Збірник наукових праць. Галузеве машинобудування, будівництво
Academic journal. Industrial Machine Building, Civil Engineering
http://journals.nupp.edu.ua/znp
https://doi.org/10.26906/znp.2021.57.2591

UDC 629.331

Determination of spatial interaction of the individual road train links

Orysenko Oleksandr[1*], Skoryk Maksym[2], Kryvorot Anatoliy[3], Rassoha Inna[4]

[1] National University «Yuri Kondratyuk Poltava Polytechnic» https://orcid.org/0000-0003-3103-0096
[2] National University «Yuri Kondratyuk Poltava Polytechnic» https://orcid.org/0000-0001-9001-4913
[3] National University «Yuri Kondratyuk Poltava Polytechnic» https://orcid.org/0000-0001-5919-7352
[4] National University «Yuri Kondratyuk Poltava Polytechnic» https://orcid.org/0000-0001-7681-5124
*Corresponding author E-mail: oleksandr.orysenko@gmail.com

When designing traction-coupling devices and studying the operational properties of road trains, it becomes necessary to determine the size and direction of applying loads that are transmitted from one link of the road train to another. This is convenient to carry out, first by designing a spatial system of forces acting on a separate link, on the axis of the spatial coordinate system, which is fixedly connected with this link, and then bringing these projections to the coordinate system, which is fixedly connected with another link. So, the problem is to develop a mathematical apparatus that allows you to make the transition between coordinate systems that are rigidly connected with individual links of the road train. For a category M1 road train, it is proposed to make a transition between coordinate systems using a table, which is a transformed product of rotation matrices around the coordinate system axes, which is accepted as stationary. At the same time, stationary, depending on the task, can be considered a coordinate system associated with any link of the road train. Since the product of matrices is not commutative, and the positions of individual links during movement change all the time according to an arbitrary sequence of turns, the resulting matrix will depend on the accepted sequence of turns, which will further affect the projections magnitude of the force one link influences on another part.

Keywords: road train, rotation angle, rotation matrix, stationary and moving coordinate systems, traction-coupling device, tractor car, trailer.

Визначення просторової взаємодії окремих ланок автомобільного поїзда

Орисенко О.В.[1*], Скорик М.О.[2], Криворот А.І.[3], Рассоха І.В.[4]

[1, 2, 3,] Національний університет «Полтавська політехніка імені Юрія Кондратюка»
* Адреса для листування E-mail: oleksandr.orysenko@gmail.com

При проектуванні тягово-зчіпних пристроїв та дослідженні експлуатаційних властивостей автопоїздів виникає необхідність у визначенні величини та напрямку прикладання навантажень, які передаються від однієї ланки автопоїзда до іншої. Це зручно здійснити, спочатку спроектувавши просторову систему сил, що діють на окрему ланку, на осі просторової системи координат, яка нерухомо пов'язана з цією ланкою, а потім привести ці проекції до системи координат, яка нерухомо пов'язана з іншою ланкою. Отже, задача полягає у розробленні математичного апарату, який дозволяє здійснювати перехід між системами координат, які жорстко пов'язані з окремими ланками автопоїзда. Для автопоїзда категорії М1 пропонується здійснювати перехід між системами координат за допомогою таблиці, яка являє собою трансформований добуток матриць поворотів навколо осей системи координат, яка прийнята за нерухому. При цьому нерухомою, залежно від поставленої задачі, можна вважати систему координат пов'язаною з будь якою ланкою автопоїзда. Оскільки добуток матриць не є комутативним, а положення окремих ланок під час руху весь час змінюються за довільною послідовністю поворотів, то результуюча матриця буде залежати від прийнятої послідовності поворотів, що у подальшому впливатиме на величину проекцій сили впливу однієї ланки на іншу. Також було доведено, що плоскі розрахункові схеми не дають можливості враховувати просторову взаємодію ланок автопоїзда. Знехтувавши зазорами в тягово-зчіпному пристрої, зміну положення причепа відносно автомобіля можна описати у вигляді трьох поворотів навколо осей системи координат, яка нерухомо пов'язана з автомобілем. Основним результатом є те, що дійсно можна здійснити приведення сил впливу однієї з ланок автопоїзда на іншу через таблицю переходу між системами координат, що описує повороти навколо кожної з осей системи.

Ключові слова: автопоїзд, кут повороту, матриця повороту, нерухома та рухома системи координат, тягач, причіп, тягово-зчіпне пристосування.

Introduction

During the road train movement, each of its links is exposed to a spatial forces system, the size and direction of which depends on a number of factors. Such factors are: the strength of the traction of the tractor car, the resistance to movement, wind, inertial and dynamic loads, aftershocks from road irregularities and a number of others [1, 2].

At the same time, the road train links interaction occurs through a traction-coupling device. It is this node that perceives the loads arising from the movement of one of the links of the road train and transmits this load to another. Therefore, the correct determination of the size and forces direction brought to the traction-coupling device is an urgent issue, since it allows you to solve a number of engineering problems related to the design and operation of road trains.

Review of the research sources and publications

The dynamic road train links interaction is devoted to a significant number of scientific studies.

Fundamental in this direction is the work [3] which analyzes the structure and working conditions of traction and coupling devices of road trains. Based on the studies, the author derived and solved differential equations of the tractor car interaction with conventional and active trailers in different modes of movement.

The work [4] contains systematic material relating to the analysis of the structure, methods of calculation and basic requirements for individual units and components of road trains.

Also, a number of works show that the road train links interaction in the longitudinal direction is influenced not only by longitudinal forces, but also by those acting in other directions. When considering the issues of road train kinematics and dynamics when driving in the works [5, 6] it is indicated that the forces road train links interaction does not remain constant even with stable movement. The authors found that one of the reasons for this phenomenon is the influence of irregularities in the road surface.

Currently, the issue of road trains operational properties is not completely resolved, which causes the relevance of research in this direction as domestic authors [7-10], and foreign [11-15].

In the work [7] itis established that the lateral accelerations acting in the traction car mass center and trailer when performing maneuvers "steering wheel jerk" and "rearrangement" at a speed of 5 m/s are almost the same, that is, the road train stability in the performance of these maneuvers should be judged by the size of lateral accelerations operating in the any link road train mass center.

The author [8] developed the road train category M1 mathematical model, with the help of which the road train critical speed is determined and factors influencing its numerical value are analyzed, in particular, the road train mass and layout parameters and the tires rigid characteristics of its axles.

In the work [9] it was established that for a preliminary road train maneuverability assessment, it is possible to consider the wheels rigid in the lateral direction, and it is also proved that the road train with trailers of category O1 and O2, which is being considered, can provide an acceptable value of maneuverability according to DIRECTIVE 2002/7/EC, taking into account all possible restrictions (tractor car base, location of the hitch point, the trailer drawbar length, the trailer base).

In [10] the road train movement was considered as horizontal. As a research result, the road train flat-parallel traffic equations system with a single-axle trailer categorizes O1 has been improved, side reactions on the car wheels and the trailer at the body roll have been determined, the wheels removal angles of the car and the trailer, due to their body roll, have been determined, a spatial road train mathematical model an in-transverse plane.

In [11] the car model motion equation for and a caravan with twenty-four degrees of freedom are developed using Lagrange equations for quasi-coordination. It is argued that only with the help of a nonlinear simulation model, which includes the basic degrees car freedom and the caravan, you can have reasonable confidence in the forecast accuracy. This approach is common in car dynamics, but as far as the author knows, it was not used to predict the car/caravan coupling pairs.

The work [12] investigated the impact dampers (shock absorbers) nonlinear properties during road tests tractor car suspensions on the dynamic road trains stability. This nonlinearity is modeled using the Magic Formula damper model and then integrated into an extended single-track model with a trailer with a tandem axis.

In [13] existing RVMSs are reviewed and each of the main RVMS subsystems related to vehicle dynamics R&D is discussed, and the possibility of using motion simulators for driving and handling test scenarios is explored.

In [14], a method for planning maneuvers with simple speed profiles and steering control is presented. This method can easily be used in autonomous vehicles as well as driver assistance systems. The trailer orientation change maneuver is presented in detail. The practical application of the proposed method was tested on the ROMEO4R autonomous car, which performs autonomous parallel parking.

The work [15] investigates the road train braking on the dynamic stability effect, braking is simply simulated and integrated into a single-track model with a single-axle trailer. On this basis, some fundamentals and analysis results related to the dynamic stability of the system are presented through simulation. In addition, it was found that the load on the axis transfer and the braking force distribution have a great impact on the system dynamic stability. For further these two factors influence analysis, both braking force distribution and pitch are taken into account in the simulation. Finally, an ideal brake strength distribution area is proposed. The results can be taken to explain the experimental phenomenon and serve as a benchmark for the differential inhibition strategy when controlling stability.

In work [16] it was established that the load on the tractor car traction-coupling device significantly affects the body roll and the support reactions redistribution surface along the wheels of its sides. It is shown that with an increase in the steered wheels rotation angle and the load on the traction-coupling device, the road train critical speed, taking into account the roll, significantly decreases due to the support surface reactions redistribution and the change wheels resistance coefficients of different road train sides.

The paper [17] provides systems of differential equations that take into account the law of changing the force arising in a traction-coupling device in the case of using the usual and dynamic drawbar of the road train trailer link. It is also shown that the cause of longitudinal dynamic loads in a traction-coupling device is the oscillation of the trailer in the longitudinal vertical plane.

This road train interaction is explained by the fact that any spatial system of forces that affect a separate road train link can be brought to one equilibrium, which can then be decomposed into projections along the axes of the spatial coordinate system [18]. Since the power interaction between the links of the road train is carried out coupling a traction-coupling device, it becomes necessary to bring equilibrium projections of the spatial system of forces to this particular device and decompose into projections along the axes of the spatial coordinate system associated with this device.

Definition of unsolved aspects of the problem

Analyzing the works devoted to the study of road train link interaction, we come to the conclusion that the authors use flat design schemes in horizontal or vertical planes. However, during the road train movement, its links undergo spatial loads that may not lie in these planes, but affect only due to projections on these planes. Therefore, there is a need to develop a mathematical apparatus that would allow bringing spatial forces to the axes of coordinate systems that are associated with a tractor car or trailer.

Problem statement

This study purpose is to develop a mathematical apparatus that allows you to make the transition from a spatial coordinate system that is fixedly connected with one of the road train links, for example, a trailer, to a spatial coordinate system that is fixedly connected with another link, for example, a tractor car.

Basic material and results

Consider the passenger car road train links interaction with a single-axle trailer. Analyzing the structure of the traction-coupling device the car category M1, namely the hinge in the form of a ball, we come to the conclusion that in the absence of gaps in the hinge, the trailer has three degrees of freedom in relation to the tractor car. These degrees of freedom are the possibility of its rotations in horizontal and two vertical planes that pass through the center of the hinge. Torque, which occurs when twisting the road train along the longitudinal horizontal axis, this hinge does not transmit.

It is in these planes that there will be projections of all forces that arise during the movement of the road train and affect the tractor car. Also, these degrees of freedom can be represented in the form of turns around the spatial coordinate system, which is fixedly connected with the tractor car.

Since the position of the trailer relative to the tractor car during movement changes all the time, it is obvious that the values of these force projections will depend on the position of the trailer, namely its deviations from the longitudinal axis, both in the vertical and horizontal planes.

To obtain mathematical expressions that will allow us to bring the force of influence on the trailer to the traction-coupling device, and in the future to another link of the road train, we apply the following approach. We assume that while driving, the tractor car is always on a flat horizontal surface, and when overcoming the unevenness of the road, only the trailer changes its position.

With the hinge center of the traction-coupling device, we associate the OXYZ coordinate system, which is rigidly connected with the tractor car and does not change its position relative to it while driving (Fig. 1). The coordinate axes system position is as follows: the OH axis is horizontal and is located along the longitudinal axis of the car symmetry and is directed in the opposite direction; the OY axis is also in the horizontal plane and is directed to the left side of the car; the OZ axis is directed vertically upwards. Rotation from the OX axis to the OZ axis is clockwise (a left-sided coordinate system).

Another coordinate system OXYZ also originates in the traction-coupling device hinge center, the direction of its axes in the initial period of time coincides with the OXYZ axes direction coordinate system, but it is rigidly connected to the trailer and does not change its position relative to it during movement. Thus, we have two coordinate systems, the stationary OXYZ and the OXYZ motion (in relation to the tractor car), which originate in the center of the hinge of the traction-hitch device and coincide in the initial period of time (Fig. 1).

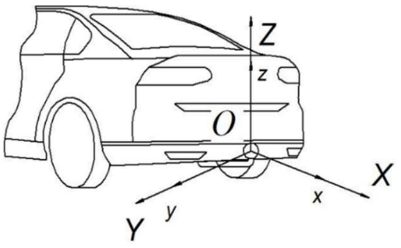


Figure 1 – Car and trailer coordinate systems in the initial time period

The choice of the beginning location and axes direction of the coordinate systems is due to the following considerations. When considering the car dynamic processes (car with a trailer), the main research areas are the vehicle movement on the road surface in the acceleration, braking, movement, and rotation modes. The vehicle as a whole and its components are studied to determine the impact of the forces that each of these components causes and the vehicle's response to the impact of these forces.

According to SAE (Fig. 2) when describing the car dynamic processes, a right-hand orthogonal coordinate system is adopted, with the vehicle's mass center beginning.

– OX – is located in the car symmetry plane of the longitudinal axis and is directed in the direction of its movement forward;

– OY – lies in a horizontal plane and is directed towards the right vehicle side;

– OZ – is directed downwards in relation to the vehicle. Turns around these axes have the following names:

– p – rotation around the x-axis (roll);

– q – rotation around the Y axis (pitch);

– r – rotation around the Z axis (yaw).

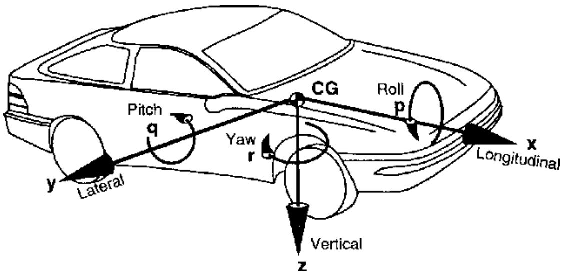


Figure 2 – Car axle system according to SAE

When describing the processes that occur during maneuvers, the specified coordinate system changes its position relative to the stationary coordinate system that is connected to the earth. As a rule, at the maneuver initial moment, it is assumed that the centers and the two coordinate systems axes (fixed car and immovable land) coincide.

The fixed car position coordinate system in relation to the stationary Earth coordinate system is determined using the Euler angles or others that are obtained in a similar way.

We adopted the coordinate system beginning location traction-coupling device in the hinge center, and the coordinate system axes directions associated with the trailer and car are mirrored to the coordinate system of the adopted SAE.

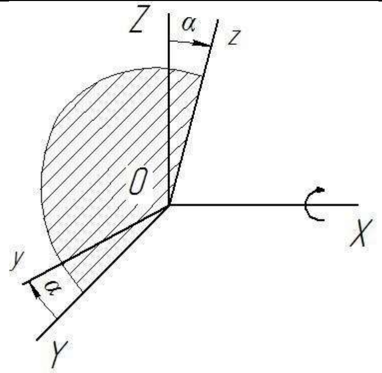
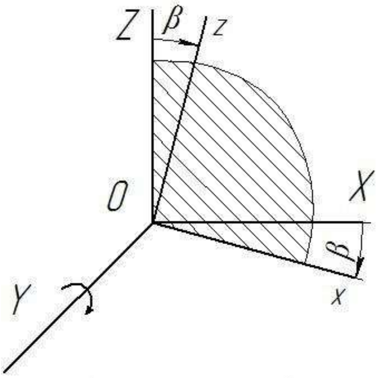
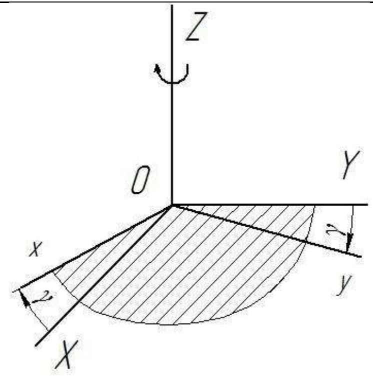
When driving, overcoming irregularities of the supporting surface, the trailer will change its position relative to the car. The OXYZ coordinate system axes will deviate from their original position, and therefore from the OXYZ coordinate system axes.

As is known [18] such a deviation of coordinate systems can be described using three turns, which in turn are described by the corresponding rotation matrices.

Assume the following symbols: rotation around the axis OX is carried out at an angle α, rotation around the axis OY - at an angle β, rotation around the axis OZ - at an angle γ. Then the rotation matrices around each spatial coordinate system axes, which is accepted as stationary, will look like (Table 1).

Since during the road train movement the OXYZ coordinate system axis can deviate from all three OXYZ coordinate system axes at the same time, the trailer relative position to the car will determine the resulting matrix of turns, which we obtain as the product of rotation matrices around each of the axes.

Table 1 − Three consecutive turns around OX, OY, OZ axes

Rotate around the OX axis
 $\begin{pmatrix} 1 & 0 & 0 \\ 0 & cos\alpha & -sin\alpha \\ 0 & sin\alpha & cos\alpha \end{pmatrix}$
Rotate around the OY axis
 $\begin{pmatrix} cos\beta & 0 & sin\beta \\ 0 & 1 & 0 \\ -sin\beta & 0 & cos\beta \end{pmatrix}$
Rotate around the OZ axis
 $\begin{pmatrix} cos\gamma & -sin\gamma & 0 \\ sin\gamma & cos\gamma & 0 \\ 0 & 0 & 1 \end{pmatrix}$

So, for example, when the sequence of rotations around the axes OX, OY, OZ (Fig. 3) the product of the matrices will look like

$$\begin{pmatrix} \cos\gamma & -\sin\gamma & 0 \\ \sin\gamma & \cos\gamma & 0 \\ 0 & 0 & 1 \end{pmatrix} \times \begin{pmatrix} \cos\beta & 0 & \sin\beta \\ 0 & 1 & 0 \\ -\sin\beta & 0 & \cos\beta \end{pmatrix} \times \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\alpha & -\sin\alpha \\ 0 & \sin\alpha & \cos\alpha \end{pmatrix} =$$

$$= \begin{pmatrix} \cos\beta\cdot\cos\gamma & \sin\alpha\cdot\sin\beta\cdot\cos\gamma - & \cos\alpha\cdot\sin\beta\cdot\cos\gamma + \\ & -\cos\alpha\cdot\sin\gamma & +\sin\alpha\cdot\sin\gamma \\ \cos\beta\cdot\sin\gamma & \sin\alpha\cdot\sin\beta\cdot\sin\gamma + & \cos\alpha\cdot\sin\beta\cdot\sin\gamma - \\ & +\cos\alpha\cdot\cos\gamma & -\sin\alpha\cdot\cos\gamma \\ -\sin\beta & \sin\alpha\cdot\cos\beta & \cos\alpha\cdot\cos\beta \end{pmatrix}$$

It should be noted that when obtaining the rotation matrix product, the sequence of matrices in the equation is taken inversely to the sequence of turns, that is, in the first place in the equation there is a matrix that corresponds to the last turn.

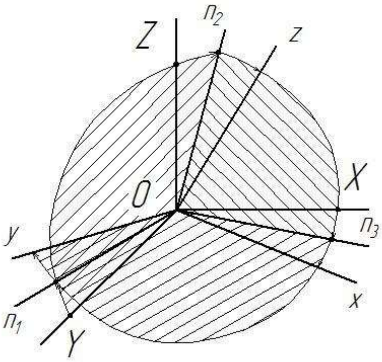


Figure 3 – Three consecutive turns around the OX, OY, OZ axes

However, this matrix allows you to determine only the new force vector position, which affects the road train link, but its coordinates remain on the same basis.

To bring the forces created by one of the road train links to another link coordinate system, it is necessary to have a transition between the coordinate systems matrix, which is achieved by transposing the resulting matrix.

The matrices product is not commutative, so the resulting matrix will depend on the accepted sequence of turns, which will further affect the magnitude of the force projections trailer's impact on the car. According to the combinatorics rules, the turn sequence possible variants number, in this case, is six. It is this transition tables number that must be created to study the trail link with the tractor car interaction.

The resulting matrices, which are a transposed product of rotation matrices around each of the individual axes of the fixed coordinate system OXYZ, depending on the accepted sequence of turns, are given in (Table 2).

Having written down the transposed matrix in the table form we receive the transition table between the mobile and fixed coordinate systems. For example, the transition table between the movable and immovable coordinate systems in the turns around sequence the OX, OY, OZ axes will look like (Table 3).

The use of this approach allows you to carry out operations with forces that affect one of the road train links in its own coordinate system, and then, if necessary, bring these forces to the coordinate system of another link.

Table 2 – Resulting transposed matrices depending on the turns accepted sequence

The turns around sequence OX, OY, OZ axes
$\begin{pmatrix} \cos\beta\cdot\cos\gamma & \cos\beta\cdot\sin\gamma & -\sin\beta \\ \sin\alpha\cdot\sin\beta\cdot\cos\gamma - & \sin\alpha\cdot\sin\beta\cdot\sin\gamma + & \sin\alpha\cdot\cos\beta \\ -\cos\alpha\cdot\sin\gamma & +\cos\alpha\cdot\cos\gamma & \\ \cos\alpha\cdot\sin\beta\cdot\cos\gamma + & \cos\alpha\cdot\sin\beta\cdot\sin\gamma - & \cos\alpha\cdot\cos\beta \\ +\sin\alpha\cdot\sin\gamma & -\sin\alpha\cdot\cos\gamma & \end{pmatrix}$
The turns around sequence OX, OZ, OY axes
$\begin{pmatrix} \cos\alpha\cdot\cos\gamma - & \cos\alpha\cdot\sin\gamma + & -\cos\alpha\cdot\sin\beta \\ -\sin\alpha\cdot\sin\beta\cdot\sin\gamma & +\sin\alpha\cdot\sin\beta\cdot\cos\gamma & \\ -\cos\alpha\cdot\sin\gamma & \cos\alpha\cdot\cos\gamma & \sin\alpha \\ \cos\gamma\cdot\sin\beta + & \sin\beta\cdot\sin\gamma - & \cos\alpha\cdot\cos\beta \\ +\sin\alpha\cdot\sin\gamma\cdot\cos\beta & -\sin\alpha\cdot\cos\beta\cdot\cos\gamma & \end{pmatrix}$
The turns around sequence OY, OX, OZ axes
$\begin{pmatrix} \cos\beta\cdot\cos\gamma - & \cos\beta\cdot\sin\gamma + & -\cos\alpha\cdot\sin\beta \\ -\sin\alpha\cdot\sin\beta\cdot\sin\gamma & +\sin\alpha\cdot\sin\beta\cdot\cos\gamma & \\ -\cos\alpha\cdot\sin\gamma & \cos\alpha\cdot\cos\gamma & \sin\alpha \\ \sin\beta\cdot\cos\gamma + & \sin\beta\cdot\sin\gamma - & -\sin\alpha\cdot\cos\beta\cdot\cos\gamma \\ +\sin\alpha\cdot\sin\gamma\cdot\cos\beta & -\sin\alpha\cdot\cos\beta\cdot\cos\gamma & \cos\alpha\cdot\cos\beta \end{pmatrix}$
The turns around sequence OY, OZ, OX axes
$\begin{pmatrix} \cos\beta\cdot\cos\gamma & \cos\alpha\cdot\cos\beta\cdot\sin\gamma + & \sin\alpha\cdot\cos\beta\cdot\sin\gamma - \\ & +\sin\alpha\cdot\sin\beta & -\cos\alpha\cdot\sin\beta \\ -\sin\gamma & \cos\alpha\cdot\cos\gamma & \sin\alpha\cdot\cos\gamma \\ \sin\beta\cdot\cos\gamma & \cos\alpha\cdot\sin\beta\cdot\sin\gamma - & \sin\alpha\cdot\sin\beta\cdot\sin\gamma + \\ & -\sin\alpha\cdot\cos\gamma & +\cos\alpha\cdot\cos\beta \end{pmatrix}$
The turns around sequence OZ, OX, OY axes
$\begin{pmatrix} \cos\beta\cdot\cos\gamma + & \cos\alpha\cdot\sin\gamma & \sin\alpha\cdot\cos\beta\cdot\sin\gamma - \\ +\sin\alpha\cdot\sin\beta\cdot\sin\gamma & & -\sin\beta\cdot\cos\gamma \\ & & \sin\beta\cdot\sin\gamma + \\ \sin\alpha\cdot\sin\beta\cdot\cos\gamma - & \cos\alpha\cdot\cos\gamma & +\sin\alpha\cdot\cos\beta\cdot\cos\gamma \\ -\cos\beta\cdot\sin\gamma & -\sin\alpha & \cos\alpha\cdot\cos\beta \\ \cos\alpha\cdot\sin\beta & & \end{pmatrix}$
The turns around sequence OZ, OY, OX axes
$\begin{pmatrix} \cos\beta\cdot\cos\gamma & \sin\alpha\cdot\sin\beta\cdot\cos\gamma + & \sin\alpha\cdot\sin\gamma - \\ & +\cos\alpha\cdot\sin\gamma & -\cos\alpha\cdot\sin\beta\cdot\cos\gamma \\ -\cos\beta\cdot\sin\gamma & \cos\alpha\cdot\cos\gamma - & \cos\alpha\cdot\sin\beta\cdot\sin\gamma + \\ & -\sin\alpha\cdot\sin\beta\cdot\sin\gamma & +\sin\alpha\cdot\cos\gamma \\ \sin\beta & -\sin\alpha\cdot\cos\beta & \cos\alpha\cdot\cos\beta \end{pmatrix}$

Table 3 – Transition table between coordinate systems

Coordinate system axes	OX	OY	OZ
OX	$\cos\beta\cdot\cos\gamma$	$\cos\beta\cdot\sin\gamma$	$-\sin\beta$
OY	$\sin\alpha\cdot\sin\beta\cdot\cos\gamma-\cos\alpha\cdot\sin\gamma$	$\sin\alpha\cdot\sin\beta\cdot\sin\gamma+\cos\alpha\cdot\cos\gamma$	$\sin\alpha\cdot\cos\beta$
OZ	$\cos\alpha\cdot\sin\beta\cdot\cos\gamma+\sin\alpha\cdot\sin\gamma$	$\cos\alpha\cdot\sin\beta\cdot\sin\gamma-\sin\alpha\cdot\sin\gamma$	$\cos\alpha\cdot\cos\beta$

Conclusions

As the research result, is following were established:

1. When studying the road train links interaction, it becomes necessary to bring forces to coordinate systems stationary associated with these links.
2. Flat design schemes do not make it possible to take into account the spatial road train links interaction.
3. Neglecting the gaps in the traction-coupling device, the change in the trailer relative to the car position can be described in the form of three turns around the coordinate system axes, which is fixedly connected with the tractor car.
4. To carry out bringing the forces one of the road train links influences to another allows the transition table between coordinate systems, which is a transposed matrices describing the rotations around each coordinate system axes conventionally accepted as fixed.

References

1. Сахно В.П., Сирота В.І., Поляков В.М. та ін. (2017). *Автомобілі. Теорія*. Одеса: Військова академія

2. Подригало М.А., Шелудченко В.В. (2015). *Нове в теорії експлуатаційних властивостей автомобілів та тракторів*. Суми: Сумський національний аграрний університет

3. Щукин М.М. (1961). *Сцепные устройства автомобилей и тягачей: Конструкция, теория, расчет*. Л.: МАШГИЗ

4. Сахно В.П., Поляков В.М., Шарай С.М., Мурований І.С., Омельницькій О.Є. (2021). *Шарнірно-зчленовані автобуси. Маневреність та стійкість.* Луцьк: ІВВ Луцького НТУ

5. Поляков В.М., Сахно В.П. (2014). *Триланкові автопоїзди: маневреність*. Луганськ: Ноулідж

6. Сахно В.П., Поляков В.М., Шарай С.М., Босенко В.М. (2016). *Прикладна теорія руху автопоїзда*. Київ: НТУ

7. Сахно В.П., Кузнєцов Р.М., Стельмащук В.В., Козачук Л.С. (2014). До визначення показників стійкості автопоїзда категорії М1 у перехідних режимах руху. *Сучасні технології в машинобудуванні та транспорті*, 2, 123-128
https://doi.org/10.36910/automash.v2i2

8. Козачук Л.С. (2014). До визначення стійкості руху автопоїзда категорії М1. Вісник Житомирського держ. техн. університету «Технічні науки», 2(69), 121-128

9. Сахно В.П., Кузнєцов Р.М., Стельмащук В.В., Пазин Р.В. (2018). Маневреність автопоїзда з причепами категорії О1, О2. *Сучасні технології в машинобудуванні та транспорті*, 1(10), 102-111
https://doi.org/10.36910/automash.v1i10

10. Сахно В.П., Шарай С.М., Мурований І.С., Човча І.В. (2021). До розробки математичної моделі автопоїзда з причепом категорії О1 у поперечній площині. *Сучасні технології в машинобудуванні та транспорті*, 2(17), 151-160
https://doi.org/10.36910/automash.v2i17.645

11. Fratila D., Darling J. (1996). Simulation of Coupled Car and Caravan Handling Behaviour. *Vehicle System Dynamics*, 26:6, 397-429
https://doi.org/10.1080/00423119608969317

1. Sakhno V.P., Sirota V.I., Polyakov V.M. et al. (2017). *Cars. Theory*. Odesa: Military Academy

2. Podrigalo M., Sheludchenko V. (2015). *New in the theory of operational properties of cars and tractors.* Sumy: Sumy National Agrarian University

3. Shchukin M.M. (1961). *Coupling devices of cars and tractors*: Design, theory, calculation. L.: MASH-GIZ

4. Sakhno V.P., Polyakov V.M., Sharay S.M., Murovany I.S., Omelnytskyi O.E. (2021). *Articulated buses. Maneuverability and stability.* Lutsk: IVV Lutsk NTU

5. Polyakov V.M., Sakhno V.P. (2014). *Three-lane road trains: maneuverability.* Luhansk: Knowledge

6. Sakhno V.P., Polyakov V.M., Sharay S.M., Bosenko V.M. (2016). *Applied theory of road train motion.* Kyiv: NTU

7. Sakhno V., Sakhno V., Kuznetsov R., Stelmashchuk V., Kozachuk L. (2014). To determine the stability indices of a M1 category train in transitional modes of movement. *Modern technologies in machine building and transport*, 2, 123-128
https://doi.org/10.36910/automash.v2i2

8. Kozachuk L. (2014). To determine the stability of the road train category M1. *Bulletin of ZhSTU "Technical Sciences"*, 2(69), 121-128

9. Sakhno V., Kuznetsov R., Stelmashchuk V., Pazin R. (2018). Maneuverability of the road train with trailers of category O1, O2. *Modern technologies in machine building and transport*, 1(10), 102-111
https://doi.org/10.36910/automash.v1i10

10. Sakhno V., Sharay S., Murovany I., Chovcha I. (2021). To the development of a mathematical model of a road train with a trailer of category O1 in the transverse plane. *Modern technologies in machine building and transport*, 2(17), 151-160
https://doi.org/10.36910/automash.v2i17.645

11. Fratila D., Darling J. (1996). Simulation of Coupled Car and Caravan Handling Behaviour. *Vehicle System Dynamics*, 26:6, 397-429
https://doi.org/10.1080/00423119608969317

12. Zhang N., Yin G., Mi T., Li X., Chen N. (2017). Analysis of Dynamic Stability of Car-trailer Combinations with Nonlinear Damper Properties. *Procedia IUTAM*, 22, 251-258
https://doi.org/10.1016/j.piutam.2017.08.033

13. Mohajer N., Abdi H., Nelson K., Nahavandi S. (2015). Vehicle motion simulators, a key step towards road vehicle dynamics improvement. *Vehicle System Dynamics*, 53:8, 1204-1226
https://doi.org/10.1080/00423114.2015.1039551

14. Gomez-Bravo F., Cuesta F., Ollero A. (2005). Autonomous tractor-trailer back-up manoeuvering based on changing trailer orientation. *IFAC Proceedings*, 38(1), 301-306
https://doi.org/10.3182/20050703-6-CZ-1902.01320

15. Zhang N., Wu J., Li T., Zhao Z., Yin G. (2021). Influence of braking on dynamic stability of car-trailer combinations. *Automobile Engineering*, 235(2-3), 455-464
https://doi.org/10.1177/0954407020959895

16. Сахно В.П., Кузнецов Р.М., Стельмащук В.В., Козачук Л.С. (2015). Вплив навантаження на тягово-зчіпний пристрій на стійкість руху автопоїзда категорії М1 у перехідних режимах руху. *Сучасні технології в машинобудуванні та транспорті*, 1(3), 48-157
https://doi.org/10.36910/automash.v1i3

17. Orysenko O.V., Skoryk M.O., Kryvorot A.I., Shapoval M.V. (2018). The Dynamic Processes Mathematical Modeling in the Traction Coupling Device From Cars to the Trailers. *International Journal of Engineering & Technology*, 7(4.8), 473-477
https://doi.org/10.14419/ijet.v7i4.8.27291

18. Павловський М.А. (2002). *Теоретична механіка*. Київ: Техніка

12. Zhang N., Yin G., Mi T., Li X., Chen N. (2017). Analysis of Dynamic Stability of Car-trailer Combinations with Nonlinear Damper Properties. *Procedia IUTAM*, 22, 251-258
https://doi.org/10.1016/j.piutam.2017.08.033

13. Mohajer N., Abdi H., Nelson K., Nahavandi S. (2015). Vehicle motion simulators, a key step towards road vehicle dynamics improvement. *Vehicle System Dynamics*, 53:8, 1204-1226
https://doi.org/10.1080/00423114.2015.1039551

14. Gomez-Bravo F., Cuesta F., Ollero A. (2005). Autonomous tractor-trailer back-up manoeuvering based on changing trailer orientation. *IFAC Proceedings*, 38(1), 301-306
https://doi.org/10.3182/20050703-6-CZ-1902.01320

15. Zhang N., Wu J., Li T., Zhao Z., Yin G. (2021). Influence of braking on dynamic stability of car-trailer combinations. *Automobile Engineering*, 235(2-3), 455-464
https://doi.org/10.1177/0954407020959895

16. Sakhno V.P., Kuznetsov R.M., Stelmashchuk V.V., Kozachuk L.S. (2015). Influence of loading on the traction coupling device on stability of movement of a road train of category M1 in transient modes of movement. *Modern technologies in mechanical engineering and transport*, 1(3), 148-157
https://doi.org/10.36910/automash.v1i3

17. Orysenko O.V., Skoryk M.O., Kryvorot A.I., Shapoval M.V. (2018). The Dynamic Processes Mathematical Modeling in the Traction Coupling Device From Cars to the Trailers. *International Journal of Engineering & Technology*, 7(4.8), 473-477
https://doi.org/10.14419/ijet.v7i4.8.27291

18. Pavlovsky M.A. (2002). *Theoretical mechanics*. Kyiv: Tekhnika