U.P.B. Sci. Bull., Series D, Vol. 79, Iss. 2, 2017 ISSN 1454-2358

MECANUM WHEEL MODELING FOR STUDYING ROLLER-GROUND CONTACT ISSUES

Tiberiu GIURGIU[1], Constantin PUICĂ[2], Cristina PUPĂZĂ[3], Florin-Adrian NICOLESCU[4], Miron ZAPCIU[5]

Today industrial and technical fields are more and more dependent on automation and autonomous systems. The idea of replacing human intervention with robotics or self-guided structures is preferred especially in the domains requiring repetitive actions and a high quality of the work. Regarding industrial applications, Autonomous Ground Vehicles - AGVs are already used at a large scale, but studies to improve their mobility and stability are still needed due to their design models diversity. The paper deals with a particular case of Mecanum drive train for industrial AGVs studying the contact between Mecanum wheels and the running surface through FEM analysis.

Keywords: industrial AGV, Mecanum wheel, mobility, rubber, simulation, FEM

1. Introduction

Industrial logistics has become very important in the management of an enterprise. At present requirements are related to totally control the raw and finite materials flow, from their supplying to the factory until the final product's exit. This purpose can be achieved by implementing Autonomous Ground Vehicles – AGVs environments, in order to replace or to reduce human intervention in particular areas in the manufacturing flow. The benefits of this automated environment are translated in:

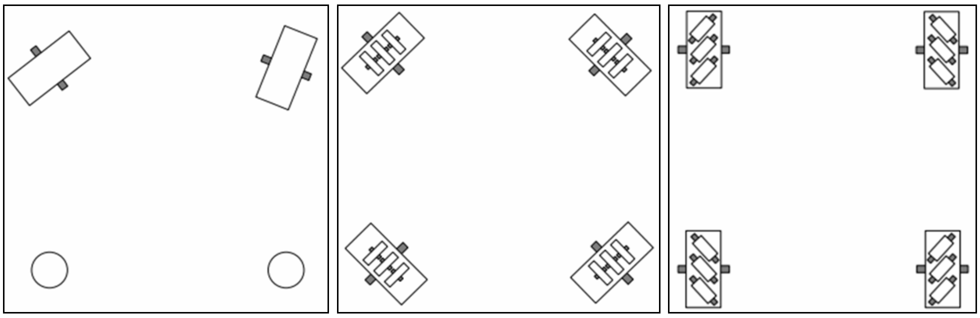
- greater productivity;
- higher flexibility;
- continuous manufacturing flow;
- dead times reducing;
- better work quality – by eliminating human subjective influence.

[1] PhD student, Faculty of Engineering and Management of Technological Systems, University POLITEHNICA of Bucharest, Romania, e-mail: giurgiutiberiu@yahoo.com
[2] Dipl. eng., Test, Evaluation and Scientific Research Weapons Systems Centre, Military Equipment and Technologies Research Agency, Romania, e-mail: cpuica@acttm.ro
[3] Prof., PhD, Machines and Manufacturing Systems Department, University POLITEHNICA of Bucharest, Romania, e-mail: cristinapupaza@yahoo.co.uk
[4] Prof., PhD, Machines and Manufacturing Systems Department, University POLITEHNICA of Bucharest, Romania, e-mail: afnicolescu@yahoo.com
[5] Prof., PhD Coordinator, Machines and Manufacturing Systems Department, University POLITEHNICA of Bucharest, Romania, e-mail: miron.zapciu@upb.ro

AGVs are high precision, safe, efficient, flexible and fast. Therefore they represent the perfect solution for logistic purposes in any field, but especially in industrial applications. According to [1], global new demands for Autonomous Ground Vehicles were about 16,000 units in 2015, up to 35% more than in 2014. Moreover, 4,280 units– or 27% of the global total, were directed in China, rising by 36% from the year before, largely due to small factory area, fast task time, and fading demographic dividend. It is expected that China's new demand will hit 22,000 units in 2020.

One of the most important characteristic of an AGV is the ability to move in a complex and usually crowded working space. For example, on an assembly line from the automotive industry, a guided vehicle could accomplish requirements related to transportation of different parts or components from a point to another by traveling along the assembly line. Because of space economy requirements, usually the workspace provides narrow paths between fixed components or systems. Therefore mobility, maneuverability and stability of AGVs in such an environment, represent real issues that still need improvements.

Regarding AGVs mobility, there are two major types of drives: traditional drive and omni-directional drive. Also, omni-directional drive can be split into holonomic drive and Mecanum drive (see Fig.1.). As presented in [2], the advantages of omni-directional wheels are related to the ability of AGV to move rapidly in any direction without having a steering system.



a b c

Fig.1. AGV types of drive: a) serve drive; b) holonomic drive; c) Mecanum drive [2]

Omni-directional AGVs usually have four wheels which consist in a central rim and a number of rollers (6, 8, 12, 15 etc.) disposed at a certain angle on its circumference. The rollers angles of holonomic wheels are 90 degrees against the traveling direction and 45 degrees in the case of Mecanum wheels. In order to move in the desired direction, the AGV should be equipped with electric motors for each Mecanum/holonomic wheel. Regarding the possible motions of an AGV equipped with Mecanum wheels, in [3] were presented in detail some scenarios and summarized in Fig.2.

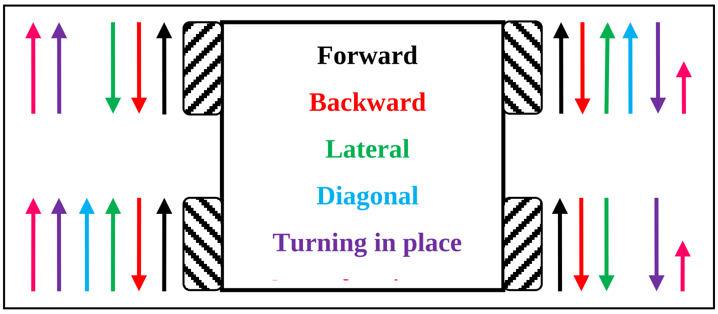


Fig.2. AGV motion according to the direction and angular speed of the wheels

Most of the studies [2] are conducted to analyze issues related to the command and control of AGVs with Mecanum wheels, path optimization, or guiding methods in a specific work space. There are also several papers [6] that present authors work on improving the mobility of this kind of robots and on vibration and noise reduction, mostly by redesigning the wheels, in order to obtain a smoother and continuous contact of the Mecanum wheel with the ground. In [6] the study presents the influence of the shape and curvature of the rollers using dynamic simulations and a solution of fork support for the rollers that works as a suspension system when the wheel is loaded.

Though, there are only few authors that analyze the contact between the rollers and the running surface by using the Finite Element Method (FEM) in order to see the behavior of different materials, or the influence of the exterior layer thickness of the roller. In [10], the authors present the strength and fatigue failure analysis for the Mecanum wheel parts using FEM, considering different working conditions of the wheel. Their paper also highlights the maximum values of stress and deformation of roller, roller spindle and hub frame in two situations: when the middle of the roller touches the ground and when one of the ends touches the ground.

Similarly, in [11], the authors present FEM analysis results on an omni-directional wheel with rollers disposed at 90 degrees against the forward travelling direction. The rigid-flexible dynamic simulations were performed in Recurdyn software and results regarding the vibration were obtained. The shape design of their CAW5 (Continuous Alternate Wheel with 5 rollers set) allowed to consider only a quarter of each roller surface as being a flexible body. This was possible because when the omni-robot moves forward the rollers rotational velocity is zero, so the contact with the running surface always occurs in this area. The other parts of the rollers were defined as rigid bodies, so the model is efficient when considering computation times. In contrast to CAW5, Mecanum wheels do not offer this possibility as the rollers are rotating freely when the AGV travels in longitudinal direction.

2. Mathematical approach

2.1. Multi-Body Dynamics (MBD)

The Rigid Dynamics tool in ANSYS Workbench offers the possibility to study the motion of the assemblies of undeformable bodies that can move rigidly in tridimensional space. The free motion of bodies is restrained by joints, which are characterized by the degrees of freedom (DOF) that they allow between the connected bodies.

The output quantities of the MBD study are the forces that develop in the joints and are transmitted to the rigid bodies, as opposed to a structural analysis where the output quantities are strains or stresses. MBD analysis is based on the Runge-Kutta method [14], which represents an algorithm for explicit and implicit iterative methods that are used in temporal discretization for the approximation of solutions of ordinary differential equations. The fourth order method is based on four estimations. Given an initial value *y* at time value *t*, and a time step value *dt*, the following estimations may be expressed as:

$$\dot{y}_1 = f(y,t) \tag{1}$$

$$\dot{y}_2 = f\left(y + \frac{dt}{2}\dot{y}_1, t + \frac{dt}{2}\right) \tag{2}$$

$$\dot{y}_3 = f\left(y + \frac{dt}{2}\dot{y}_2, t + \frac{dt}{2}\right) \tag{3}$$

$$\dot{y}_4 = f\left(y + dt\,\dot{y}_3, t + dt\right) \tag{4}$$

A fourth order approximation of $y(t+dt)$ is given by:

$$y(t+dt) \cong y + \frac{dt}{6}\left(\dot{y}_1 + 2\dot{y}_2 + 2\dot{y}_3 + \dot{y}_4\right) \tag{5}$$

The time step *dt* must be chosen carefully for the integration of the ordinary differential equations to ensure that it is stable and accurate, which means the difference between the approximation of the solution and the exact solution is controlled.

2.2. Transient Structural - Hyperelastic materials

ANSYS software offers a series of hyperelastic materials which can be selected from its library accessing Engineering Data tool. As written in [12], the models that are commonly used in nonlinear contact analysis are:

- Neo-Hookean: strain < 30% (1 parameter);
- Mooney-Rivlin: strain < 100% or 200% (2 and 3 or 5 and 9 parameters);
- Polynomial Form: strain < 300% (3rd order);
- Arruda Boyce and Gent: strain < 300% (2 parameters);

– Yeoh model: strain < 300 % (3rd order);
– Ogden model: strain < 700 % (3rd order).

The Odgen material model which was considered for this analysis (Rubber1 from ANSYS library) assumes that the material behavior can be described by means of a strain energy density function, from which the stress-strain relationship can be derived. The Ogden form [13] is based on the principal stretches of the left Cauchy-Green tensor. The strain energy potential is:

$$W = \sum_{i=1}^{N} \frac{\mu_i}{\alpha_i}\left(\bar{\lambda}_1^{\alpha_i} + \bar{\lambda}_2^{\alpha_i} + \bar{\lambda}_3^{\alpha_i} - 3\right) + \sum_{k=1}^{N} \frac{1}{d_k}(J-1)^{2k} \tag{6}$$

where:

- W – strain energy potential
- $\bar{\lambda}_p (p = 1,2,3)$ – deviatoric principal stretches, defined as $\bar{\lambda}_p = J^{-\frac{1}{3}}\lambda_p$
- λ_p – principal stretches of the left Cauchy-Green tensor
- J – determinant of the elastic deformation gradient
- N, μ_p, α_p and d_p – material constants

The initial shear modulus expression is:

$$\mu = \frac{1}{2}\sum_{i=1}^{N} \alpha_i \mu_i \, . \tag{7}$$

The initial bulk modulus is defined by:

$$K = \frac{2}{d_1} \, . \tag{8}$$

3. Mecanum wheel design, materials and applicability

As presented before, a Mecanum wheel - also known as “Swedish wheel” from its first inventor – Bengt Ilon [9], consists in a central rim and a number of rollers disposed on its circumference, oriented at an angle of 45° relative to the wheel axis of rotation. Three types of wheel design are exposed in Fig.3 as they were identified on the international market [15], with details regarding the dimensions, carrying capacity or materials that are used (see Table 1).

a b c

Fig.3. Mecanum wheels identified on international market: a) Nexus© 203 mm lightweight wheel; b) Nexus© 254 mm heavy-duty wheel; c) HANGFA© 310 mm super heavy-duty wheel

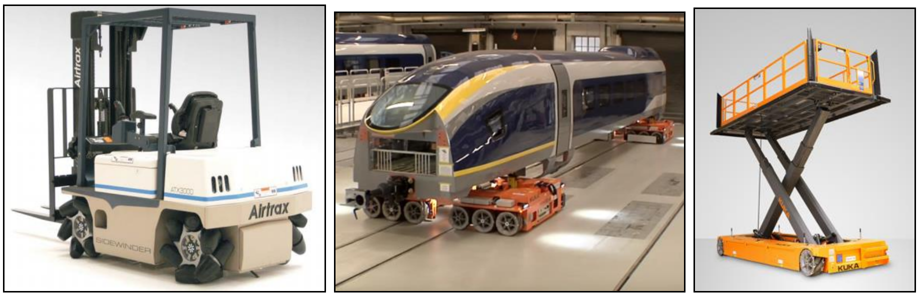
Table 1

Main parameters of Mecanum wheels

Supplier	Diameter (mm)	Width (mm)	Self-weight (kg)	Carrying capacity (kg)	Number of rollers	Materials	
						Rim	Rollers
NEXUS©[15]	203	78	2.4	50	12	Aluminum	Nylon/Rubber
	254	128	15	375	8	Stainless steel	Steel core and polyurethane
HANGFA©	310	150	16	600	14	High strength aluminum	Polyurethane

As presented in Table 1, usually the Mecanum wheel rim is made of metal and the rollers, or at least their covering material, are either polyurethane or rubber. Depending on the carrying capacity, working environment and applicability, the material parameters and dimensions of the wheels may vary significantly.

For this study two Mecanum wheels were chosen from Nexus© producer [15], both with 203 mm diameter, but with different maximum loading capacities: 50 respectively 250 kg. If the first can be used in robotics or light-weight special vehicles – wheelchairs for example, the heavy-duty one can easily equip an industrial AGV designed to carry parts from a point to another along the assembly line of an automotive factory. Other possible industrial applications for Mecanum wheels identified on the international market are presented in Fig. 4.



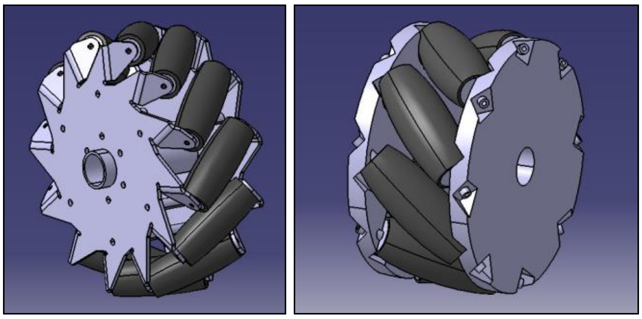
a b c

Fig.4. Mecanum wheel industrial applications: a) Airtrax© fork-lifter [17];b) Kuka© omnidirectional platforms [18]; c) Kuka© flexible lift [18]

4. CAD models of Mecanum wheels

The two studied wheels were chosen from Nexus© products list [15], not only because of the consistent technical information offered by the producer, but also in order to allow including experimental data in future analysis attempts. The 3D models of the wheels achieved in CATIA V5 are presented in Fig.5. In order to reduce the computation time in the FEM analysis, the models were simplified.

Therefore, all bearings, bolts and nuts were eliminated. Moreover, only a 3 mm thick layer of elastic material has been considered from the same reasons. Though, the values of the masses of the two Mecanum wheels, after adding materials from the software library, were respected: ~2.4 kg and 8 kg respectively.



a b

Fig.5. 3D models of Mecanum wheels: a) light-weight b) heavy-duty

5. Simulation of the Mecanum wheel behavior using ANSYS

4.1 Rigid Dynamics

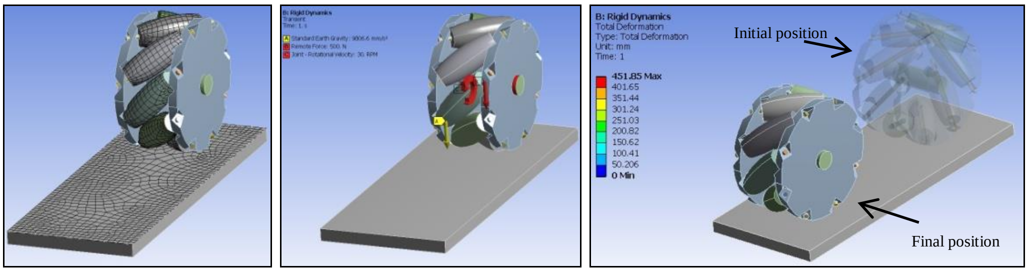
For this analysis the heavy-duty wheel was chosen, due to its compact design and because it has only 8 rollers instead of 12, as in the light-weight wheel situation. Therefore the number of joints and contacts that need to be defined (see Table 2) is smaller, so the simulations are easier to be performed, with more reasonable calculation times.

Table 2

Connections definition for MBD

Connections	Type	Affected parts		Connections number
		Reference/Target	Mobile/Contact	
Joints	Fixed	Rollers spindles	Rollers	8
		Ground	Running surface	1
	Revolute	Rim	Rollers spindles	8
		Wheel hub	Rim	1
	General	Ground	Wheel hub	1
Contacts	Forced Frictional Sliding	Running surface	Rollers	8

Because in Rigid Dynamics the mesh is generated only for the faces that are defined as being in contact with other parts, only 10,873 nodes and 3,430 elements resulted. In Fig. 6 are presented the meshed parts, the conditions imposed for this simulation and also the initial and final positions of the moving wheel. The exterior loads applied to the wheel are: gravitational force, a vertical load of 500N and 30 rpm angular velocity. The purpose of the MBD analysis is to study the behavior of the rollers during and after the contact with the running surface and also the influence of the frictional coefficient over the entire motion of the Mecanum wheel.



a b c

Fig.6. a) Meshed parts; b) Motions and loads; c) Initial and final position of the wheel

The vertical behavior of the wheel hub during a complete rotation of the Mecanum wheel when a 30 rpm rotational velocity was imposed is presented in Fig.7. This plot offers a good picture on the wheel vibrations caused by the discontinuous contact of the 8 rollers with the running surface.

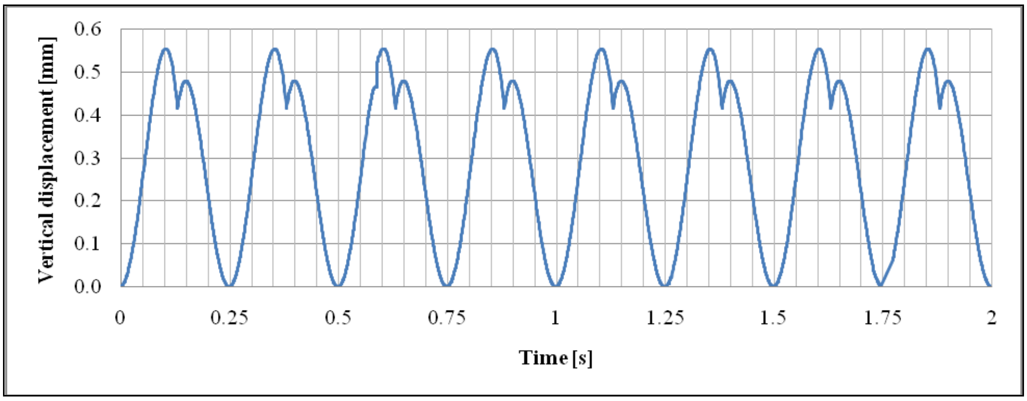


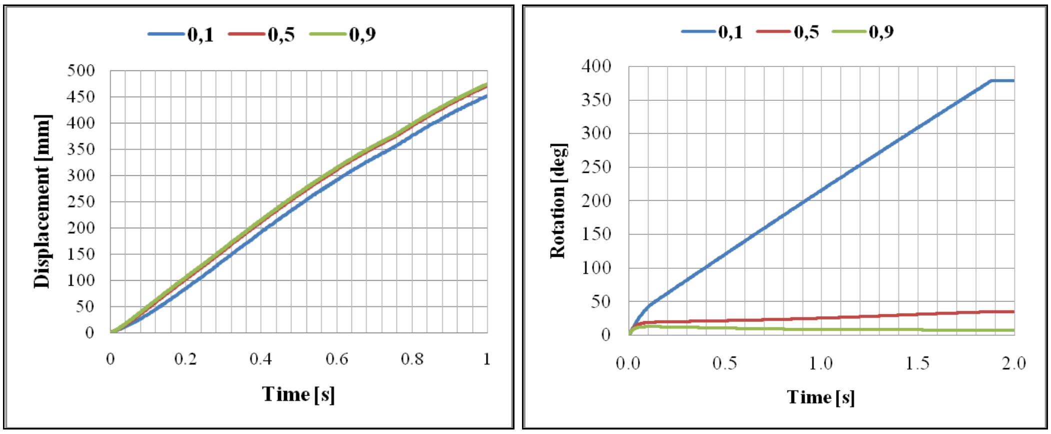
Fig.7. Wheel hub vertical displacement during one rotation of the Mecanum wheel

For this study, three different values for the friction coefficient were chosen in order to see their influence on the motion and behavior of the wheel and its rollers: *0.1* (plastic vs. concrete), *0.5* (polyurethane vs. concrete or steel) and *0.9* (rubber vs. concrete/asphalt). Therefore in Fig. 8 two phenomena are exposed:

– the influence of the friction on longitudinal displacement during 1s;

– the influence of the friction on the rotation of the roller for the initial contact, during a complete rotation of the Mecanum wheel (2s).

Analyzing the two plots, it can be observed that the growth of the frictional coefficient gives better traction and smaller rotational inertia of the rollers when the Mecanum wheel works at 30 rpm rotational velocity.



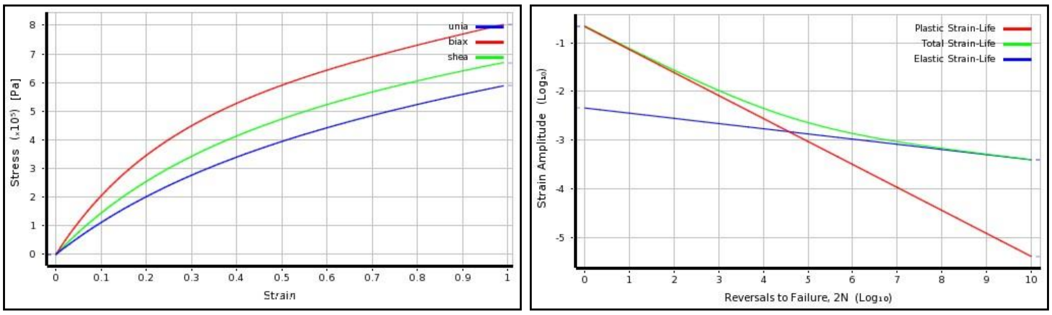
a b

Fig.8. Frictional coefficient influence at 30 rpm rotational velocity on:
a) Maximum displacement in longitudinal direction, b) Rotation of the roller in initial contact

4.2 Transient Structural Analysis

The next step was to import the results from the MBD analysis and to prepare the models for the Transient Structural analysis. Materials, meshing procedures, contacts and joints were established in the pre-processing phase (see Fig. 10.). In order to perform a transient simulation the forces and motions need to be defined and analysis settings must be carefully adjusted to obtain a good convergence, as the Transient Structural analysis requires significantly higher calculation times than the Rigid Dynamics case.

Regarding the exterior layer of each roller, it has to be made of a wear resistant and elastic material, with good adherence properties in order to assure traction. As presented in Table 1 - rubber, nylon and polyurethane are most commonly used for this type of rolling components. Therefore, “Rubber1” from ANSYS material library was chosen for the exterior layer of the rollers and “Structural steel” for the other parts of the two Mecanum wheels (see fig. 9).



a b

Fig.9. Materials mechanical properties: a) Rubber1; b) Structural Steel

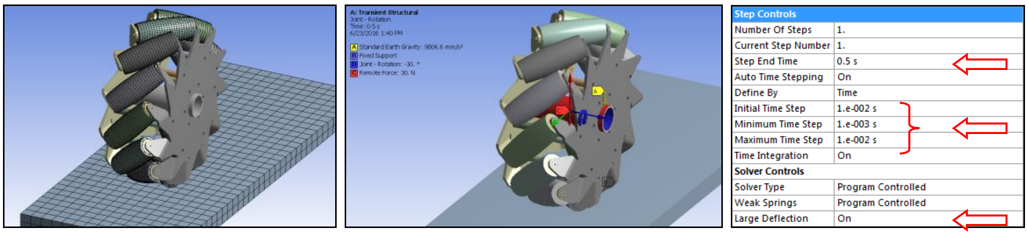
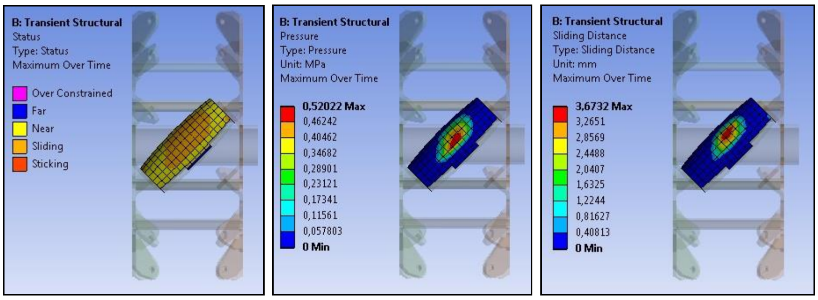


Fig.10. Light-weight Mecanum wheel – Pre-processing phase in ANSYS Workbench

Because the main purpose is to study the behavior of the elastic parts of the rollers, a rigid-flexible analysis was chosen. In this case, the rim and all other metallic parts were defined as rigid bodies and only the exterior layer of the rollers was defined as a flexible body. This procedure is very helpful as it significantly reduces the calculation time. In Fig. 10 it can be noticed that only the flexible parts were meshed, obtaining 88,503 nodes and 15,569 elements, more than 50% less as in the entirely flexible model case. In order to improve the accuracy of the results the mesh was successively refined and tuned with the computation time, as well.



a b c

Fig.11. Roller-ground contact analysis: a) Status; b) Pressure; c) Sliding distance

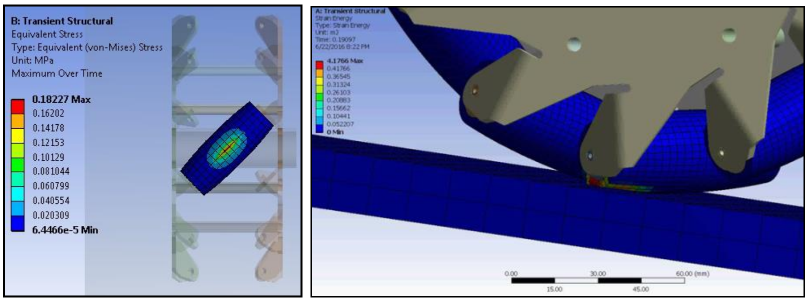


Fig.12. Equivalent Stress and Strain Energy at ~ 0.2s

The results of the simulation at maximum values time are presented in Fig. 11, highlighting the contact patch phenomena that occurred. The status of the roller in contact with the running surface, the contact pressure and the sliding distance are the parameters of high interest in this type of analysis. The Equivalent

Stress and the Strain Energy are presented in fig. 12, where it can also be noticed the deformation of the rubber material at the real scale.

The results of the simulation at the imposed loads (gravitational force, 30 N vertical load and 30 rpm angular velocity) give us the following information:

- the value of Equivalent Stress (0,18 MPa) is far below the ultimate tensile strength of rubber (~20 MPa);
- the simulation results regarding the area of contact were compared with preliminary analytical computations and the error was less than 3%. For a more precise determination of the contact area, the mesh density can be further increased;
- the contact area between the roller and the running surface represents an ellipse, with major radius oriented along the roller's axis of rotation. Though, the ellipse shape is deformed as the wheel is also sliding in diagonal direction due to 45 degrees orientation of the roller;
- the "Rubber1" material chosen from ANSYS library proves to be too deformable for this kind of applications, even at small loads imposed to the Mecanum wheel. Therefore, other materials should be considered for further research.

6. Conclusions and further research

The paper presents a particular case of omni-directional drive system for industrial Autonomous Ground Vehicles, giving more insights on Mecanum wheels – ground contact issues. If most of the literature in this area offers analytical and experimental information regarding the kinematics, command and control of this type of AGVs or robots, this study was conducted to highlight the influence of frictional coefficient on the wheel behavior in motion and the importance of materials, shape and thickness of the Mecanum wheel's rollers covering layer when running on a flat surface.

The results offer new insights on modeling and simulation of the Mecanum wheels, including information regarding the frictional contact in the kinematic analysis. Concluding results were also achieved in the Rigid Dynamics environment, offering information on rollers behavior during a complete rotation of the Mecanum wheel.

Research on other rim-roller materials has to be performed, as "Rubber 1" from the software library has proven to be too deformable when higher loads are applied. This could be possible either by modifying an existing material in order to reduce its elasticity or by defining a new one based on experimental data. The shape of the rollers and the thickness of their covering material could also have a significant influence on the AGVs mobility in a specific industrial environment.

Acknowledgement

This work has been funded by the Sectorial Operational Programme Human Resources Development 2007-2013 of the Ministry of European Funds through the Financial Agreement POSDRU/159/1.5/S/138963

R E F E R E N C E S

[1]. *ResearchInChina*, Global and China AGV (Automated Guided Vehicle) Industry Report, 2016-2020, March 2016.
[2]. *F. Adăscăliței and I. Doroftei*, Practical Applications for Mobile Robots based on Mecanum Wheels - a Systematic Survey, Proceedings of International Conference On Innovations, Recent Trends And Challenges In Mechatronics, Mechanical Engineering And New High-Tech Products Development – MECAHITECH'11, **vol. 3**, 2011, pp. 112-123.
[3]. *I. Doroftei, V. Grosu and V. Spinu*, Omnidirectional mobile robot - design and implementation, Bioinspiration and Robotics: Walking and Climbing Robots, I-Tech Education and Publishing Vienna, September 2007, pp. 511–528.
[4]. *H. Chaojie*, Heavy-Duty Omni-directional Mecanum Mobile Robot, project number MT - 21, Department of Mechanical Engineering University of Auckland, 2013.
[5]. *V. Kálmán*, On modeling and control of omnidirectional wheels, PhD Dissertation, University of Technology and Economics, Budapest, 2013.
[6]. *J.-J.Bae and N. Kang*, Design optimization of a Mecanum wheel to reduce vertical vibrations by the consideration of equivalent stiffness, Hindawi Publishing Corporation − Shock and Vibration, **vol. 2016**, Article ID 5892784.
[7]. *J.-B. Song and K.-S. Byun*, Steering control algorithm for efficient drive of a mobile robot with steerable omni-directional wheels, Journal of Mechanical Science and Technology, **vol. 23**, no. 10, pp. 2747–2756, 2009.
[8]. *D.B. Harris*, Low vibration omni-directional wheel,US Patent No.6,340,065 B1, 2002.
[9]. *B.E. Ilon*, "Wheels for a course stable selfpropelling vehicle movable in any desired direction on the ground or some other base," US Patent No. 3,876,255, 1975.
[10]. *S. Kang, X. Zhang and Y. Xie*, Mechanics Analysis of Omni-Directional Mecanum-Wheel Based on FEM, Applied Mechanics and Materials, Trans Tech Publications, **vols. 271-272**, pp. 1012-1016, Switzerland, 2013.
[11]. *Y.K. Park, P. Lee, J.K. Choi and K.-S. Byun*, Analysis of factors related to vertical vibration of continuous alternate wheels for omnidirectional mobile robots, Intelligent Service Robotics, **vol. iss. 2016**.
[12]. *Y. Gorash, T. Comlekci and R. Hamilton*,CAE-based application for identification and verification of hyperelastic parameters, Proceedings of the Institution of Mechanical Engineers, Part L: Journal of Materials: Design and Applications, 2015.
[13]. *R.W. Ogden, G. Saccomandi and I. Sgura*, Fitting hyperelastic models to experimental data, Computational Mechanics, **vol. 34**, pp 484-502, 2004.
[14]. ***ANSYS® User's Guide, SAS IP, Inc., 2011.
[15]. *** *http://www.nexusrobot.com/*
[16]. *** *http://www.hangfa.com/*
[17]. *** *http://www.airtrax.com/*
[18]. *** *http://www.kuka-robotics.com/en/*