The method of synthesis of new structural schemes of additional working equipment of the motor grader with the use of graphs and matrices

V A Mikhailovskaya

Moscow Automobile and Road Construction State Technical University (MADI), 64, Leningradsky prospect, Moscow, Russia
E-mail: valeriymikhailovskaya7@gmail.com

Abstract. The article explores existing methods for the synthesis of structural schemes, but special attention is paid to a method based on the theory of graphs and matrices. The paper presents structural schemes of the additional working equipment of the motor grader and matrices of kinematic pairs, and graphs of fastening of elements of the structural scheme obtained by this method. The authors compare possible variants of these schemes and describe their advantages and disadvantages. The researchers suggest some test results conducted on a grader. The article calculates the stress-strain state, taking into account experimental data, and two design options for additional equipment of the grader.

1. Introduction

It is difficult to imagine modern life without the use of road construction equipment, which makes it possible to comprehensively mechanize the most difficult construction works, such as building, repairing and cleaning roads, preparing foundation ditches for building houses, clearing trees from territories, and developing high-strength soils etc.

Graders are mainly designed for planning and profiling, so the work performed by the grader is an important stage in the construction of roads. In addition to their primary purpose, they can also perform other operations when using additional working equipment. For example, clearing territories can be carried out much more efficiently if we use a bulldozer blade and an additional side blade [1].

Design of the working equipment of the grader, taking into account the structural schemes with the best characteristics, is a difficult task for modern industry engineers. Often, the development of new equipment is based on examples of existing structures and calculation methods, but such way hardly helps to find the optimal design. A design with the most favorable characteristics for these conditions and tasks can be selected when all possible structural schemes are obtained. Therefore, the search for structural schemes of the working equipment of the grader is an important and urgent task today.

The aim of the paper is to demonstrate the method which helps to obtain new structural schemes of the additional working equipment of the motor grader, which will expand the range of options for the
equipment of the motor grader in real constructions. Moreover, the article describes some designs in order to identify their advantages and disadvantages and prospects for further application in practice.

2. Materials and methods
A significant part of the machines has redundant connections. The work of L. Reshetov proves that the presence of redundant connections does great harm, since they require precision in manufacturing, and eventually make assembly of machines impossible, reduce the load capacity of the machine, reduce efficiency due to high friction forces in the joints, increase mass and dimensions, which leads to reduced productivity and reliability of the machine [2].

There are a large number of methods for structural synthesis of mechanisms: the Frank method, a method based on graph theory, a method for obtaining new structural schemes by adding Assur groups, a method based on grouping theory, etc. [3]. To obtain new structural schemes of the additional working equipment of the grader, we will use the method based on graph theory.

To determine the presence or absence of redundant connections, we use the Somov-Malyshev formula:

$$W = 6 * n - 5 * P_5 - 4 * P_4 - 3 * P_3 - 2 * P_2 - 1 * P_1 - W_m,$$

where
- \(n\) – number of elements in the structural scheme;
- \(P_i\) – the number of kinematic pairs of the i-th class;
- \(W_m\) – number of mobility points.

Along with the known types of constructions for attaching the dozer blade to the grader, there are some others, the disadvantages and advantages of which will be discussed later in the article.

The same scheme can be performed with different kinematic pairs, which will affect both the performance of this design and reliability.

One of the most popular designs among manufacturers is a dozer blade mounted on four rods, where the two lower blades are fixed to each other by means of a reinforcing plate that prevents lateral loads from affecting the hinges. The blade is raised and lowered by a hydraulic cylinder, which is attached either to the blade or to the reinforcement plate with the head of the rod, both options are used in practice.

![Figure 1](image1.png) An example of a bulldozer equipment when the blade is attached to the blade.

![Figure 2](image2.png) An example of a bulldozer equipment when the blade is attached to a reinforcement plate.
3. Model

Possible structural schemes for this type of additional construction equipment:

![Figure 3. Structural scheme for bulldozer equipment with hydraulic cylinder mount on the blade, option 1.](image)

Let’s check availability of redundant connections by the formula:

\[
W = 6 \times 5 - 3 \times 6 - 2 \times 4 - 4 = 0
\]

Let’s make a matrix and a graph for this structural scheme.

![Figure 4. The matrix of kinematic pairs of the structural scheme in Figure 3.](image)

The compilation of such matrices makes it possible to more clearly and quickly assess whether the created structural scheme differs from existing ones. Moreover, it is easier to store it in a computer in this form, creating entire databases of such matrices. In addition, looking at the obtained matrix of kinematic pairs, we can immediately assess whether the structural scheme contains redundant connections or not, because the matrix of kinematic pairs of the structural scheme that does not contain excess mobilities is symmetric with respect to the main diagonal.

The graph for the structural scheme is as follows:

![Figure 5. The graph of connections of the elements of the structural scheme in Figure 3.](image)

Looking at this graph, we can conclude that link 3 has several links with both link 5 and link 0. Due to manufacturing errors that are inevitable in production, the axis of attachment of link 3 to links 5 and
0 may not coincide, therefore it was necessary to carry out one of the fastenings with axial movement, thus allowing the structure to self-mount.

It is possible to reduce this graph, the third-class kinematic pair in conjunction with the second-class kinematic pair gives a fifth-class pair.

![Reduced graph for the structural scheme in Figure 3.](image)

Using graph theory, we can also simplify the process of tracking new structural schemes and even automate it using software [4].

An example is the bulldozer equipment mounted to the motor grader through three rods and a hydraulic cylinder.

![Structural scheme for bulldozer equipment with hydraulic cylinder mount on the blade, option 2.](image)

Let’s check the presence of redundant connections by the formula:

\[ W = 6 \times 4 - 3 \times 5 - 2 \times 3 - 3 = 0 \]

![The matrix of kinematic pairs for the structural scheme in Figure 7.](image)
Today, there is a large number of designs that are not inferior to the existing ones in terms of performance and manufacturing costs, but they are not so popular among the already familiar parallelogram suspension. Let’s consider the design and structural schemes of some of them.

Let’s check the presence of redundant connections by the formula:

![Figure 9. The graph corresponding to the structural scheme in Figure 7.](image)

![Figure 10. The reduced graph for the structural scheme in Figure 7.](image)

![Figure 11. Structural scheme of bulldozer equipment suspended on a triangular frame, option 1.](image)

|   | 0   | 1   | 2   | 3   | 4   |
|---|-----|-----|-----|-----|-----|
| 0 | P5  | P3  | P3  |     |     |
| 1 | P5  |     |     |     |     |
| 2 | P5  | P5  | P3  | P3  |     |
| 3 | P3  | P3  |     |     |     |
| 4 | P3  | P3  |     |     |     |

![Figure 12. The matrix of kinematic pairs for the structural scheme in Figure 11.](image)
\[ W = 6 \times 4 - 3 \times 5 - 2 \times 1 - 5 \times 1 - 2 = 0 \]

**Figure 13.** Connection graphs of the elements of the structural scheme in Figure 11 a) Complete graph b) Compressed graph.

**Figure 14.** The structural diagram of the bulldozer equipment suspended on a frame in the form of a rhombus.

**Figure 15.** a) A matrix of kinematic pairs; and b) a graph of the connection of elements for the structural scheme in Figure 14.

Considering the scheme in Figure 11, we can see that when attaching the triangular frame with the back side, we obtain a new scheme. Let’s look at it, calculate the stresses obtained by loading both design options in the SolidWorks software and compare it.
Figure 16. Structural scheme of bulldozer equipment suspended on a triangular frame, option 2.

|   | 0 | 1 | 2 | 3 | 4 | 5 | 6 |
|---|---|---|---|---|---|---|---|
| 0 |   | P3| P3|   | P3| P3|   |
| 1 | P3|   | P5|   |   |   |   |
| 2 | P3|   |   | P3|   |   |   |
| 3 | P3| P5| P3| P3| P3| P3|   |
| 4 | P3|   |   |   | P3|   | P3|
| 5 | P3|   | P3|   | P3|   | P3|
| 6 | P3|   | P3|   | P3|   | P3|

Figure 17. The matrix of kinematic pairs for the structural scheme in Figure 16.

Let’s check the presence of redundant connections by the formula:

\[ W = 6 \times 6 - 3 \times 10 - 2 \times 1 - 4 = 0 \]

Figure 18. Connection graphs of the elements of the structural scheme in Figure 16 a) Complete graph b) Compressed graph.

There was an experiment at the MADI University training ground to determine the stresses in the metalwork of the motor grader at additional calculated positions, in which the motor grader abutted the edge of the main working equipment of the dump into an insurmountable obstacle. At the same time, strain gauges were glued at control points of the metal structure, according to which stresses were recorded in the metal structure. The experiment was carried out taking into account various calculated provisions of the grader. As a result of the experiment, it was found that the maximum traction force on the dump of the grader at one of the calculated positions is 49850 N. Therefore, under a real existing load of this value, we calculated the models of additional equipment of the grader.
Figure 19. One of the points (blue mark) on the metal structure of the grader, where the strain gauge was glued. In the illustration, a spinal beam is at the attachment point of the hydraulic cylinders.

Calculation of the design model of the bulldozer equipment corresponding to the structural scheme in Figure 16 showed maximum stresses equal to 154 MPa, which is less than the yield strength, so we can conclude that the design has retained its performance under this load.

Figure 20. The stress state of the metal structure of the bulldozer equipment when a load of 49850 N is applied to the edge of the blade.

Calculation of the structure corresponding to the structural scheme in Figure 11, showed maximum stresses three times higher than the values obtained in the calculation of the previous design. The calculation showed that the thin spots are the fastening of the hydraulic cylinders for raising / lowering and turning the blade.
Figure 21. Stresses arising in the metal structure corresponding to the scheme in Figure 11. The calculation of both models was carried out at the same load, which was applied in both cases to the edge of the blade. Thus, the second design is recommended for use on light graders.

4. Conclusion
1. The use of structural schemes without redundant connections allows to reduce the stress-strain state of the metal structures of the grader.
2. The use of graph and matrix methods for synthesizing new structural schemes allows accelerating the identification of structural schemes without redundant connections.
3. Using experimentally identified real powers on the working body of the grader, we can determine the actual design position of the grader, thereby reducing its stress-strain state and increasing the strength in some nodes of the metal structure, which will increase its productivity by increasing the working effort on the working bodies.
4. The presented method for the synthesis of new structural schemes in conjunction with traditional methods of calculation forms a powerful and comprehensive tool for designing new designs of working equipment of the grader.

References
[1] Saveliev A G 2000 Obosnovanie parametrov strukturnykh skhem i sterzhnevykh sistem rabochego oborudovaniya dorozhno-stroitelnikh mashin: dis ... d-r tekhn. nauk: 05.05.04 364
[2] Reshetov L N 1985 Samoustanavlivayushchiesya mekhanizmy – 2-e izd. – M : Mashinostroenie, 272
[3] Huafeng Ding 2015 Automatic structural synthesis of planar mechanisms and its application to creative design Doctor thesis, university of Duisburg-Essen, Germany
[4] Pucheta M A 2008 Computational methods for design and synthesis of planar mechanisms Doctor thesis, Argentina (in Eng)
[5] Pennestri E and Belfiore N P 2015 On Crossley’s contribution to the development of graph based algorithms for the analysis of mechanisms and gear trains, Mechanism and Machine Theory, 92-106
[6] Glazunov V A 1991 Sintez prostranstvennykh rychazhnykh mekhanizmov parallelnoy struktury i razrabotka metodov ikh analiza: dis . d-r tekhn. nauk: 05.02 18. – Moskva, 311
[7] Mruthyunjaya T S 2003 Kinematic structure of mechanisms revisited, Mechanism and Machine Theory, 279-302
[8] Voloboev V G 2003 Metodologiya optimalnogo vybora parametrov elementov rabochego oborudovaniya zemleroynyh i zemleroyno-transportnykh mashin: dis .. d-r. tekhn. nauk: 05.05 04. – Omsk, – 351
[9] Shevchenko V, Chaplygina O and Beztseanny Zh 2015 Methods to determine measures providing a motor-grader road-holding ability//International Scientific Journal «Machines Technologies Materials», 78-83 (ISSN: 1313-0226)