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MECHANICAL PERFORMANCE AND HERTZIAN CONTACT ANALYSIS OF MECANUM-WHEELED UNMANNED GROUND VEHICLES: A FINITE ELEMENT APPROACH

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Abstract: *Within the framework of Industry 5.0 and the increasing autonomy of logistical systems, Mecanum-wheeled platforms represent a benchmark for omnidirectional mobility. As contemporary military operations progressively integrate autonomous technologies, Unmanned Ground Vehicles (UGVs) equipped with Mecanum wheels provide enhanced manoeuvrability for tactical and indoor logistics. Given their expanding deployment in heavy-duty applications, a rigorous understanding of wheel–ground contact behaviour is essential. This study examines the Hertzian contact mechanics of Mecanum rollers through Finite Element Analysis (FEA) conducted in ANSYS Workbench. Stress distribution and deformation under elevated loads are assessed, elucidating their influence on structural integrity and odometric precision. The findings inform the design of robust, high-accuracy omnidirectional platforms for dual-use applications.*

Keywords*: Mecanum wheel, FEA, ANSYS Workbench, Hertzian contact, UGV dynamics*

1. INTRODUCTION

The demand for flexible and autonomous transport systems has led to the widespread adoption of Mecanum-wheeled platforms in various sectors [1]. These systems, characterized by their unique roller-based geometry, offer exceptional maneuverability in confined spaces, a feature that has become indispensable for the "Smart Factory" environments of the present. Beyond the standard assembly line, the applicability of these omnidirectional platforms is extending towards more demanding sectors, including aerospace manufacturing and tactical logistics or humanitarian demining within military operations [2].

Whether navigating a high-tech distribution center or a military supply hangar, the core challenge remains the same: the complex interaction between the rollers and the running surface [3]. Unlike conventional wheels, Mecanum wheels rely on a series of peripheral rollers that create a discontinuous contact pattern. This discontinuity is the primary source of structural vibrations and positioning inaccuracies, which are amplified when the platform carries heavy payloads such as industrial molds or specialized tactical equipment.

The reliability of Unmanned Ground Vehicles (UGVs) in these environments nowadays depends on the precision of their "Digital Twin" models. Accurately predicting how a roller deforms under load and how the contact pressure is distributed is vital for preventing material fatigue and ensuring the stability of onboard sensors.

While industrial applications prioritize longevity and smooth operation, the tangential application in tactical logistics adds a requirement for extreme robustness under peak loads and on varied surfaces (metallic flooring or treated concrete).

This paper addresses these multi-sectoral challenges by conducting a rigorous numerical analysis using ANSYS Workbench software.

By simulating the contact mechanics under load profiles relevant to both industrial and tactical logistics, we aim to map the Von Mises stress concentrations and the deformation of the

roller's elastic layer. The findings provide a technical foundation for optimizing wheel design, ensuring that the next generation of Mecanum-based UGVs can handle the rigorous demands of modern autonomous transport, regardless of the operational environment.

2. PROBLEM DESCRIPTION

The operational efficiency of Mecanum-wheeled UGVs is fundamentally dictated by the quality of the contact between the rollers and the running surface. Despite their kinematic advantages [4], these systems face a significant contact paradox: the rollers that enable omnidirectional motion also introduce periodic instabilities [5]. In both high-capacity industrial warehouses and tactical military depots, this interaction involves critical challenges that need an in-depth numerical study.

2.1 Contact discontinuity and load transfer

Unlike standard pneumatic or solid wheels, a Mecanum wheel transitions the supporting load from one roller to the next. This transition is not instantaneous but it involves a complex handover where the contact geometry (Figure 1) changes dynamically.



Fig. 1. KUKA Mecanum wheel contact detail [9]

Analytical models often assume a single point of contact, leading to significant errors in predicting the actual stress distribution. The roller's geometry and its material elasticity cause a distributed footprint that shifts during motion [6]. Failure to accurately model this transfer results in underestimated peak stresses that cause premature material degradation.

2.2 Nonlinear deformation and odometry drift

When a UGV carries heavy industrial payloads or tactical equipment, the rollers undergo significant nonlinear deformation. This deformation effectively alters the wheel's radius and the roller's slip angle. Standard kinematic equations do not account for this flattening effect, leading to a discrepancy between the commanded velocity and the actual displacement (odometry drift). Determining the exact relationship between vertical load and contact area deformation is necessary for calibrating control algorithms [7].

2.3 Material fatigue in dual-use fields

The rollers of a Mecanum wheel are typically composite structures, consisting of a rigid metallic or polymer core and a hyperelastic outer layer (e.g., Polyurethane) [7]. In industrial settings, repetitive stress cycles lead to delamination or permanent set. In tactical scenarios, the wheel may encounter high-friction metallic surfaces or abrasive concrete, which intensifies the thermal and mechanical stress at the contact interface. Without a Finite Element Analysis (FEA) to identify these internal Von-Mises stress concentrations, designing a wheel that balances shock absorption with structural durability remains a trial-and-error process.

2.4 Objective of the study

Given these complexities, the problem addressed in this study is the quantification of the mechanical state of the roller during the most critical phases of its rotation. By using ANSYS Workbench, we aim to move beyond simplified assumptions and provide a high-fidelity map of the pressure distribution and internal stresses. This data is necessary for ensuring that the UGV maintains structural integrity and navigation precision under the varying load profiles encountered in modern industrial and defense logistics.

3. MATERIALS AND METHODS

The in-depth study on the Hertzian contact [8] between the Mecanum wheel rollers and the

running surface can provide valuable information on their behavior, by analyzing elements such as:

- roller shape: curvature and width.
- the thickness of the roller's material.
- the types of material used for rollers.
- the way of attaching the roller to its axis.
- variation in the coefficient of friction between the rollers and the running surface.

The modeling and simulation were carried out with the help of the ANSYS program, in the Workbench module. It offers a wide variety of types of analyses, allowing both Multi-Body Dynamics (MBD) simulations in the Rigid Dynamics (RD) module, and finite element analysis (FEA) – static or transient.

The study focused on the Mecanum wheel model Nexus code Nex-NM203A [10] which has the following characteristics:

- Diameter: 203 mm.
- Width: 103 mm.
- Number of rollers: 8.
- Wheel material: Steel.
- Roller material: Polyurethane.
- Spacer material: Aluminum.
- Weight of a wheel: 8 kg.
- Maximum load per wheel: 150 kg.

In Figure 2 can be seen both the real Mecanum wheel and its 3D model designed in ANSYS Workbench.

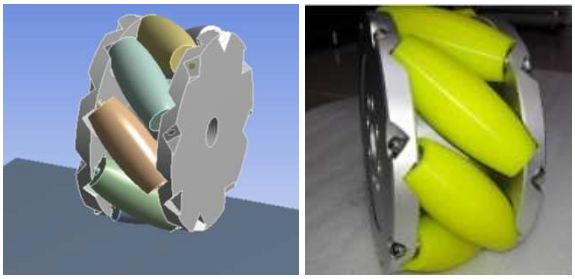


Fig. 2. The 3D model of the Mecanum wheel (left), designed based on Nex-NM203A [10] (right)

An evaluation of the extensive polyurethane elastomer family reveals that "Acrylic Thermoplastic" exhibits mechanical properties (Young's modulus and compressive strength) that closely align with the high-durometer polymers typically utilized for Mecanum roller coatings in heavy-duty applications. Figure 3 depicts a comparison of how the material characteristics influence the contact pressure. Here we can observe how the contact pressure varies depending on the contact force, for materials having the modulus of elasticity between 2.8 and 655 GPa, respectively the Poisson coefficient between 0.2 and 0.4.

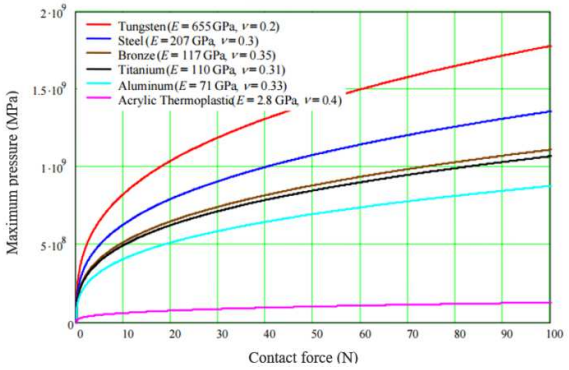


Fig. 3. Influence of material characteristics on contact pressure [11]

The material "Acrylic thermoplastic" from the ANSYS library was used in our simulations in ANSYS Workbench for the rollers coating (E=2.8G Pa, v=0.4, density 1180 kg/m^3). The other parts of the wheel are made from "Structural steel", and the running surface was considered "Concrete" covered.

The specific scope of the study centers on the static Hertzian contact interaction of a convex roller on a flat track (Figure 4). Accordingly, the numerical investigation is conducted through FEM within the Static Structural framework of ANSYS to evaluate the localized stress distribution.

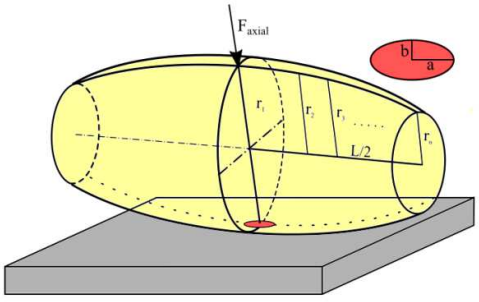


Fig. 4. Main parameters of a roller's geometry (own contribution)

According to [12], the contact between an ellipsoidal body and a body with flat surfaces, under the action of an axial force (F_{axial}), generates an elliptical contact area, represented

in Figure 4. As can be seen, the contact ellipse is positioned with the major semi-axis a in the longitudinal plane of the roller, and the minor semi-axis b, in the transverse plane.

In Figure 5 we can notice the variation of parameter r (in-section radius) along the length of the roller (due to simmetry, study focused on half or quarter of the roller).

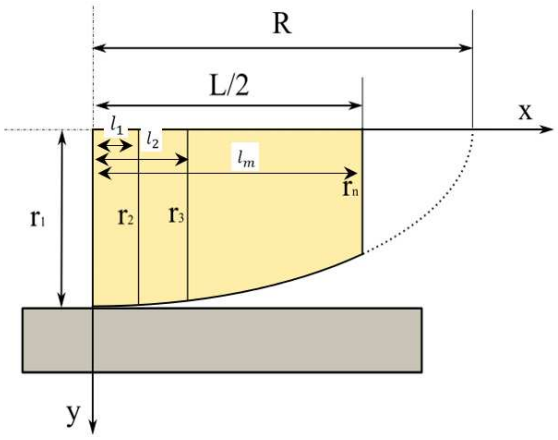


Fig. 5 Variation of parameter *r* along *L/2* (own contribution)

For the analytical model, an application has been developed in MATLAB which allows the problem to be quickly solved by modifying some key parameters. The analytical model therefore starts with the equation of the ellipse with the major semi-axis (R) and the minor semi-axis (r), which is the basis for generating the contour of the studied roller:

$$\frac{x^2}{R^2}+\frac{y^2}{r^2}-1=0 \qquad (1)$$

The parameter R is responsible for the variation in the curvature of the roller. For this, the range of variation [50, 100] mm was established, so that it was defined in MATLAB as a vector with 6 elements, of the form:

$$\mathrm{R}=[50,60,70,80,90,100] \qquad (2)$$

The major semi-axis of the roller was divided into 6 equal segments, so this parameter was also defined as a vector with 7 elements, having the form:

$$\mathrm{L/2}=[0,8,16,24,32,40,48] \qquad (3)$$

As for each value of R, the parameter r will have 7 values, it was defined in MATLAB as an array with 6 lines and 7 columns of the following form:

$$\mathrm{r}=\begin{bmatrix}\mathrm{r}_{11} & \cdots & \mathrm{r}_{17}\\ \vdots & \ddots & \vdots\\ \mathrm{r}_{61} & \cdots & \mathrm{r}_{67}\end{bmatrix} \qquad (4)$$

The mesh quality has been monitored based on three parameters - Element Quality, Orthogonal Quality and Skewness, all being more than 95% accomplished. A mesh convergence study was also performed to ensure numerical accuracy, determining that a minimum of 200.000 nodes were required for the analysis. To generate the mesh of the simplified 3D model (Figure 6), the method of influence bodies was applied, creating an ellipsoid originating in the center of the contact area, having a 7 mm major semi-axis and a 3 mm minor semi-axis, respectively. Subsequently applying the method of dimensioning the elements of the bodies (Body Sizing), with 0.2 mm in the area of the ellipsoid of influence, resulted in a discretization with 424638 nodes and 308653 elements. It should also be noted that in this case, the Size Function was applied to the curvature.

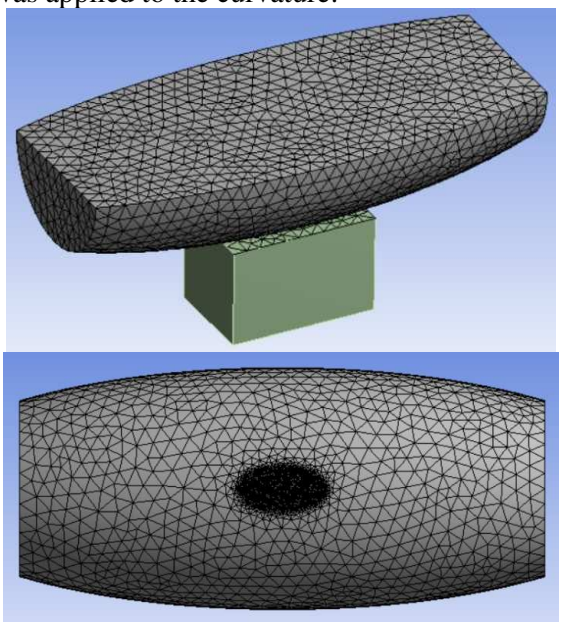


Fig. 6 Meshing the simplified 3D model of the roller in contact with a flat surface (own contribution)

For this analysis, the contact formulation was Augmented Lagrange, the friction assumption – frictionless and the contact

stiffness settings – Program controlled – Normal stiffness factor – 0.1.

4. RESULTS

The variation of the area of the contact ellipse and maximum contact pressure along *X* axis on half length of the roller, analytically determined using MATLAB, is presented in Figures 7 and 8.

It can therefore be seen that the contact pressure reaches maximum value at the end of the roller (when $r = r_7$) and it decreases the lower the curvature of the roller (when R has maximum values).

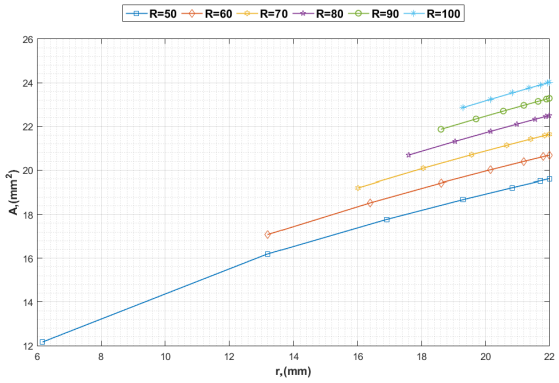


Fig. 7 Variation of the area of the contact ellipse along X axis on *L/2* length – analytical (own contribution)

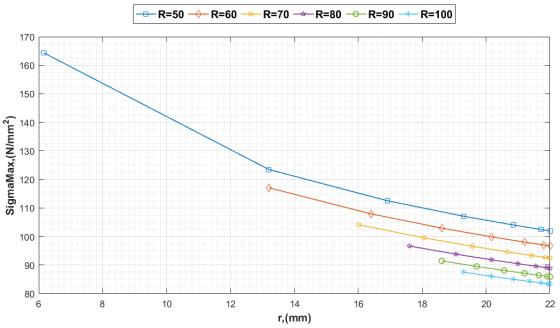


Fig. 8 Variation of the maximum contact pressure along X axis on *L/2* length – analytical (own contribution)

To validate the results obtained, the raw values determined by the simulation needed to be processed. Therefore, the parameter that creates the most relevant image for the study of roller-surface contact is the contact area. The ANSYS program does not allow direct determination of the contact surface, so the results obtained for the contact pressure were taken and the method of image processing in MATLAB was subsequently used.

On the graphs presented in Figures 9 and 10, the curves resulting from the simulation will be marked with a continuous line, and with a dotted line - the analytical data. Therefore, Figure 9 shows the variation of the contact pressure, for the 7 sets of values related to the parameter r and the 6 values of the radius R. A good correlation can be observed of the two methods presented (general average error -7%), with a smaller error for $R > 70\ mm$ (approximately -2%). So, the smoother the curvature of the roller, the closer the results of the FEM analysis are to the analytical model.

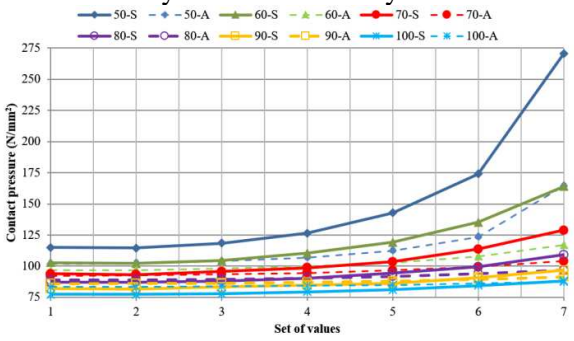


Fig. 9 Variation of the maximum contact pressure along the roller (own contribution)

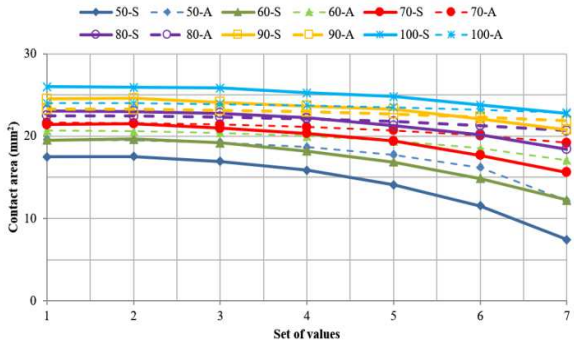
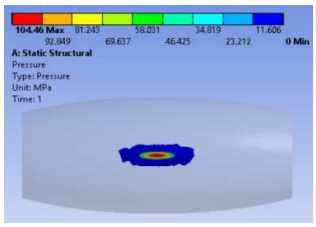
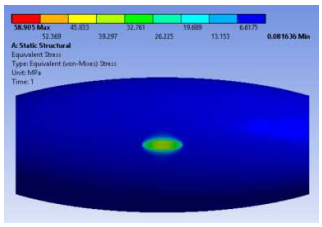
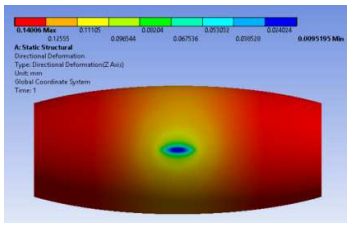
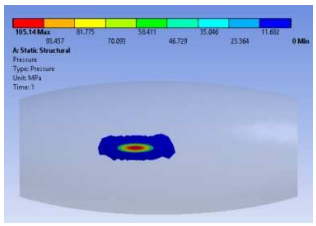
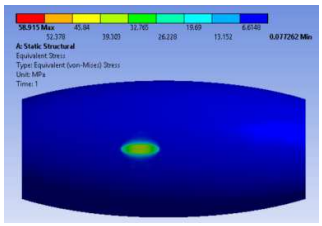
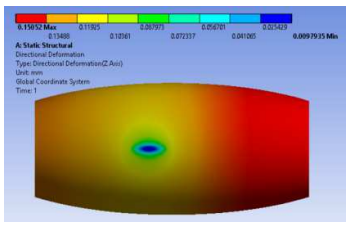
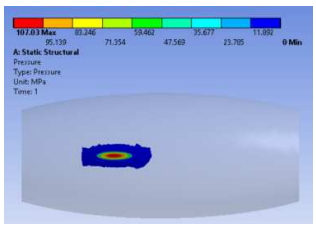
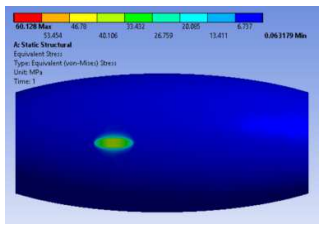
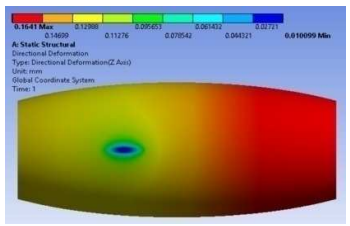
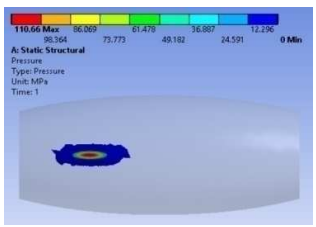
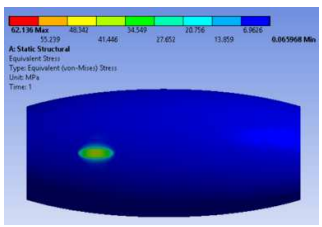
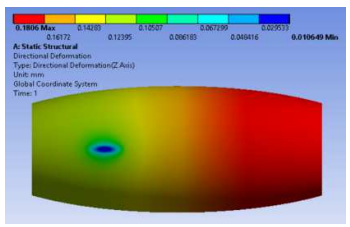
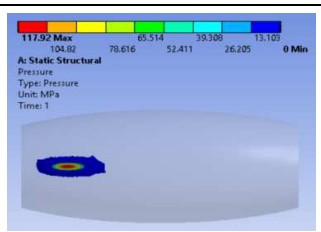
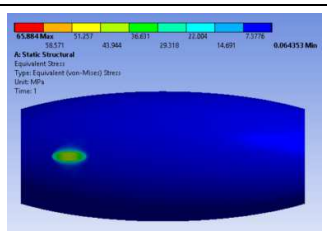
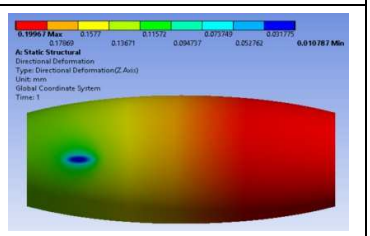
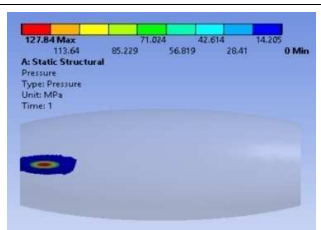
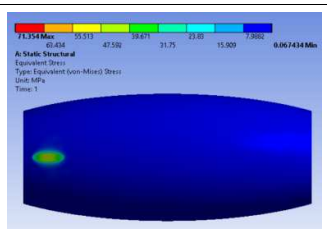
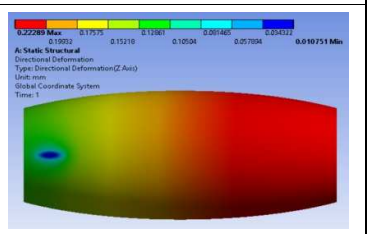
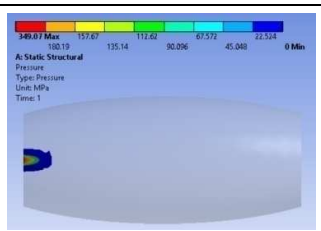
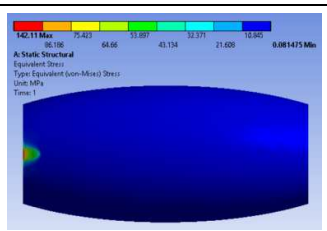
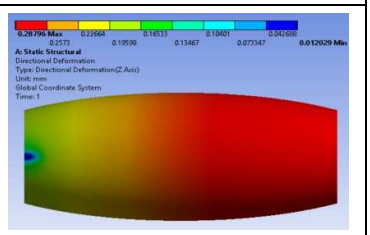


Fig. 10 Variation of the contact area along the roller (own contribution)

In Table 1 we can see the results obtained from the variation of the position of the roller in relation to the running surface for $R = 70\ mm$, when the curvature of the roller is closest to real Mecanum wheel. The main output parameters are contact pressure, von-Mises stress, and roller material directional deformation on Z axis.

Analyzing the images presented in Table 1, as the place where the contact between the two bodies takes place, approaches the end of the roller, the three output parameters of interest have higher values.

Table 1 Variation of output parameters along the roller's length for R=70 mm

VS	Contact Pressure [MPa]	Von-Mises Stress [MPa]	Directional deformation on Z axis [mm]
1			
2			
3			
4			
5			
6			
7			

It should be noted that the mesh for this parameterized model was achieved by sizing the elements by means of the influence ellipsoid by 0.2 mm. Thus, approximately 310000 elements were obtained, and the total calculation time for the 7 sets of values (SV) was approximately 18 hours.

As for the variation of the contact pressure along the roller, it can be seen that its value increases, as the contact between the roller and the running surface occurs towards its extremity.

5. CONCLUSIONS AND DISCUSSIONS

Following the conducted analysis, the general Hertzian contact theory for two elastic bodies, defined by their respective Young's moduli and Poisson's ratios, was particularized for the specific interaction between a Mecanum wheel roller and the running track. The developed analytical model was subsequently implemented and solved using a custom MATLAB script. This application facilitates the rapid determination of material deformation, contact area, and contact pressure by varying key parameters within predefined intervals. The inherent flexibility and generality of this computational tool allow for the efficient resolution of both the current case and similar contact mechanics problems through simple parameter customization.

To validate and expand upon these analytical findings, a series of numerical simulations were performed within the Static Structural module from ANSYS. A significant methodological contribution of this study is the identification of an efficient multi-scenario simulation workflow based on a parameterized model integrated into the DesignXplorer environment. This approach was applied to the studied roller, utilizing the major semi-axis (R) of the generating ellipsoid and the relative position of the support along the roller's entire length as primary input parameters. The integration of parameterized FEA ensures a robust optimization framework for future Mecanum wheel designs, bridging the gap between theoretical contact models and practical engineering applications for both industrial and tactical UGVs.

The most significant practical implications derived from this analysis pertain to the influence of roller curvature on the contact area variation. It was observed that a smoother curvature, corresponding to a higher value of the major semi-axis (R) of the generating ellipsoid, causes the roller to converge toward a cylindrical geometry. This geometric shift leads to an expansion of the contact area, subsequently resulting in a substantial reduction in the peak contact pressure. Consequently, from a design perspective, it is desirable to minimize the roller's curvature to ensure lower contact pressure values. Such an optimization would directly enhance the mobility and structural load capacity of industrial AGVs or tactical UGVs with such propulsion system.

Furthermore, the study highlights important findings regarding the migration of the contact ellipse along the roller's axis. The analysis confirms that during the operation of a Mecanum-wheeled AGV/UGV, the rollers engage with the running surface across their entire longitudinal span. Numerical results indicate that the contact area decreases as the interaction point approaches the roller's extremities, leading to a localized increase in contact pressure. This variation along the roller's length has a dual impact: first, it affects the vehicle's dynamic performance through inconsistent traction and second, it significantly reduces the component's operational lifespan. The resulting non-uniform wear patterns, driven by these pressure gradients during motion, necessitate careful material selection and geometric calibration to ensure long-term reliability in both industrial and tactical environments.

6. FUTURE RESEARCH DIRECTIONS

Building upon the static contact maps established in this study, future research will transition toward transient simulations to evaluate the impact of rolling friction and centripetal forces on the contact footprint. A primary objective is to investigate the acoustic signature and vibrational profiles generated during the roller-to-roller load transfer.

Furthermore, future investigations will explore the integration of non-linear

hyperelastic material models (such as Mooney-Rivlin or Ogden) to more accurately reflect the behavior of advanced polyurethane composites under extreme thermal gradients. This will be coupled with wear evolution modeling to predict the degradation of the roller's profile over extended operational cycles. By correlating localized pressure peaks with material loss rates, we aim to develop a predictive maintenance framework that optimizes the replacement intervals for Mecanum wheels.

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Performanța mecanică și analiza contactului hertzian a UGV-urilor cu roți Mecanum: o abordare bazată pe metoda elementului finit

Rezumat: În cadrul Industry 5.0 și al autonomizării crescânde a sistemelor logistice, platformele cu roți Mecanum reprezintă un reper pentru mobilitatea omnidirecțională. Pe măsură ce operațiunile militare contemporane integrează tot mai mult tehnologii autonome, vehiculele terestre fără echipaj (UGV) echipate cu roți Mecanum oferă manevrabilitate sporită pentru logistica tactică și operațiunile la interior. Având în vedere extinderea utilizării lor în aplicații ce necesită o sarcină utilă ridicată, este necesară o înțelegere riguroasă a comportamentului contactului roată–sol. Studiul analizează mecanica de contact hertziană a rolelor Mecanum prin analiza cu elemente finite (FEA) realizată în ANSYS Workbench. Sunt evaluate distribuția tensiunilor și deformațiile la sarcini ridicate, evidențiind influența asupra integrității structurale și preciziei odometrice. Rezultatele sprijină proiectarea unor platforme omnidirecționale robuste, de înaltă precizie, pentru aplicații duale.

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