countries cannot afford the ponderous and expensive tyre changing machines that are available in various designs for automatically loosening beads and changing tyres. In addition, the locally fabricated bead-breaking tool, which is the only tyre changing tool commonly available at the tyre service centers of tyre technicians across Nigeria, is not portable, is only marginally useful for the bead-breaking operation, and is completely insufficient for the tyre extracting and inserting operation. Because of this, the procedure of changing tyres at these tyre servicing outlets is one that is defined by drudgery and waste of time. As a result of the foregoing, there is a demand for a manually operated tyre changer machine that is more portable, comprehensive, and cost-effective. This machine should be able to carry out the tyre changing process effectively, thereby reducing the ergonomics, time wasted, effort expended, injuries sustained, and drudgery associated with the process, which is currently carried out in Nigeria and other developing countries using locally fabricated bead-breaking equipment (Rajopadhye et al., 2017; Pornima et al., 2016).

In the current market environment, there is always a demand for better tool and equipment design, with a focus on time and cost reductions to achieve the required results. No matter the industry, this is the reality (Godbole et al., 2016). The great majority of engineering designs fall into one of two categories: either they are new, human-made inventions or systems that have never been seen before, or they are improved versions of existing devices or systems. Due to their complexity and intricate nature, many inventions and technologies might also be regarded as engineering designs. Engineers are always given the exclusive responsibility of creating quick, inexpensive fixes to problems that people face on a daily basis, particularly in Nigeria and other developing nations throughout the world. This is particularly true in Nigeria. This is especially true in light of the challenges Nigeria is currently facing. This will have the impact of promoting local production of goods, equipment, tools, and services that can aid in the rehabilitation and expansion of the economies of developing countries. Both developed countries and those that are developing will experience this. As a consequence, a motivated research project with the working title " The Simulation Modelling of An Improved Manual Tyre-Changer Machine (MTCM)" was carried out with the aim of making life simpler for local vulcanizers in Nigeria. The goal of this research is to close the gap between the expensive imported tyre changer equipment and the current locally available tyre bead breaking tools used by vulcanizers. This will be accomplished by designing and fabricating a more simple, cost-effective, and time-saving machine to extract and insert tyre on the rim of a vehicle, which would be suitable for use by local vulcanizers in Nigeria.

2. LITERATURE REVIEW

Tyres fails in static and dynamic situations for a variety of reasons, including manufacturing faults, the complexity of tyre design, a lack of quality control, construction handling; usage conditions, and mounting processes, which often result in a failure that leads to serious accidents. Car’s ride and stop on a few square millimeters of rubber, and because they are a key element of a braking system, a tyre body, inner tube, wheel assembly, and bead assembly must work in harmony. Brakes stop the wheels; tyres stop the vehicle (Adetan et al., 2008). These circumstances impose an extremely high safety factor on tyres, and built-in production flaws may cause tyres to fail dynamically.

The vehicle tyre is a complex construction consisting of flexible materials that can’t be manufactured to close tolerances. About 200 distinct raw ingredients are combined into a one-of-a-kind blend of physics, chemistry, and engineering to provide users with the greatest level of comfort, efficiency, dependability, and performance. The manufacturing process starts with the selection of many varieties of rubber, as well as particular carbon black, oils, pigments, silica, and antioxidants. The diverse raw ingredients for each compound are then combined to make a homogenized batch of a black substance with the consistency of gum (Adetan et al., 2008). The mixing process is computer-controlled to ensure homogeneity. The materials that are compounded are then processed further into treads, tyre sidewalls, and other components.

The inner liner, which is resistant to air and moisture penetration, is the first component to be placed on the tyre manufacturing machine. In the event of tubeless tyres, it serves as the inner tube (Adetan et al., 2008). Then belts and body plies, which are often made from nylon, rayon, and polyester, are added to the machine. Tyres are made stronger and more flexible thanks to the use of plies and belts. Different performance qualities dictate how the belts are shaped and sized; therefore, they are custom-made. All of the tyre's components are represented in Figure 2.2, where they are all integrated and function as one. Due to the fact that the plies run diagonally to each other, we call this kind of tyre "biased-ply." Tyres with radial-direction sidewall cords are known as "radial tyres" (Taheri, 2014). In both cases, the beads and belts are interchangeable.

Two hoops made of steel wire with a bronze coating are implanted into the tyre sidewall to produce the bead. Before pressing all elements into place, the tread and sidewalls have to be aligned and placed on top of each other. A green or uncured tyre is what you get. When the green tyre is inflated in a mould, the tread and tyre-identifying information on the sidewall are formed. This is followed by 12 to 15 minutes of vulcanization, during which they are heated to roughly 2.76 N/mm2 and a temperature of about 148.9 degrees Celsius. Vulcanization is the process in which sulphur is applied to the green tyre. Rubber hardens and loses its stickiness. At the molecular level, rubber goes through chemical changes, and molecules with different parts are physically and chemically connected to make a strong bond (Adetan et al., 2008).

The Tyre-Rim Combination

The tyre-rim combination, as illustrated in figure 2.3, is one of the most significant of the numerous parts that are assembled to form an automobile. It is as significant as the engine of the automobile because, without its presence, the engine's power will not be transmitted into the motion of the vehicle. It offers the only contact point between the road and the automobile (Adetan et al., 2013).

3. MATERIALS AND METHOD

This chapter presents the research methodology that guided the data collection, analysis, and fabrication of the MTCM in this research work. It provides a suitable methodology for achieving the research's aim and objectives.

3.1 Research Approach

To design, simulate, and fabricate an improved MTCM in Nigeria. The information and data for the design are gotten from primary sources through interviews with the current TCM operators in Rivers State, Bayelsa State, and other parts of Nigeria, as well as from secondary sources through a review of literature.

i. Conceptual Design I

MTCM Design Powered by a Bevel Gear System

The manual tyre-changing machine illustrated in figures 3.2 – 3.4 comprises a two-straight bevel gear system enclosed in a metal box housing, roller bearings, a t-bolt to enable adjustment of the insertion/extraction arm, a duck head attached to the insertion and extraction arm known as the assistance arm, a shaft attached to the bevel gear and turntable, a bead breaker tool, and a bolt and nut used for fastening the assistance arm to the machine housing. The manual tyre-changing machine is a man-assisted machine powered by a bevel gear system with the aid of a hand wheel. It is employed with the sole aim of carrying out bead breaking, tyre removal, and tyre insertion operations.

2. Selection of the Best Conceptual Design

The process of selecting the best conceptual design involves evaluating each of the concepts against some stated design criteria or requirements that provide a quantitative basis for judging each design. One widely used method to formalize the decision-making process in engineering is the decision matrix (Olisa, 2016).

matrix, and the result is presented in table 3.1. The result obtained from the application of the decision matrix presented in table 1 disclosed that design concept I has the highest score of 1080 over the other generated concepts when evaluated against the stated criteria. Consequently, concept I is selected for this research work.

Table 3.1: Decision matrix for evaluating the alternative conceptual design for the MTCM

Criteria	**Weighting (100%)**	**Rating of Suitability of Alternatives**		
		Concept Design I	**Concept Design II**	**Concept Design III**
Manufacturability	20	10	8	6
R x W		200	160	120
Cost (planning, material and fabrication)	20	10	10	4
R x W		200	200	80
Feasibility	15	10	8	8
R x W		150	120	120
Maintainability	10	10	10	6
R x W		200	200	60
Ergonomics	10	10	8	8
R x W		100	80	80
Shape and Size	10	8	8	10
R x W		80	80	100
Weight	10	10	10	6
R x W		100	100	60
Reliability	5	10	8	8
R x W		50	40	40
Total Score	100	1080	980	660
Rank		1	2	3
Selected?		Yes	No	No

i. R rating/score (the maximum score is 10)

ii. W weighting

Solid Works CAD and the Ansys Mechanical 2021 R2 workspace were utilized in this research work. Using the design data and Solid Works CAD software, a three-dimensional model of the MTCM will be created. The operating performance of the machine was analyzed with the Ansys 2021 workbench and Solidworks computer simulation software.

i.	**ITEM**
1	Hand pedal
2	Turntable
3	Tyre Extractor/Inserting Arm
4	Centre post sleeve
5	Duck-head Arm Sleeve
6	T-handle Bolt
7	Tyre Extractor/Insertion Sleeve
8	Duck-head Arm
9	Bevel gear shaft
10	Duck-head
12	Straight bevel gear - 3
13	Bead Breaker Arm Mount attached to Stanchion
14	Frame (frame for holding bevel gear system and the general internal frame of the machine)
15	Bolt and Nut for fastening
16	Bead Breaker Shoe
17	Bolt for Bead Breaker
18	Swing Arm for Bead Breaker
19	Locking pin
20	Roller contact bearing with housing - 3
21	Pry Bar
22	Bead Breaker Arm
23	Sandpaper of grit size 80, 120, and 240
24	Welding electrode
25	Electric Arc Welding Machine
26	Hack Saw
27	Angle Grinder Machine
28	Spraying Machine
29	Paint materials (Containing Anti Rust primer, autobody filler, putty, autocryl paint, thinner and clear coat to give a glossy finishing)

3.6.3 Design Calculations for the Tyre Insertion/Extraction Part

The insertion/removal portion of the tyre changer machine is equipped with a duck-head bar on which a plastic duck-head is attached. The duck-head bar is intended to be movable between 45 mm and 350 mm from the fulcrum, which symbolizes the center of the centring post sleeve, on the tyre insertion/extraction arm. It is assumed that the TCM is used to remove or install a tyre on a 7-inch-wide, 16-inch-diameter wheel rim. Therefore, the duck-head bar on the tyre insertion/extraction arm will be adjusted to a distance of about 250mm from the centre point of the centring post sleeve which is tagged the fulcrum. The length of the duck-head bar will also be adjusted to about 250mm from the center of the tyre insertion/extraction arm to the rim surface. Figure 3.16 illustrates how the insertion/extraction arm and pry bar assembly will be modeled using the second-class lever approach.

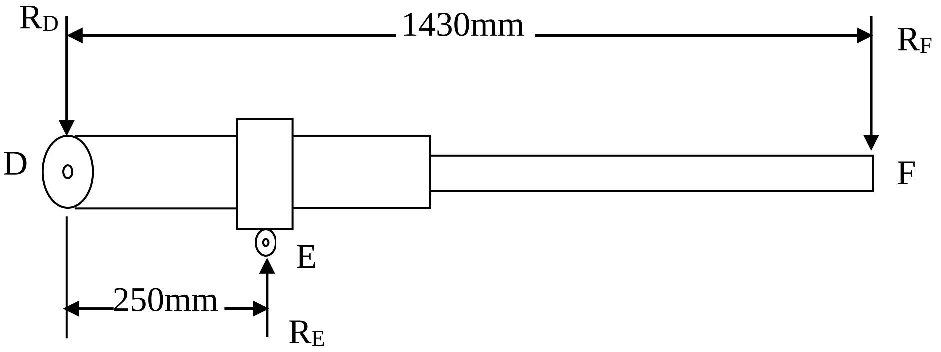

Figure 3.16: Free body diagram of the insertion/extraction arm and pry bar assembly of the MTCM

4. RESULTS AND DISCUSSION

4.1 Results

The analysis of the MTCM design was performed utilizing the design input data, which included the type of material, its mechanical-physical properties, and the geometric data required to create the machine. The MTCM's 3-D model was created using the Solid Works 2021 Computer Aided Design (CAD) Tool with data from its design characteristics, and the MTCM's performance was analyzed using Ansys 2021 R2 and Solidworks 2021 workstation.

4.1.1 MTCM Machine Design Input Parameters

Some design inputs were required for computing the design results of the MTCM. These input parameters and their specifications are shown in Table 4.1.

Table 4.1: Machine Design Input Parameters

Input Parameter	**Value**	**Unit**
Mass of tyre	150	Kg
Yield strength in tension, Syt	400	N/mm2
Yield strength in shear, Ssy	200	N/mm2
Modulus of Rigidity, G	77×10^9	N/mm2
Length of bead breaker load arm, l1B	150	mm
Length of bead breaker effort arm, l2B	1330	mm
Length of insertion/extraction arm load arm, l1M	250	mm
Length of insertion/extraction arm effort arm, l2M	1430	mm
Length of insertion/extraction arm subjected to torsion, LT	250	mm
Perpendicular distance from the longitudinal axis of the insertion/extraction arm to RL, L	350	mm
Force applied at effort point of insertion/extraction arm and pry bar assembly, RF	733	N

Table 4.2: MTCM Design Results

Parameter	**Value**	**Unit**
Allowable bending stress, σb	80	N/mm^2
Allowable shear stress, τ	40	N/mm^2
Mechanical Advantage of bead breaker arm, MAB	8.67	-
Outer radius of bead breaker arm, r_o	29.2428	mm
Inner radius of bead breaker arm, r_i	24.369	mm

Wall thickness of bead breaker arm, t_B	4.8738	mm
Shank diameter of bolt at A, dA	10.84949	mm
Shank diameter of bolt at B, dB	11.3743	mm
Height/Thickness of nut at A and B, h	9.6	mm
Mechanical Advantage of tyre insertion/extraction arm, MAM	5.72	-
Length of a side of the outer square section of tyre insertion/extraction arm based on bending stress, b_o	46.296	mm
Length of a side of the inner square section of tyre insertion/extraction arm based on bending stress, bi	38.58	mm
Wall thickness of tyre insertion/extraction arm based on bending stress, t_{MB}	3.858	mm
Torque on the insertion/extraction arm	1439200	N·mm
Length of a side of the outer square section of tyre insertion/extraction arm based on torsional stress, lo	61.092	mm
Length of a side of the inner square section of tyre insertion/extraction arm based on torsional stress, li	50.91	mm
Wall thickness of mount/demount arm based on torsional stress, t_{MT}	5.091	mm
Length of centre line of tyre insertion/extraction arm, s	220	mm
Area bounded by centre line of tyre insertion/extraction arm, α	3,025	mm^2
Angle of twist of a 50mm × 50mm × 4mm tyre insertion/extraction arm while inserting and extracting a tyre on 16” × 7” rim, ϕ50	9.8141×10^{-9}	rad
Angle of twist of a 60mm × 60mm × 5mm tyre insertion/extraction arm while inserting and extracting a tyre on 16” × 7” rim, ϕ60	3.6848×10^{-9}	rad
Circular pitch for the pinion gear	9.426	Mm
Circular pitch for the driven gear	6.284	Mm
Module for the pinion gear	3	Mm
Module for the driven gear	2.4	Mm
Number of teeth for pinion gear	20	
Number of teeth for driven gear	30	
Diametral pitch for pinion gear	0.333/mm	
Diametral pitch for driven gear	0.42/mm	
Pitch velocity for pinion gear	1500	mm/sec
Pitch velocity for driven gear	1800	mm/sec
Velocity ratio for the gear system	1.2	
Bevel factor	0.667	
Torque on driven gear	4340.02	N-mm
Force acting on gear teeth	144.67	N
Bending strength of bevel pinion gear	13.74	N/mm2
Bending strength of bevel driven gear	17.169	N/mm^2
Contact stress for the pinion gear	3.65	N/m2
Contact stress for the driven gear	4.00	N/m^2

5. CONCLUSION AND RECOMMENDATIONS

5.1 Conclusions

After generating conceptual designs for the manual tyre-changer machine (MTCM), carrying out detailed design of the MTCM, proper material selection, fabricated and carried out performance evaluation of the designed MTCM. The following conclusions were drawn from the work:

i. Decision matrix was utilized for evaluating and selecting the best alternative conceptual MTCM designs. The best conceptual design with a two-bevel gear system and bearing was selected for this work.

ii. Solidworks CAD software was employed to model the improved manual tyre changer machine with respect to the design characteristics.

iii. The analytical values of various machine components were determined from the design analysis carried out on the MTCM.

iv. The 60mm × 60mm × 5mm square pipe was selected for the insertion/extraction arm because it has a lesser angle of twist compared to a 50mm × 50mm × 4mm insertion/extraction arm.

v. The ANSYS simulation results showed that the maximum value of equivalent stress for the MTCM bevel gear is 4.8699×10^{8} Pa. The equivalent stress is larger in the centre and smaller on both sides of the contact surfaces. Likewise, the stress is larger on the junctions of the bottom width angles and pitch angles of the ribbed patterns. The ANSYS simulation results showed that the maximum value of equivalent elastic strain for the MTCM bevel gear is 0.0022615m/m. The equivalent elastic strain is larger in the centre and smaller on both sides of the contact surfaces. Likewise, the elastic strain is larger on the junctions of the bottom width angles and pitch angles of the ribbed patterns. The ANSYS simulation results showed that the maximum value of total deformation for the MTCM bevel gear is 9.654 x 10-5m. The total deformation is smaller in the centre and moderate around its periphery. Likewise, the total deformation is larger on the junctions of the bottom width angles and pitch angles of the gear.

vi. The ANSYS simulation results showed that the maximum value of equivalent stress for the MTCM shaft for pry bar is 34950Pa. The equivalent stress is larger at the joint near the fulcrum represented with a yellow color. The ANSYS simulation results showed that the maximum principal elastic strain for the MTCM shaft is 1.4946×10^{-7} m/m. The equivalent principal elastic strain is larger at the joint near the fulcrum represented with a light green color. The ANSYS simulation results showed that the maximum value of total deformation for the MTCM shaft for pry bar is 5.7215×10^{-8}m. The total deformation reduces significantly from the shaft length end section from the right (contact point) to the joint near the fulcrum and then increases slightly from the joint to the fulcrum.

vii. The ANSYS simulation results showed that the maximum value of equivalent stress for the MTCM roller bearing is 3.2406Pa. The equivalent stress is moderate around the larger circumference of the bearing. Likewise, the stress is larger around the smaller circumference of the bearing near the centre. The ANSYS simulation results showed that the maximum value of equivalent elastic strain for the MTCM roller bearing is 7.8388×10^{-10}m/m. The ANSYS simulation results showed that the maximum value of total deformation for the MTCM roller bearing is 9.3328×10^{-7}m which represents that there is a very little elastic strain and relevant equivalent elastic strain distribution experienced in the roller bearing. These results show that there is fairly good agreement between the analytical results and finite element results.

viii. ANSYS and Solidworks simulation tool applied in this study have shown that it is possible to predict how the machine components will behave in a real case and allows the engineer to see where the stresses, elastic strains, total deformations, and displacements will be the greatest and how the machine will behave with such occurrence. Based on the analysis of the ANSYS and Solidworks simulation results, the stress, strain, displacement, and total deformation concentrates on the machine components will provides a better reference for redesign of the machine.

ix. A prototype MTCM was designed and fabricated in this work. The performance testing of the MTCM was carried out to ascertain its operation and time using three various sizes of tyres such as 381mm, 406.4mm and 431.8mm.

x. Lastly, this work has shown to a greater degree that the fabricated MTCM using locally available materials in this research work saves time, requires lesser effort to rotate the turntable, and reduces musculoskeletal disorders and tyre-rim damage experienced by road side vulcanizers while using the manual techniques in replacing or repairing tyres.

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