Structural schemes analysis of road and construction machines

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Abstract. The paper develops a methodology for computation external movability of mechanisms with two-sided and one-sided ties. These mechanisms are often used in the design of road-building machines. Also this article provides with the some of examples of structural schemes of bulldozers, excavators, motor graders and loaders. Describing the main motions of the operating equipment, here is given some example of using different types of hinges.

1. Introduction

Track type tractors, excavators, loaders and motor graders are widespread machines due to their majority of application. All these machines can be united in groups by structural features.

The first group – machines that have as operating equipment blade. Machines in this group have operating equipment, that are design for cutting and moving engaged material, for example track type tractors with tilted and not tilted blades, motor graders. Track type tractors equipment consist of rods couplings, like straight frames, that attached blade with undercarriage. Also there are one or several rods for misalignments compensation. And this rods take horizontal loads.

The second group – machines that have buckets type of operating equipment. The thing that characterizes them is all motions of the operating equipment are for the filling out or unloading. Excavators and loaders have such equipment. Loaders bucket is attached to the carriage of machine due to hinged boom. Excavators buckets can have more operating motions in comparison with the loaders, bulldozers and motor graders (Figure 2).

2. Goal

The purpose of this article is to develop methods, which will help engineers to create new structural schemes of mechanisms according to working motions that these mechanisms perform and according to tie that these mechanisms have in their design.
3. Analytical model

Track type tractors with tilted equipment have one distinction – the possibility of rotating in the horizontal plane. This motion is possible due to frame, that pivotally connected to frame and to undercarriage. As an example, motor graders have a draw bar, more often joined by spherical pivot with a main frame.

A circle member is rotatably attached to a draft frame. A blade is mounted to blade support, that has tilt frame. The tilt frame is attached to the legs for pivotally movement of the blade support and the blades movement relative to the circle frame. Also this construction allows a sideshifting of the blade. Figure 2. shows possible movement of blades operating equipment. Possible movements of blades and buckets are:

- In vertical plane – to lift and to down blade or bucket, this movement can do track type tractors without tilted blade and with rigid attachment of frame with blade, for example DZ-42G (motion $V_1$, along axis Z).
- Additionally lateral motion is possible in the vertical plane of X axis. It is the usual movement for motor graders, the track type tractors, loaders, excavators-manipulators (motion $V_2$).
- Also the equipment rotation around Z axis is possible in the horizontal plane. It is typical motion for the motor graders, track type tractors, loaders and excavators (motion $V_3$).
- Equipments rotation in vertical longitudinal plane (relatively Y axis) is necessary to change the angle of cutting edge. It is also typical movement for graders, track type tractors, loaders and excavators (motion $V_4$).
- Additionally equipments sideshifting in the horizontal plane in lateral direction (along Y axis) is possible. It is typical motion for motor graders and for some track type tractors (motion $V_7$).
- Movement forward or backward is possible by the movement of the machine or by movement of the operating equipment. (motion $V_5$, along axis X).

![Figure 1. Operating equipments, schematic drawings.](image-url)
Excavator equipment (Second group)  Loader equipment (Second group)  Bulldozer and motor grader equipment (First group)

Figure 2. Possible motions of the operating equipment.

Thus, all six motions of the blade that is possible have been described. All possible motions of the equipment are revealed due to analysis of technical materials and constructions of well-known machines. Connections of machine operating equipment elements are implemented through kinematic pairs. There are revolute and prismatic joints, cylindrical joints and in rare cases Hooke’s joint, spherical joint with translation motion. Kinematic pairs, that have been used in design of road and construction machines, are presented in Figure 7.

As was proved in the Reshetov’s paper [1], machines will be able to move their operating equipment, if the design of machines has no redundant constraints. Otherwise in the design of operating equipment will appear self-breaking internal forces, which will have value, that will exceed value of forces, that appear due to loads on the blade or other operating equipment. Moreover, if operating equipment has redundant constraints, the movements of this equipment will be possible only due to clearances in the joints. And the value of these joints will set the range of movements of operating equipment.

You can measure the number of redundant constraints by using the equation of Chebyshev-Malishev [1]:

\[ W = 6 \times n - 5 \times P_y - 4 \times P_y - 3 \times P_y - 2 \times P_y - W_M, \]

\( W \) – a number of external movability;
\( P_i \) – a number of kinematic pairs of certain class;
\( W_M \) – a number of local movability.

Below there are some variants of operating equipment schemes for bulldozer, excavator and motor grader.

Figure 3. Track type tractors operating equipment without tilted blade, schematic drawing.

Figure 4. Track type tractors operating equipment with tilted blade, schematic drawing.
Figure 5. Excavators operating equipment with jointed elements of boom and stick, schematic drawing.

Figure 6. Motor graders operating equipment, schematic drawing.

| Classification                  | Scheme |
|---------------------------------|--------|
| Revolute joint                  |        |
| Prismatic joint                 |        |
| Cylindrical joint               |        |
| Hooke’s joint                   |        |
| Spherical joint                 |        |
| Spherical with longitudinal motion joint («ball in pipe») | |

Figure 7. Kinematic pairs, that are used in the design of construction and road machines.

Local movability (relative motion) will appear, when the rods are attached by spherical joints, therefore the relative rotation of the rods around their own axis appears. And this axis passes through this spherical joints.

Most part of machines, that have been using in a construction area, has redundant constraints. In the L. N. Reshetov’s book was proved, that existence of redundant constraints causes great harm for machines design. If redundant constraints are in design of machine, then it will better to make parts of the design with more accuracy, because this redundant constraints can make assemble of part impossible, reduce a value of possible loads on the blade, reduce performance of a machine, due to high level of friction in joints, and also increase the weight and overall sizes.

In addition to this, redundant constraints can reduce a functionality of operating equipment and reliability.

Modern operating equipment of road machinery should have high performance, low metal intensity, high reliability and low cost of production.

Nowadays road and construction machines use hydraulic systems for realizing their operating functions, for example to change the position of the motor graders blade, vertical hydrocylinders are engaged or if it is necessary to sideshift the circle and draft frame of a motor grader then inclined cylinder should be engaged.

If design of a machine has additional degrees of freedom, that are technologically proved, it will expand possibilities of operating equipment and will increase a performance.

Date about limits in the functionality of motor graders operating equipment are in the Table 1.
Table 1.

| Country | Company, Power, kW | Blade sideshift right and left, mm | Maximum lift and depth of blade, mm | Blade tip range, ° |
|---------|---------------------|-----------------------------------|------------------------------------|-------------------|
| USA     | CAT, motor grader 160 K, 139 kW | 943 851 | 452 790 | 40; -5 |
|         | John Deere, motor grader 770 G, 138 kW | 683 683 | 490 No data | 42; -5 |
| USA     | Shantui, motor grader SG18-3, 132 kW | No data No data | 440 500 | 44; -1 |
| China   | Hidromek, motor grader HMK 600MG, 140 kW | No data no data | 525 660 | 46 |
| Turkey  | Road Machinery Factory, motor grader DM-14.0, 132 kW | 800 800 | No data 500 | No data |

Similar data can be gotten about other operating equipment of road machines.

The equation Chebysheva-Malisheva has gotten from the condition, that the body has six degree of freedom in space: three – revolute and three – prismatic. But, in certain cases, it is better to take into consideration the direction of possible movement of operating equipment and direction of holding bonds, for example, in case of using one side types of bonds like ropes in rope excavators.

\[ W = 12 n - 11 P_11 - 10 P_10 - 9 P_9 - 8 P_8 - 7 P_7 - 6 P_6 - 5 P_5 - 4 P_4 - 3 P_3 - 2 P_2 - P_1 - W_m, \]  

(2)

where \( P_{10} \) – revolute pair;
\( P_8 \) – cylindrical pair or Hooke’s hinge;
\( P_6 \) – spherical pair;
\( P_4 \) – type of pair like «ball in pipe»;
\( P_2 \) – kinematic connection like rod with several spherical hinge;
\( P_{11} \) – ratchet gear;
\( P_6 \) – cylindrical pair, that cannot rotate or translationally move any side (a combination of ratchet gear and prismatic pair);
\( P_7 \) – ratchet gear with universal joint (spherical pair with pin, if the stroke of pin has settled);
\( P_5 \) – «ball in the tube», if the stroke of ball has settled (ball on the bottom of the pipe);
\( P_3 \) – ratchet translational pair on the flat;
\( P_1 \) – cam; one sided rod: from one side is spherical joint, from another – pair \( P_5 \); or connection through a cable.
In the design of machines by action of external forces. For example, then there will not be a holding pair of ties and redundant scheme. Therefore, if you want to avoid mistakes in creating new schemes of road machines, you have to consider certain movability and bonds. Balance equation is:

\[
\frac{n}{w_{i+}} - \frac{f_{i+}}{S_{i}} = 0
\]

where \(w_{i+}\) – degree of freedom of rotation every part in all sides around every axis; \(f_{i+}\) – degree of freedom of translational motion every part in all sides along every axis; \(n\) – number of bodies (elements of construction); \(K_j\) – number of bonds in every translational or rotational bonds, that named \(S_j\).

You can represent all kinematic pairs or joints as a set of ties, for example, ratchet gear, that have rotating degree of freedom \(w_{i+}\), you can present like:

\[
S_{z+} + S_{z} + S_{y+} + S_{y} + S_{x+} + S_{x} + S_{wz} + S_{wy} + S_{wy} + S_{wz} + S_{wz}.
\]

Rotational pairs, that have rotational degree of freedom in both sides around axis \(OZ\) you can present \(w_{i+}\) and \(w_{i-}\) as:

\[
S_{z+} + S_{z} + S_{y+} + S_{y} + S_{x+} + S_{x} + S_{wz} + S_{wy} + S_{wy} + S_{wz} + S_{wz}.
\]

Similarly, any kinematic pair can be represented.

There are particular cases, when instantly changeable scheme appears and you can consider this cases, if each link has its own coordinate system. For example, if longitudinal axis of rods, that are connected by spherical hinges, match with each other, than will appear instantly changeable scheme. Thus, you can consider particular cases, when you define mutual arrangement of ties coordinate systems. It means, that ties, for example, \(S_{y+}\) and \(S_{y-}\); \(S_{y+}\) and \(S_{y-}\). (Figure 8) eliminate degrees of freedom along the \(OY\) axis in both sides, because axis \(O'Y'\) and \(O''Y''\) of ties system coordinate, when it intersects with the axis \(OX\) of the main coordinate system, it forms the arm, that named 1.

Also you should take into consideration the direction of the action of external forces. For example, there is a beam, hinged fixed by one end and freely leaned by another end (Figure 9). Ties of system: \(S_{y+}\) and \(S_{y-}\); \(S_{y+}\) and \(S_{y-}\); \(S_{y+}\) and \(S_{y-}\); \(S_{y+}\) and \(S_{y-}\); \(S_{y+}\) and \(S_{y-}\); \(S_{y+}\) and \(S_{y-}\); \(S_{y+}\) and \(S_{y-}\) – of revolute joint A; \(S_{y+}\) – of carriage B. Rotational moment of the force of gravity \(G\) is balanced, because the pair of ties \(S_{y+}\) and \(S_{y-}\) forms the arm, if this pair of ties in intersection with flats, that formed by axis of main coordinate system. If the force \(G\) acts in the opposite direction, then there will not be a holding pair of ties and redundant mobility will appear.

This approach is also important, for example, in the design of bulldozer units, when the ground ties are set vertically down and horizontally in all directions from the adhesion forces of a machine with the ground. This allows you to exclude from the design of a machine redundant breakout connection, especially when the bulldozer unit is operating on the rough surface or when dozer is operating at different levels and at different angles to the horizontal plane.
Therefore to ensure a fixed position of the construction and road machines relative to the base surface and fixed position of the working equipment relative to the machine, it is not necessary to have twelve one-sided links. It is necessary to identify the possible directions of external forces of construction and road machine and to ensure links that would counteract possible external forces. For example, for a road roller, a vertical link down Sy is not necessary. For a blade of a bulldozer with a non-tilted blade in the traditional version, it is necessary to have all twelve one-sided links, because external force on the blade can be applied at any point and directed in any direction. Existence of more than twelve one-way links leads to the appearance of additional stresses in the working equipment of machines, and the incorrect arrangement of the links leads to excessive mobility of the construction and road machine.

4. Example
Let’s consider as an example working equipment of track type tractor DZ-110A (Figure 10). The blade has following movabilities: \( w_{x+}, w_{x-}, w_{y+}, w_{y-}, w_{z+}, w_{z-}, f_{x+}, f_{x-}, f_{y+}, f_{y-}, f_{z+}, f_{z-} \). Hydrocylinder AB sets the links \( S_{y+, y-} \). Rods CD and EF set the links \( S_{w_{y+}, w_{y-}} \) and \( S_{w_{z+}, w_{z-}} \), because there is a shoulder for the moment C’E’. Rods KL and MN set the links \( S_{w_{y+}, w_{y-}} \) and \( S_{w_{x+}, w_{x-}} \), rod QP – the links \( S_{w_{x+}, w_{x-}} \). There are no redundant links in the picture below and tilt of blade can be set without any extra stresses in the design.
5. Conclusions
Thus, in order to increase the efficiency of construction and road machines with a significant simplification of the structure and reduction of production costs, it is necessary to analyze their structural schemes. And then decide which links apply in the design one-sided or both-sided. To extend the functionality of construction and road machines by eliminating redundant links in the design, it is better to use in the design the number of links less than the number of links that external forces set on machine.

It is necessary to create the way to formalize analyzing and synthesizing new structural schemes of the construction and road machines in order to speed up this work. At the same time, it is possible to accelerate the memorization and analysis of structural schemes by creating database of already existing structural schemes. It could speed up searching for new ones and comparing them with each other.

In the design of machines it is necessary to use schemes without redundant links. Otherwise, self-extinguishing forces will occur even before the application of the workloads.

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