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Research paper

Simulation Technique of Kinematic Processes in the Vehicle Steering Linkage

Sergii Chernenko [1*], Eduard Klimov [1], Andrii Chernish [1], Olexandr Pavlenko [1], Volodymyr Kukhar [2]

[1]Kremenchuk Mykhailo Ostrohradskyi National University
[2]Pryazovskyi State Technical University
**Corresponding author E-mail: sercher174l@gmail.com*

Abstract

The results of the investigation of the turning kinematics of the steerable wheels of the KrAZ-7634NE off-road vehicle with a wheel formula 8x8 and two front steer axles are given. The theoretical relations between the steer angles of the steerable wheels on the basis of the scheme of double-axle steering turning of the vehicle are shown. The mathematical model of flat four-bar vehicle steering linkage is developed, it determines the relation between the steering linkage left and right steering arms turning angles at any turning radius of the vehicle. KrAZ-7634HE steering three-dimensional model was created and simulation technique of its work was carried out using Creo software. It has been shown that the flat steering linkage model provides sufficient accuracy of calculations in analysis of turning kinematics. The design data can be used for any vehicles that have a similar steering linkage, they allow to analyze the impact of the vehicle design parameters on the turning kinematics and optimize them. Further study of the impact of the kingpin inclinations on the steering linkage kinematic and power characteristics are required.

Keywords: *Ackerman Steering Linkage; Creo; Steerable Wheels; Steer Angle; Simulation Technique.*

1. Introduction

During the curvilinear motion all the wheels of the vehicle roll towards a single instantaneous turning center. Its position depends on the radius of the movement trajectory, the wheel arrangement, the slip angles, and so on. The steering linkage should ensure the coordination of the steerable wheel turning kinematics with the vehicle turning kinematics directly. Turning kinematics and design parameters of steering directly affect controllability, stability, ease of operation, and stabilization of steerable wheels, as indicated in works [1, 2]. In terms of perfect steering linkage, steerable wheels during the curvilinear motion will roll with the minimum rolling resistance without lateral distortion and lateral slip.
Adjustment of steer angles of the outer and inner steerable wheels by means of real steering linkage will take place with some falli-angles for the insertion of steering arms were found. Optimization of the parameters of the steering linkages of vehicles is considered in works [6, 7].
The analysis of publications has shown that the problem of optimization of the mechanisms is rather common and relevant. Different methods of optimization such as genetic algorithms (GA), neural networks, simulated annealing, ant an algorithm, bee algorithm and particle optimization (PSO) are considered in the literature [8]. Shariati and Norouzi [9] used the method of sequential quadratic approximation to optimize the function taking into account the accuracy.
Papers [10, 11] are devoted to issues of optimization and synthesis of four-bar mechanisms of vehicle steering linkage. Simulation technique and design of the steering mechanism are under analyses in [10]. For this purpose the ADAMS software was used. Software for calculating the geometric parameters of the mechanism by the example of “press-and-die” system given in the bility. The precision depends on the structural features of the steering linkage, the constitutive parameters of its components.
Researches concerning vehicle steering linkage kinematics are considered in the papers [3-8]. In the paper [3] algorithms for determining the correlation between the kinematic parameters of flat four-bar mechanism are analyzed, and the most effective method of kinematics analysis is developed. In [4] geometric and operational limitations of parameters are determined; the analysis of the Ackermann steering mechanism was made by systematical using of the normed values of the mechanism elements length.
Among the domestic scientists, studies of kinematics, mathematical modeling of the steering were performed by Murog I.A. [1], Sazonov I.S. [5], Likhodii O.S. [6], Dubovik D.A. [7]. In particular, in [5], analytical dependencies were proposed for determining the actual steer angles of steerable wheels of a tractor with given parameters of the steering linkage and the optimal article [12]. As a result of optimization of the arm geometric parameters of the steering linkage, in [10] a difference between the practical or the theoretical steer angles of the wheels is obtained, which does not exceed 0.5^0. In the paper [11], one-dimensional optimization problem is solved, a series of 3D-diagrams of design parameters are proposed, which can help an automobile engineer to determine the optimal geometry of Ackerman steering linkage.
In designing modern vehicle mechanisms, in particular wheels, steering system, which are the subject for increased traffic safety requirements, it is necessary to consider not only the design features but also the advanced technology of details manufacturing [13, 14]. So in work [13] the results of theoretical studies, which allow analyze the strain rate that arises in details during their deformation, determine the complex of design and technological parameters during profiling and drawing-out operations. This

makes the design more robust and safe, which is vitally important for steering system.

Thus, the analysis of works related to the study of the steering linkage kinematics made it possible to draw the following conclusions:

- a great deal of methods for calculating steering linkage parameters specification are based on unreasonable and inaccurate assumptions. The real spatial linkage is replaced by a flat model;
- it is not clear which of the kingpin rut sizes to take in the calculations;
- the influence of kingpin inclination on the calculation accuracy is uncertain;
- there are no comprehensive recommendations concerning the choice of steering linkage parameters that would provide satisfactory kinematics;
- the three-dimensional modeling method lets reduce the time and cost of designing and optimizing the various mechanisms parameters.

2. The purpose of the Work

The purpose of the work is to develop a flat steering linkage mathematical model and to simulate the real double-axle steering mechanism vehicle turning kinematics using three-dimensional modeling

3. Methodology and Research

Fig. 1 shows double-axle steering mechanism vehicle turning scheme. Steerable wheels will turn without a lateral slide in case the perpendiculars lowered from the centers of the wheel longitudinal axes will intersect at one point O. This point must be on the extension of the line between the third and fourth axles.

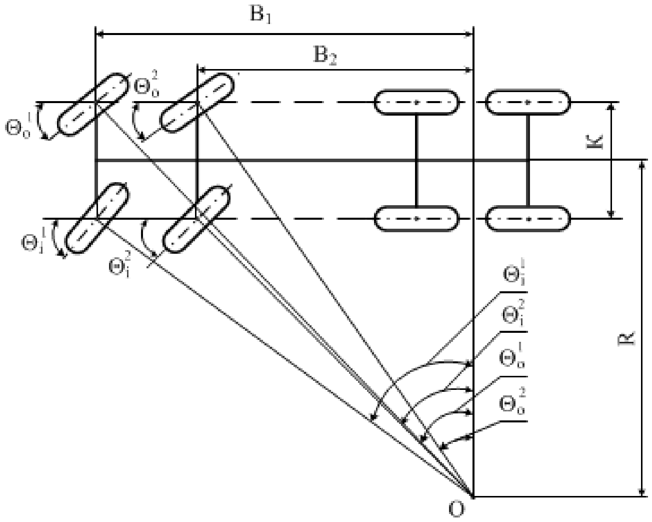

Fig. 1: Scheme of double-axle steering turning.

Obviously, during the curvilinear motion, the vehicle steerable wheels should turn to different angles [8,13,16,18]. The ratio between the wheel steer angle of the inner and outer steerable wheels is described by Ackermann's formula, which is written for the steerable wheels on the first axle, as follows

$$\mathrm{ctg}\Theta_o^1 - \mathrm{ctg}\Theta_i^1 = \frac{K}{B_1}, \quad (1)$$

for steerable wheels of the second axle

$$\mathrm{ctg}\Theta_o^2 - \mathrm{ctg}\Theta_i^2 = \frac{K}{B_2}, \quad (2)$$

where Θ_o is steer angle of outer wheel (output parameter), Θ_i is steer angle of inner wheel (input parameter), K is the distance between kingpin axes, B_1, B_2 are the wheelbase of first and second axles respectively (according to Fig. 1).

The correlation between the steer angle of the inner wheels of the first and second axles is determined by the dependence

$$\Theta_o^2 = \mathrm{arctg}\left(\frac{B_1}{B_2} \cdot \mathrm{tg}\Theta_o^1\right), \quad (3)$$

where Θ_o^1, Θ_o^2 are steer angle of the inner wheels of the first and second axles respectively.

Pay attention that equations (1-3) are valid only for absolutely rigid steerable wheels, since they do not take into account the slip angles.

The scheme for determining the functional dependence between the steer angles of the left and right steerable wheels for a flat steering linkage is shown in Fig. 2.

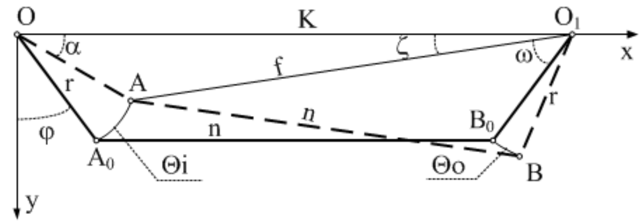

Fig. 2: Scheme for determining the functional dependence between the steer angles of the left and right steerable wheels for a flat steering linkage

When the steer angle is zero, the left steering arm OA_0 makes angle φ with the y longitudinal axis. The value of angle φ and the left steering arm length r can be determined if coordinates of point A_0 are known:

$$\varphi = \mathrm{arctg}\frac{x_0}{y_0}; \quad r = \sqrt{x_0^2 + y_0^2}, \quad (4)$$

where x_0, y_0 are A_0 coordinates when the steer angle is zero.

Turn the left steering arm to any angle Θ_i, that corresponds to vehicle left turning, then A_0 turns on a circle with radius r and occupies new position A. In this case, the right steering arm will turn to an unknown angle Θo.

Consider triangle AOO_1. Its angle $AOO_1 = \alpha$ can be easily determined from the following equation:

$$\alpha = \frac{\pi}{2} - (\varphi + \Theta_i). \quad (5)$$

Then in this triangle the length of side $AO_1 = f$, using the cosine theorem:

$$f^2 = r^2 + K^2 - 2 \cdot K \cdot r \cdot \cos\alpha. \quad (6)$$

Next, using the sine theorem, we find from this very triangle the angle $OO_1A = \xi$:

$$\frac{r}{\sin\xi} = \frac{f}{\sin\alpha} \Rightarrow \xi = \arcsin\left(\frac{r}{f} \cdot \sin\alpha\right) \quad (7)$$

Let's consider another triangle AO_1B. In it, the side $AO_1 = f$, the side AB is a tie rod, its length does not change, and the side O_1B is also known and is equal to the right steering arm length. Thus, this triangle is defined by three sides, so we can find out its angle AO_1B, applying the cosine theorem:

$$n^2 = f^2 + r^2 - 2 \cdot f \cdot r \cdot \cos AO_1B;$$
$$\angle AO_1B = arccos\frac{f^2 + r^2 - n^2}{2 \cdot f \cdot r}. \quad (8)$$

At the next stage, we define the angle AO_1B_0. Its value is determined according to the following equation:

$$\angle AO_1B = \frac{\pi}{2} - \varphi - \xi. \quad (9)$$

As shown in Fig. 2, the right steering arm turning angle is the difference between the angles AO_1B and AO_1B_0, hence

$\Theta_o = \angle AO_1B - \angle AO_1B_0$.

Substituting the equations obtained above to the last equation, we obtain the final relation for determining the right steering arm turning angle:

$$\Theta_o = \arccos\frac{f^2+r^2-n^2}{2\cdot f\cdot r} - \frac{\pi}{2} - \mathrm{arctg}\frac{x_0}{y_0} + \arcsin\left(\frac{r}{f}\cdot\sin\alpha\right). \quad (10)$$

Thus, the equation (10) determines the relation between the steering linkage left and right steering arms turning angles at any turning radius of the vehicle.
Recently computer software has been developed that enables three-dimensional design and modeling of various processes in technical systems. This software includes AutoCAD SolidWorks, Compass, Creo, etc.
The simulation method is the one where using a personal computer a generated three-dimensional model of the mechanism without making it to the metal is designed. Such model is completely similar to the physical pattern and has the same physical properties.
xCreo software is designed for three-dimensional solid and surface modeling of parts and structures of any complexity; it can effectively automate the design manufacture of products. It is widely used in automobile and aeronautical construction.
The analysis tools of the model, available in Creo, allow you to calculate their mass-inertial characteristics automatically, to conduct all the necessary measurements of distances, angles, thicknesses, and inclinations. Methods of analysis of surfaces allow measuring the two-corner angle, tangents, curvature at each point or in cross-sections and other surface characteristics. Simulation technique can reveal shortcomings at the design stage and optimize it without losing time and money. Regarding the vehicle steering linkage, it is a spatial mechanism through kingpin inclinations in two planes - longitudinal and lateral. An analytical way to determine the spatial mechanism kinematics is quite complicated, so 3D modeling is more prevalent and affordable.
The object of research is KrAZ-7634HE, a large-capacity transport vehicle (Fig. 3). It has 8 wheels, double-axle steering mechanism, a total weight of 41 tons with carrying capacity of 27 tons.

Fig. 3: The object of the research - KrAZ-7634HE.

When designing a three-dimensional model, the nodal connections coordinates of KrAZ-7634HE vehicle steering are specified when the steer angle is zero. For coordinates available, models of connecting rods, tie rods, steering arms, steering knuckle, wing spars, steer axles, as well as wheels and cabins using pulling, turning, stretching and rounding commands were constructed.
After designing steering linkage details, a mechanism was designed in the Creo Parametric software, which has the ability to move while the commands "move component" are given to it. The developed three-dimensional model is shown in Fig. 4

For the visualization of the steering linkage kinematics in the Creo software, a visual turning of the steerable wheels was carried out. The left steering knuckle of the first axle was set the twisting misalignment in 5° to the left and right to the maximum angle Θ = 30°. Each change in the steering knuckle position was carried out by measuring the minimum distances from the kingpin axis to the ball stud axis of the tie rod of the steering linkage (Fig. 5). Also, the steer angles of other steerable wheels were measured regarding to the left steerable wheel of the first axle.

Fig. 4: Three-dimensional model of KrAZ-7634HE with steering linkage.

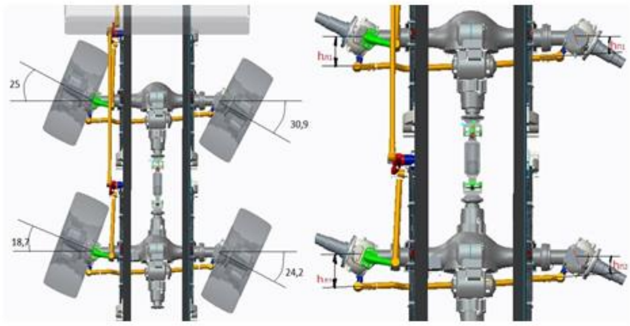

Fig. 5: Researches of steerable wheels kinematics in the Creo Parametric software.

4. Results and Application

The turning kinematics of steerable wheels, which is covered by a steering linkage, is usually estimated using the graphs of the dependence of the steer angle of the outer wheel on the steer angle of the inner wheel [5-8, 10]. The accuracy of kinematics is analysed because of the error between the real and theoretical steer angle of the steerable wheels [5, 6, 8, 10].
Since the drive from the steering goes first to the left wheel of the first axle, then as the input parameter we will use the left wheel steer angle of the first axle [5, 7, 10]. Fig. 6 shows graphs illustrating the steerable wheel's kinematics of KrAZ-7634HE.
Graphs (A) and (B) of Fig. 6 illustrate the steering linkage kinematics of the first axle. At the steer angles up to 20^0 to the left and right, the difference between the theoretical and practical steer angles of the outer wheel does not exceed 0.5^0, and the maximum error is -3.2^0 when turning 30^0 left. In [5] this error does not exceed 1^0 at the optimal angle of the installation of turning arms. Similar results after optimization of the steering linkage are given in [6, 8].
Concerning the second axle, the linkage kinematics is illustrated by the graphs (E) and (F) of Fig. 6, then the maximum error is up to 0.9^0 when turning 30^0 to the left. In this case, the values of the steer angles of the second axle wheels are smaller compared with the wheels of the first axle. The correlation between the steer angles of the inner wheels of the first and second axles is illustrated by graphs (C) and (D) of Fig. 6. The analysis confirms the satisfactory kinematics that is provided with the steering drive, since the maximum error between the practical and theoretical steer angles does not exceed 1.4^0 when turning 23^0 rights.

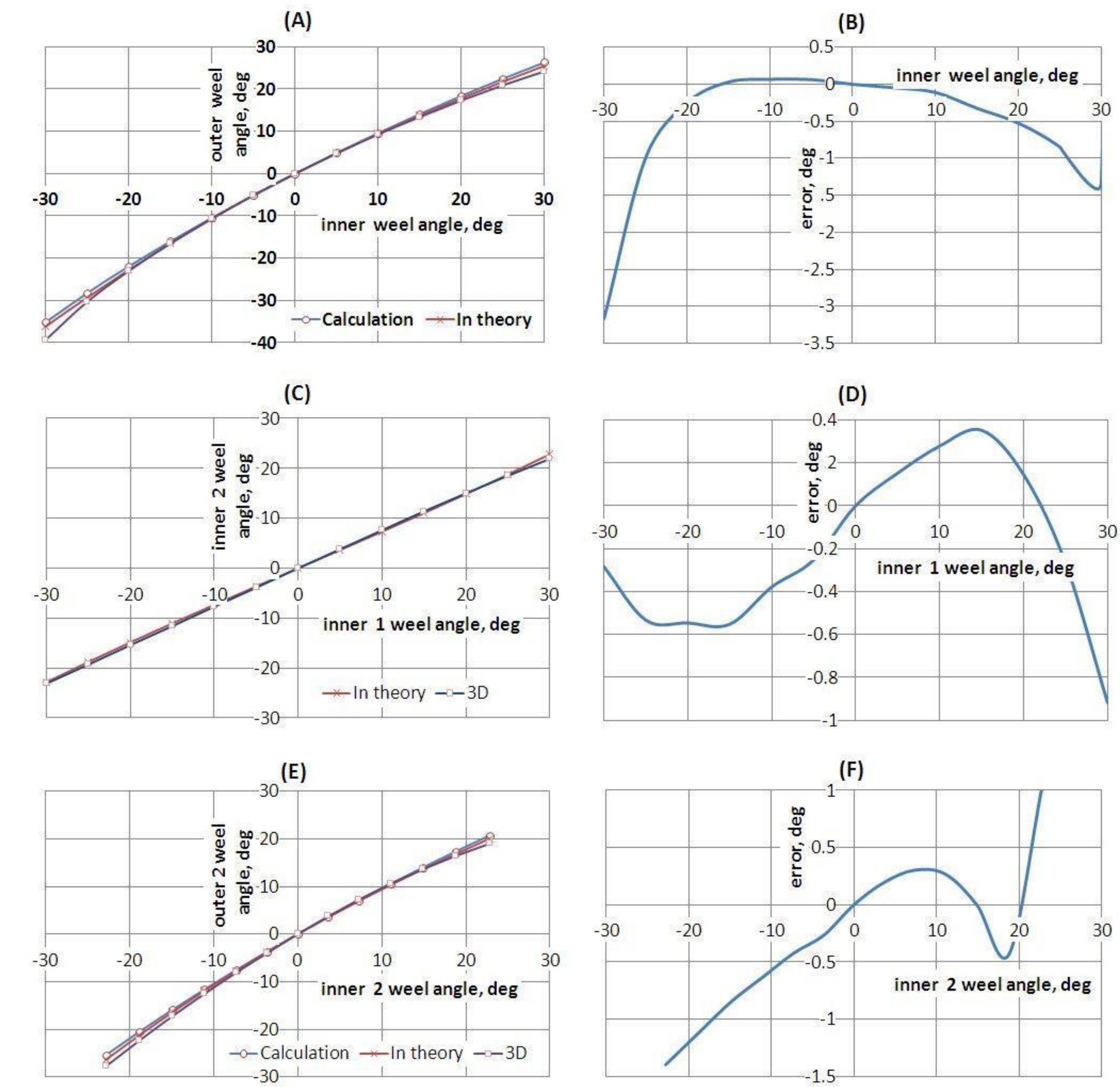

Fig. 6: Results of modelling steerable wheels turning kinematics: (A) the dependence of the steer angle of outer wheel of the first axle on the steer angle of the inner wheel of the first axle; (B) the error between the steer angles, obtained from 3D modelling and theoretical angles, calculated using the equation (1); (C) the dependence of the steer angle of the inner wheel of the second axle on the steer angle of the inner wheel of the first axle; (D) the error between the steer angles, obtained from 3D modelling and theoretical angles, calculated using the equation (3); (E) dependence of the steer angle of the outer wheel of the second axle from the steer angle of the inner wheel of the second axle; (F) the error between the steer angles, obtained from 3D modelling and theoretical angles, calculated using the equation (2).

5. Conclusions

As the result of the research, a mathematical model of a four-bar steering linkage (10) was developed, which allows determining the steer angle of the right steering arm of flat steering linkage at any radius of the vehicle's turning. This dependence is convenient for use, calculation and programming using modern software. Of vehicle KrAZ-7634HE, a three-dimensional model of steering linkage was designed, simulation studies of kinematic processes were conducted. The simulation technique has shown a satisfactory kinematics of the steerable wheels turning of double-axles, as is confirmed by slight errors between the practical and theoretical steer angles. With regard to the above mentioned, the three-dimensional model completely simulates the real spatial mechanism, and dependence (10) is obtained for the flat mechanism. Consequently, for the analysis of the kinematics of steerable wheels turning with sufficient accuracy it is possible to use a flat model. Dependence (10) is also developed, and the three-dimensional model can be used to optimize the design parameters of any four-bar steering linkage vehicles.

However, additional research needs to be done concerning the correct determination of the forces and strains in the steering details, as well as the driver's efforts attached to the steerable wheel. In our opinion, in the case of a steering linkage flat model application, these efforts will be determined with considerable error, so it is necessary to use a mathematical model that takes into account the spatial arrangement of the vehicle steering linkage and vehicle steering wheel drive. It is also required to carry out further study of the impact of the kingpin inclinations on the steering linkage kinematic and power characteristics.

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