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KINEMATIC ANALYSIS OF OPENING AND CLOSING ROOF MECHANISM FOR LOADING FREIGHT WAGON

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Abstract

Input kinematic parameters during the movement of the mechanism for opening and closing the roof of Tagnpps 95 m^3 wagon were analyzed. This included studying all components including the steering wheel, motion transmissions, and the roof of the wagon. The process of creating a 3D model of the mechanism for opening and closing the wagon roof in SolidWorks software is described, as well as the procedure of kinematic analysis of the mechanism in SolidWorks Motion. The manual force required to operate the mechanism for opening and closing the roof is calculated. To optimize the existing mechanism, the case of replacing the current reducer gear with a reducer of a smaller gear ratio is taken into consideration.

Keywords:

Freight wagon, mechanism, kinematics, SolidWorks

1 INTRODUCTION

Rail transport is a cornerstone of modern logistics and freight movement, offering a cost-effective, efficient, and environmentally friendly alternative to road transport. In this context, the design and optimization of freight wagons play a crucial role in enhancing the capabilities of the rail network. One such innovation is the Tagnpps 95m³ freight wagon, designed specifically for the transportation of agricultural products such as grains. These wagons are equipped with a mechanism that allows for the manual opening and closing of the roof, facilitating efficient loading and unloading processes.

This study delves into the kinematic analysis of the roof mechanism of the Tagnpps 95m³ freight wagon. The objective is to understand the mechanical behavior and performance characteristics of the mechanism during its operation. The mechanism's design, modeled and analyzed using SolidWorks software, is crucial for ensuring the reliability and efficiency of the loading and unloading processes. The study aims to optimize the mechanism for smoother and more efficient operation by evaluating the kinematics.

Recent studies of J Vavro jr. et al. [1] have demonstrated the significance of kinematic and dynamic simulations in optimizing the performance of the six-item planar mechanism. For instance, in their study, Nedelcu et al. [2] extensively analyzed the crank mechanism using SolidWorks Motion, which facilitated precise modeling and simulation of the mechanism's movements and forces.

Imamović et al. [3] utilize SolidWorks and SAM to perform kinematic analysis of complex mechanisms, illustrating how these tools facilitate the visualization of motion parameters including trajectory, velocity, and acceleration.

Sattar et al. [4] applied kinematic and dynamic analysis to a double-scissors link deployable mechanism for space antennas, utilizing SolidWorks, ADAMS, and MATLAB to simulate velocities and accelerations of the antenna components.

Wang et al. [5] proposed a new inverse kinematic model to quantify the relationship between the telescoping movements of cylinders and shield machine motions.

Through this investigation, the paper contributes to the broader effort of enhancing freight wagon design, aligning with the ongoing investment in rail infrastructure and equipment. This is particularly relevant in the context of Croatia's plans to revitalize its railway sector, aiming to make rail transport a preferred mode for both passenger and freight services.

2 DESIGN AND MODELING OF THE ROOF MECHANISM

The Tagnpps 95 m³ freight wagon is a specialized vehicle designed to transport bulk agricultural products, particularly

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grains. The efficiency of this wagon's operation largely depends on the effective functioning of its roof mechanism, which allows for easy and safe loading and unloading. This section details the design and modeling process of the roof mechanism, emphasizing the steps taken to create a functional and reliable system.

Fig. 1: Tagnpps 95 m³ freight wagon

2.1 Overview of the Tagnpps 95 m³ Wagon

The Tagnpps 95 m³ wagon is characterized by its large loading capacity and specialized features tailored for bulk goods. The name Tagnpps is derived from the UIC (International Union of Railways) classification system, which provides detailed designations for various types of freight wagons. The designation Tagnpps can be broken down as follows:

- T: Wagon with opening roof.
- a: Indicates that the wagon has four axles.
- g: Denotes that the wagon is suitable for the transport of grains or other bulk goods.
- n: Indicates that the wagon has a payload of over 60 tons.
- pp: Represents that the wagon has a gravitational axial operated unloading, from the underside.
- s: Specifies that the wagon is designed for high-speed service (maximum 100 km/h).

The Tagnpps wagon is intended for the transport of agricultural commodities, primarily wheat and similar grain products sensitive to weather conditions. The cargo area is protected by a hard roof, which rotates to one side when opened. The loading opening spans the entire length of the wagon and is covered by the movable roof. The roof can be manually operated from a platform using a manual opening mechanism. To ensure parallel guidance of the roof on both sides, rotating wheels connected by a shaft are installed. Springs attached to the roof supports are mounted at the ends of the wagon to balance the roof for easier handling.

The wagon's body is a self-supporting, prismatic-shaped structure reinforced with stiffeners along the sides and ends. The loading opening is strengthened with bent profiles. Unloading is performed through two bottom openings by gravity. Each opening has a slide gate that is also operated manually. The grains are directed into underground unloading bins via chutes. With a volume of 95 m³ and a payload of about 70 tons, the Tagnpps wagon offers high cargo security from external influences, combined with ease and ergonomics in loading and unloading processes. Key components of the wagon during the production phase at ‘Đuro Đakovic Special Vehicles’ in Slavonski Brod can be seen in figure 2.

Fig. 2: Wagon's body

2.2 SolidWorks Modeling Process

To understand and optimize the roof mechanism, a detailed 3D model was created using SolidWorks software [6]. The modeling process involved several steps:

Initial Sketching and Conceptual Design: The initial stage involved creating sketches of the roof and its supporting structure. This conceptual design helped in visualizing the overall layout and identifying the key components of the mechanism.

Detailed Component Modeling: Each part of the mechanism, including the roof panels, hinges, and support arms, was modeled in SolidWorks. Careful attention was paid to ensure that the dimensions and connections accurately reflected the real-life design.

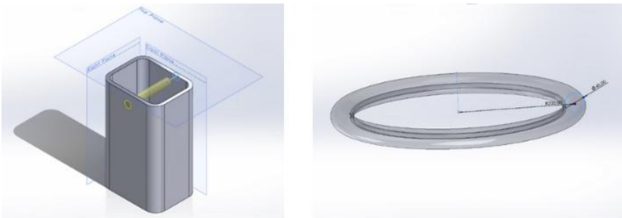

Fig. 3: Mechanism parts

Assembly and Constraint Definition: After modeling individual components, they were assembled into a complete mechanism. Assembly constraints were defined to simulate the real-world connections and movements, ensuring that the components interacted correctly during operation. In SolidWorks these assembly constraints are called ‘Mates’ and there are four categories of Mates: Standard, Advanced, Mechanical, and Analysis. Most positions are "mated" using standard mates: Concentric, Parallel, Perpendicular, Coincident, Limit Angle, and Limit Distance. From the Mechanical Mates category, the Gear mate was used, which specifies the gear ratio between gears.

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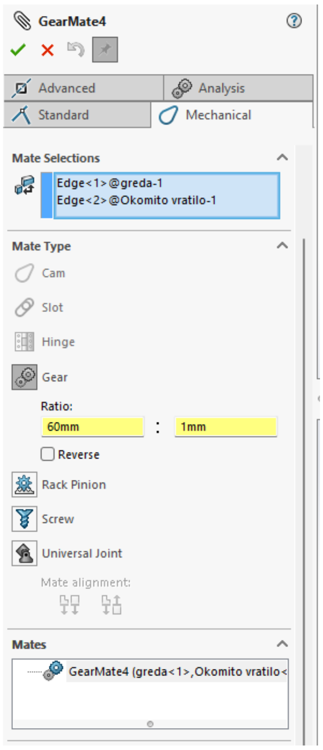

Fig. 4: Gear Mate

Simulation and Initial Testing: Preliminary simulations were conducted to test the movement and identify any potential issues in the design. This step was crucial for verifying that the mechanism could operate smoothly and without interference.

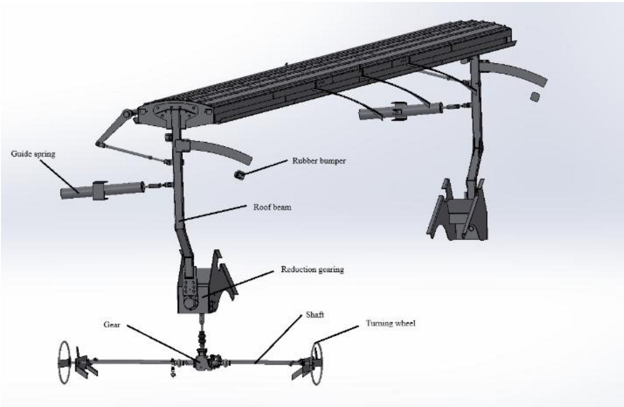

Fig. 5: Roof opening mechanism

The SolidWorks model served as the foundation for further kinematic analysis, providing a precise and manipulable representation of the roof mechanism.

2.3 Functionality of roof mechanism

This section provides a detailed description of the key components that ensure the smooth operation of the roof mechanism. The primary components are the rotating wheel, gear, reducer, and guiding spring.

2.3.1 Rotating wheel

The mechanism starts moving by manually turning the rotating wheel with a radius of 245 mm. The force applied to initiate movement should generate a moment not exceeding 100 Nm. This manual input is critical to ensure that the roof mechanism can be operated safely and effectively without overexerting the operator.

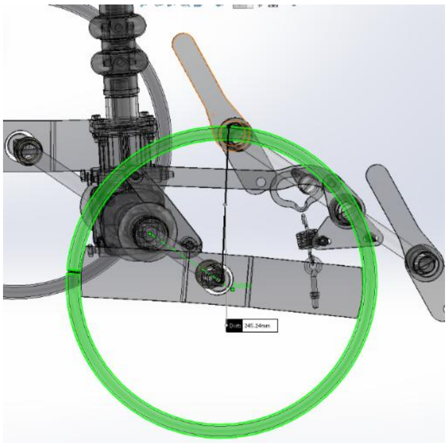

Fig. 6: Rotating wheel

2.3.2 Gear (Motion Transmission Gear)

As a result of the rotation of the rotating wheel, the horizontal shaft (shown in Fig. 7) rotates and enters a 1:1 ratio motion transmission gear, which drives the vertical shaft.

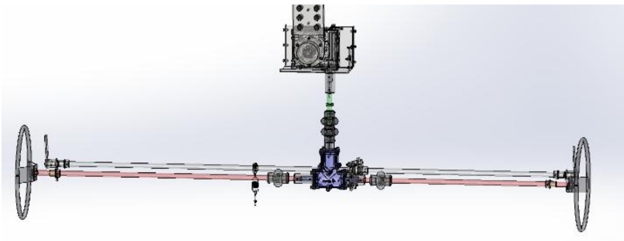

Fig. 7: Motion transmission gear

2.3.3 Reducer

The reducer is a critical component in the roof mechanism, designed to modify the speed and torque of the motion transmitted from the manual handle to the roof. It has a gear ratio of 60:1, which significantly reduces the input speed while increasing the output torque. This reduction ratio is essential for controlling the roof's movement more precisely and making the operation smoother and easier.

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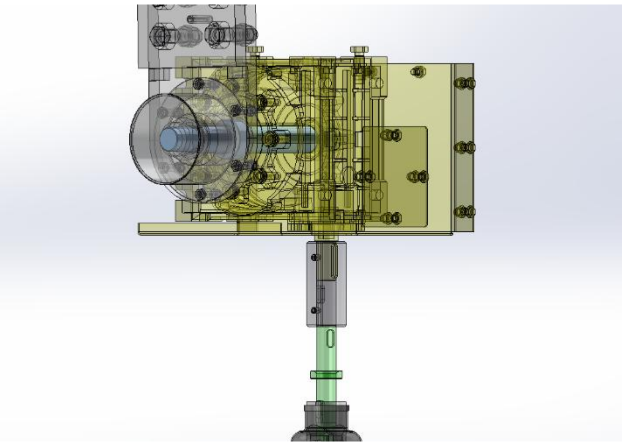

Fig. 8: Reducer

2.3.4 Guiding Spring

The guiding spring helps balance the roof, making it easier to handle during manual operations. It is mounted at the ends of the wagon and connected to the roof supports. This component aids in offsetting the weight of the roof, thereby reducing the manual force required to move it. The roof rotates through an angle of 22.3 degrees to achieve full opening. This movement is carefully controlled and limited by rubber bumpers, which serve to cushion the roof at the end of its travel and prevent damage.

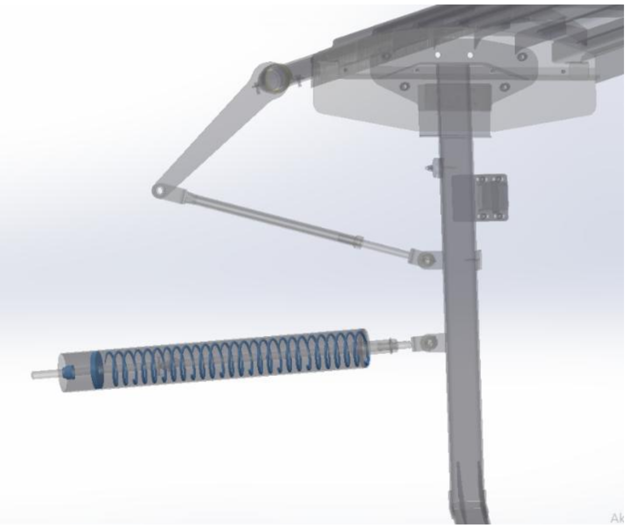

Fig. 9: Guiding Spring

2.4 Experimental data

A measurement was conducted in 'Đuro Đakovic Special Vehicles' to evaluate the real-world performance of the roof opening and closing mechanism (shown in Fig. 10). The time required to fully open and close the wagon roof and the angular rotation of the rotating wheel during that time were measured. During the process of opening, the rotating wheel completed 3.7 full turns over a period of 10 seconds to fully open the roof. During the process of closing, it took 8 seconds for the rotating wheel to complete same 3.7 full turns.

Fig. 10. Input kinematic parameters measurement on the roof mechanism of the wagon

Based on the measured data, the following calculations for opening the roof were made:

- Angular rotation of the rotating wheel:
$$\theta = 3{,}7 \times 2\pi = 23{,}248\ \mathrm{rad}$$
- Angular velocity of the rotating wheel:
$$\omega_1 = \frac{\theta}{t} = \frac{23{,}248}{10} = 2{,}32\,\frac{\mathrm{rad}}{\mathrm{s}}$$
(since the roof opening time is 10 seconds)
- Angular velocity of the roof beam:
$$\omega_2 = \frac{\omega_1}{60} = 0{,}0387\ \frac{\mathrm{rad}}{\mathrm{s}}$$
(since the reducer gearing has a ratio of 60:1)
- Roof displacement: calculated based on the angular velocity of the beam and time (measured length of the roof beam is r = 2277 mm)
$$v_1 = r \times \omega_2 = 0{,}0881\,\frac{\mathrm{m}}{\mathrm{s}}$$
$$x = v_1 \times t = 0{,}881\ \mathrm{m}$$

Based on the measured data, the following calculations for closing the roof were made:

- Angular rotation of the rotating wheel:
$$\theta = 3{,}7 \times 2\pi = 23{,}248\ \mathrm{rad}$$
- Angular velocity of the rotating wheel:
$$\omega_3 = \frac{\theta}{t} = \frac{23{,}248}{8} = 2{,}906\,\frac{\mathrm{rad}}{\mathrm{s}}$$
(since the roof closing time is 8 seconds)
- Angular velocity of the roof beam:
$$\omega_4 = \frac{\omega_3}{60} = 0{,}0484\ \frac{\mathrm{rad}}{\mathrm{s}}$$
(since the reducer gearing has a ratio of 60:1)
- Roof displacement: calculated based on the angular velocity of the beam and time (measured length of the roof beam is r = 2277 mm)
$$v_2 = r \times \omega_4 = 0{,}1102\ \frac{\mathrm{m}}{\mathrm{s}}$$
$$x = v_2 \times t = 0{,}881\ \mathrm{m}$$

These measured data were used as input parameters in kinematic analysis in SolidWorks Motion for obtaining the velocity and acceleration of the roof.

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3 KINEMATIC ANALYSIS OF THE ROOF MECHANISM IN SOLIDWORKS MOTION

This section provides how the kinematic analysis of the wagon's roof mechanism was conducted using SolidWorks Motion. The focus is on the setup and execution of the simulation, including the elements added to the model, the application of forces and constraints, and the analysis of the results.

3.1 SolidWorks Motion Setup

There are several types of motion studies in SolidWorks: Animation, Basic Motion, and Motion Analysis, with the latter being available only when the SolidWorks Motion add-in is activated.

- Animation: This is used solely for animating the movement of assemblies. Motors can be added to various parts of the assembly, primarily for presentation purposes, allowing the creation of video clips. However, it does not perform any calculations.
- Basic Motion: Provides an approximation of motor operations, springs, contact interactions, and the effects of gravity on the assembly, considering the mass of each part. It is useful for quick calculations and presenting animations based on physical laws.
- Motion Analysis: This is the most advanced option and becomes active when the SolidWorks Motion add-in is enabled. It offers robust computational support to accurately simulate and analyze the impact of motion elements such as motors, springs, forces, and friction. It considers mass and inertia and, upon completing the simulation, presents results in detailed diagrams.

Next, we define the settings for Motion Analysis. By clicking on the settings icon in the toolbar, a menu opens (see Figure 11.). The most crucial setting is the "Frames per second" option, which determines how many "ticks" or frames one second will be divided into. Setting a higher number will slow down the simulation but provide a more detailed calculation.

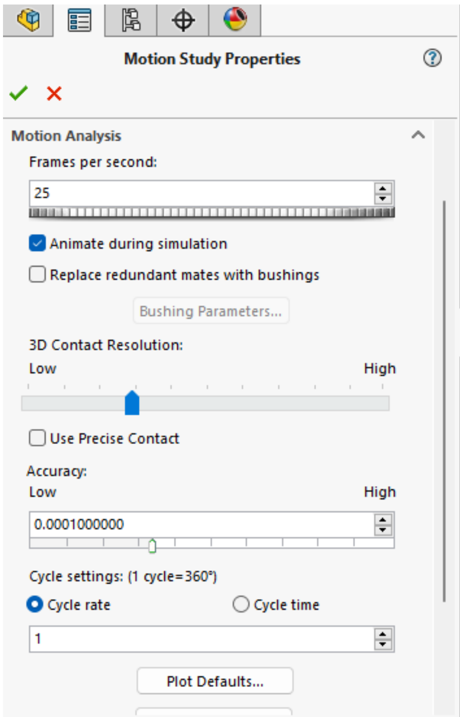

Fig. 11: Motion Study Properties

Utilization of Motion to simulate the kinematic behavior of the roof mechanism means adding and configuring several key elements to accurately replicate the movement and interactions of the components.

3.1.1 Rotational Motor

The motor needs to be set up on the rotating component, which in this case is either the rotating wheel or the horizontal shaft. There are three different types of motors available: a linear motor or actuator, a rotary motor, or a motor that follows a defined path. In addition to selecting the type, we must specify the driven component, whether the rotation is clockwise or counterclockwise, and whether a constant speed or oscillations are set. The final settings include the rotational speed or the time after which the motor will turn off.

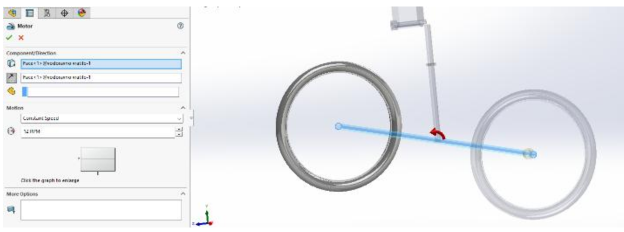

Fig. 12: Rotational Motor Properties

3.1.2 Gravitational force

The acceleration due to gravity is set by selecting the direction of the force's axis and the value of gravitational acceleration (allowing for the simulation of different gravitational acceleration value conditions if desired).

3.1.3 Spring Characteristics

The guiding spring, essential for counterbalancing the roof's weight, was defined in the simulation with its specific spring constants and damping properties. These characteristics

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ensure that the simulation accurately reflects the support and resistance provided by the springs during the roof's movement.

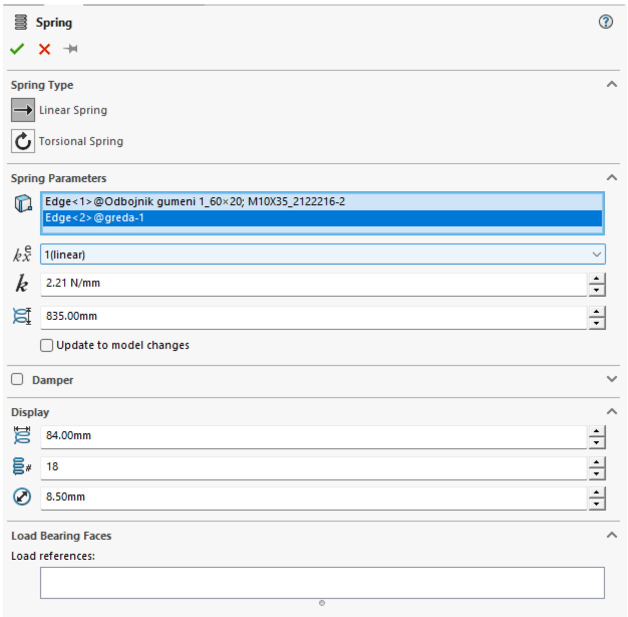

Fig. 13: Spring Characteristics

3.2 Simulation Execution and Data Collection

Once the elements were configured, the simulation was run to observe the kinematic behavior of the roof mechanism.

The software provides results individually for each axis in separate diagrams, focusing on a single point at a time. Therefore, it is crucial to mark key points, such as the highest point of the roof. This ensures that during the simulation, the velocities and accelerations of this point (the roof) are calculated and the trajectory of the roof's movement is displayed.

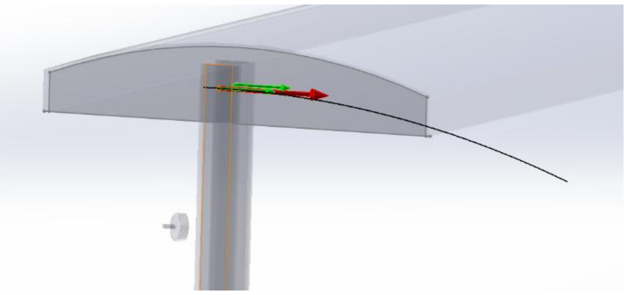

Fig. 14: Velocity and acceleration vectors

The results of the simulation were exported to Microsoft Excel for detailed analysis. This data included time-based records of the positions, velocities, and accelerations of the tracked points, providing a comprehensive view of the mechanism's kinematic behavior.

3.3 Analysis and Results Presentation

For the analysis, we examined two cases: the opening and closing of the roof. The velocities and accelerations were measured at the roof's highest point, which is of interest because it achieves the highest values of velocity and acceleration. The results are presented in diagrams with velocities in mm/s and accelerations in mm/s². These diagrams highlight the peak acceleration and velocity values for the roof's topmost point during both the opening and closing motions.

Case Study 1: Opening the Roof

During the opening sequence, the highest point on the roof was tracked to observe its kinematic behavior. The velocity and acceleration data revealed significant insights into the mechanism's performance.

- **Velocity Profile**: The maximum velocity reached was 129,36 mm/s
- **Acceleration Profile**: The peak acceleration recorded was 115,7 mm/s²

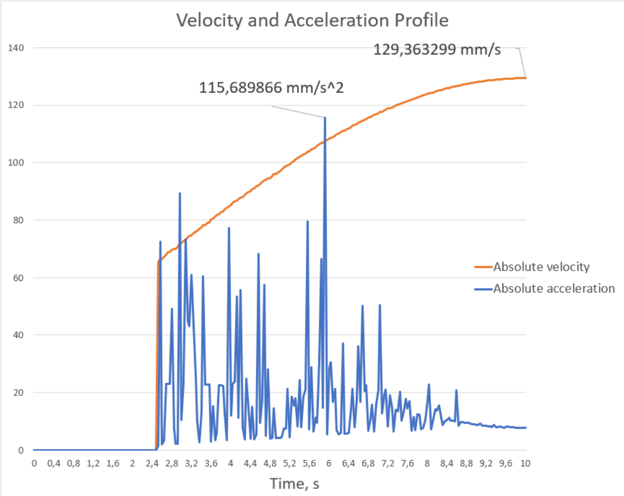

Fig. 15: Velocity and Acceleration Profile during Opening the Roof

Case Study 2: Closing the Roof

- Velocity Profile: The highest velocity during closing was 139,51 mm/s.
- Acceleration Profile: The maximum acceleration observed was 265,07 mm/s².

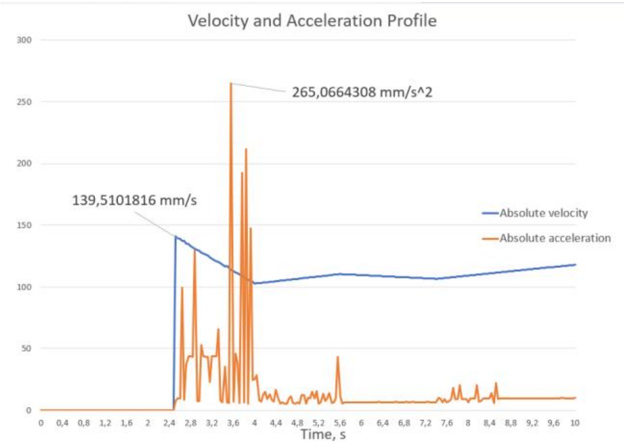

Fig. 16: Velocity and Acceleration Profile during Closing the Roof

The values shown in the previous diagrams correspond to the case of the reducer installed on the wagon, which has a gear ratio of 60:1. Additionally, we compare the performance with different gear ratios in the reduction

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mechanism: the original 60:1 ratio and a lower 30:1 ratio. This comparison helps us understand how changes in the gear ratio affect the velocities and accelerations at the highest point of the roof.

Case Study 3: Opening the Roof with Reduced Gear Ratio (30:1)

- Velocity Profile: the roof's opening saw a peak velocity of 136,97 mm/s.
- Acceleration Profile: The highest acceleration observed increased to 218,05 mm/s².

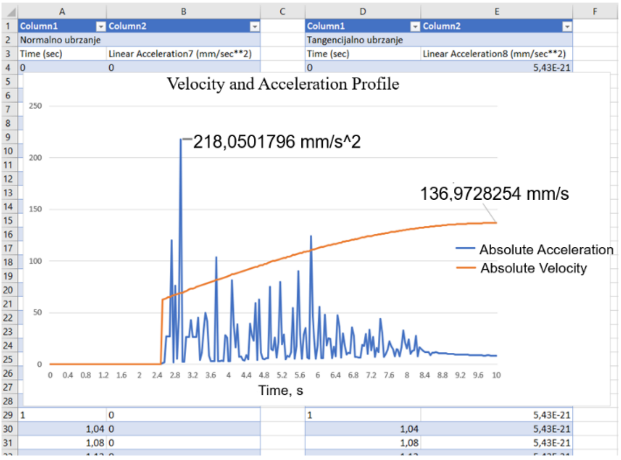

Fig. 17: Velocity and Acceleration Profile during Opening the Roof with Reduced Gear Ratio

Case Study 4: Closing the Roof with Reduced Gear Ratio (30:1)

- Velocity Profile: the roof's opening saw a peak velocity of 171,94 mm/s.
- Acceleration Profile: The highest acceleration observed increased to 534,5 mm/s².

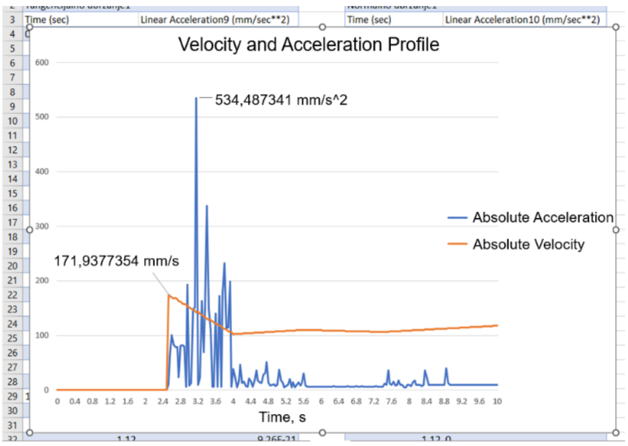

Fig. 18; Velocity and Acceleration Profile during Closing the Roof with Reduced Gear Ratio

3.4 Calculation of Manual Force

When designing the mechanisms for opening and closing the roof, it is crucial to determine the required manual force to ensure the desired movement and acceleration. Calculating this force is essential for the proper and efficient functioning of the mechanism. One of the fundamental principles used for calculating the force is Newton's Second Law.

$$F = m \times a, \qquad (1)$$

- F is the manual force [N]
- m is the total mass of the roof mechanism [kg]
- a is the maximum acceleration observed during the operation [mm/s²]

The total mass of all components involved in the roof mechanism was obtained from SolidWorks: m = 521,83 kg

During the roof closing, the highest acceleration under standard gear ratio (60:1) was calculated as 265.07 mm/s².

According to expression (1), manual force equals:

$$F = 521{,}83 \times 0{,}265 = 138{,}28\ N$$

For the scenario with a lower gear ratio reducer (30:1), the maximum acceleration was higher, at 534.49 mm/s². This indicates that a lower gear ratio results in faster and more forceful movements, requiring adjustments in manual force application. In that case, manual force equals:

$$F_r = 521{,}83 \times 0{,}535 = 279{,}18\ N$$

According to the requirements, the torque applied to the rotating wheel for opening or closing the roof must not exceed 100 Nm. Based on this requirement, we can calculate the maximum allowable force and compare it with our manual force.

Torque is defined as the product of force and the lever arm:

$$M = F \times r \qquad (2)$$

Therefore, the force can be expressed as the quotient of the known torque and the lever arm, or the radius of the rotating wheel, which is 245 mm:

$$F_{allowable} = \frac{M}{r} = \frac{100}{0{,}245}$$
$$F_{allowable} = 408{,}2\ \mathrm{N}$$

From this, we conclude that both the manual force F and the reduced ratio force F_r are less than $F_{allowable}$, indicating that the manual force in both cases meets the requirements, thus making the case for using a lower gear ratio reducer feasible.

4 CONCLUSION

In this paper, the kinematics of the opening and closing mechanism of the Tagnpps 95 m³ wagon roof are analyzed. The main goal was to study the input kinematic parameters and movement of the mechanism, develop a mathematical model, perform a kinematic analysis, and finally, determine the manual force required for operating the roof.

The analysis of the mechanism movement through all of its components, including the steering wheel, motion transmission gears, and the roof of the wagon was done. The time required to fully open and close the wagon's roof and the rotating wheel's angular rotation were measured. Opening the roof took 10 seconds while closing the roof was shorter and took 8 seconds. The angular rotation of the rotating wheel was the same for both cases which is 3,7 full turns. These data were used as input parameters for kinematic analysis in SolidWorks Motion.

The velocity and acceleration of the highest point of the roof are crucial since this point experiences the maximum values of both. For Case Study 1, the highest calculated acceleration was 115.7 mm/s², while the maximum calculated velocity was 129.36 mm/s. For Case Study 2, these values were slightly higher. This increase is expected because, unlike during opening, the roof spring does not act as a brake but rather assists the manual force due to its stiffness. The highest calculated acceleration during closing was 265.07 mm/s², and the peak velocity reached 139.51 mm/s. These maximum acceleration values are particularly significant for calculating the manual force required to open the roof.

Additionally, the values of velocity and acceleration were calculated in SolidWorks Motion for Case Studies 3 and 4 (when using a reducer with a lower gear ratio of 30:1). In this case, as anticipated, higher values were observed: the maximum acceleration during opening was 218.05 mm/s², and during closing, it was 534.5 mm/s².

Using Newton's Second Law and knowing the total mass of the mechanism and the maximum roof acceleration values, the manual force required to open the roof was calculated. For the 60:1 reducer, the force was 138.28 N, and for the 30:1 reducer, it was 279.2 N. Both forces are well below the maximum allowable force of 408.2 N. This paper thus contributes to further research, design, and calculation of similar mechanisms.

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