Effect of the angles of the earth-moving machine moldboard on the cross slope of the graded surface

M S Korytov¹, V S Shcherbakov¹ and V V Titenko²

¹Siberian automobile and highway university, Mira ave., 5, Omsk 644090, Russia
²Omsk State Technical University, 11, Mira Ave., 11, Omsk, 644050, Russia

Abstract. Investigations of the effect of the moldboard angle, the earth-moving machine of the motor grader type, on the angle of the cross slope of the formed earth surface was carried out. It is established, that the slope in the cross direction of the surface being graded, depends on the angles of installation of the moldboard blade element. The slope of the surface being graded, is not affected by the dimensions of the moldboard and the construction of the earth-moving machine. Analytical and graphical functional dependences of the angle of inclination of the moldboard blade element to the horizontal plane are obtained, which are necessary to ensure a given angle of the cross slope of the surface being graded. The results of the research can be applied in the field of development and tuning of on-board systems for indicating and controlling the operating modes of an earth-moving machine.

Keywords: earth-moving machine, moldboard, angle, motor grader, blade, cross slope.

1. Introduction
To earth-moving machines (EM), widely used in road-building and agriculture for the profiling of earth surfaces, movement and leveling of ground, a number of requirements are produced. The work of many researchers is devoted to the solution of particular problems. The operation of the machine should be economical [1, 2], and the control system should provide the convenience of control [3]. Also, a given accuracy of ground treatment should be ensured [4]. The construction of the EM should be fairly simple and reliable in operation [5, 6]. A significant number of research works solve the problem of increasing productivity [7, 8, 9].

The kinematic analysis of the working equipment of the EM is one of the most important elements in the solution of most of the above problems [10, 11]. The basis for the known methods of studying the kinematics of EM is laid flat calculation schemes, that do not take into account the spatial character of the constructions. Mathematical models of control systems for the moldboard working body of the EM, the use of which allows the formation of a certain profile of the roadbed (surface being graded) in the cross direction, as a rule, does not take into account the effect of the moldboard angle. This causes significant errors in the cross slope of the roadbed [3, 10]. At an moldboard angle is meant the angle of rotation of the blade relative to the machine about the vertical axis.

The derivation of the analytical dependencies of the blade tilt angle (angle of inclination of the moldboard to the horizontal plane) is actual. The use of dependencies in control systems of the EM will allow to provide the given values of the angle of the cross slope of the roadbed.

2. Theoretical theses
In figure 1, a, the image of the moldboard in the fixed coordinate system $O_0X_0Y_0Z_0$ is given.
Figure 1. The moldboard angle $\varphi$ and blade tilt angle $\gamma_{po}$ in the fixed coordinate system (a) and the corresponding complete spatial calculation scheme (b).

The EM moves along the axis $O_0X_0$. In figure 1, b, shows the calculation scheme for illustrating the subsequent theses. The following designations are accepted on the scheme: $Y_{po}$ – coordinate of the center of the blade in the vertical direction; $\gamma_{po}$ – blade tilt angle to the horizontal plane; $\varphi$ – the moldboard angle; $\gamma_f$ – the actual angle of the cross slope of the roadbed, at the moldboard angle $\varphi$ and at the blade tilt angle $\gamma_{po}$.

Additional notations are introduced: $L_1 = O_0 A_1$; $L_2 = O_0 A_{po}$; $L_3 = O_0 A_f$; $\Delta \gamma = \gamma - \gamma_f$ – deviation of the given cross profile from the actual in angular expression (error of the cross profile); $\Delta \gamma_{po} = \gamma - \gamma_{po}$ – correction of the blade angular position, required to ensure the slope of the graded surface in the cross direction $\gamma$.

A number of theses were formulated.

Thesis 1

The angle $\gamma$ of the cross slope of the surface, graded with the EM, with the value of the moldboard angle $\varphi \neq 90^\circ$, can be provided by setting the blade tilt angle relative to the horizontal plane $\gamma_{po}$:

$$\gamma_{po} = \arctg (\sin \varphi \cdot \tan \gamma).$$

Proof

From figure 1, b, it can be seen that

$$L_1 = \frac{Y_{po}}{\tan \gamma};$$

$$L_2 = \frac{Y_{po}}{\tan \gamma_{po}};$$

$$L_3 = \frac{L_1}{\sin \varphi}.$$  

Substituting (1) and (2) into (3) and carrying out the transformations, we get:

$$\tan \gamma_{po} = \sin \varphi \cdot \tan \gamma;$$

$$\gamma_{po} = \arctg (\sin \varphi \cdot \tan \gamma).$$

Effect 1.1
For values of the moldboard angle $\varphi$, and the blade tilt angle to the horizontal plane $\gamma$, the surface that is formed by the EM will have a slope $\gamma_f$ in the cross direction, equal to

$$
\gamma_f = \arctg \left( \frac{\tan \gamma}{\sin \varphi} \right).
$$

**Proof**

From figure 1, b, it can be seen that

$$
L_3 = \frac{Y_{\text{po}}}{\tan \gamma_f};
$$

$$
L_3 = L_1 \cdot \sin \varphi. \tag{6}
$$

Substituting (1) and (6) in (7), and carrying out the transformations, we get:

$$
\tan \gamma_f = \frac{\tan \gamma}{\sin \varphi}; \tag{8}
$$

$$
\gamma_f = \arctg \left( \frac{\tan \gamma}{\sin \varphi} \right). \tag{9}
$$

The functional dependences of $\Delta \gamma_k$ and $\Delta \gamma$ have the form:

$$
\Delta \gamma = \gamma - \arctg \left( \frac{\tan \gamma}{\sin \varphi} \right); \tag{10}
$$

$$
\Delta \gamma_k = \gamma - \arctg (\sin \varphi \cdot \tan \gamma). \tag{11}
$$

**Effect 1.2**

The change in the value of the moldboard angle creates a significant error in the profile cross slope $\Delta \gamma$. There is a need to take into account this error and correct the blade tilt angle.

**Effect 1.3**

The values of both: the errors in the cross profile $\Delta \gamma$, and the corrections of the blade angular position $\Delta \gamma_k$, do not depend on the size of the moldboard, the EM type, its geometric parameters, and are determined only by the angles of the blade tilt and moldboard $\gamma$ and $\varphi$. The validity of effect 1.3 follows from (5) and (9).

**Effect 1.4**

The changes in the moldboard angle by the values $\pm \Delta \varphi$ with respect to $\varphi=90^\circ$ cause the same error values of the cross profile $\Delta \gamma$. The validity of effect 1.4 follows from the symmetry of the function (11) with respect to $\varphi=90^\circ$.

**Effect 1.5**

The values of the error of the cross profile $\Delta \gamma$ and correction of the angular moldboard position $\Delta \gamma_k$, at identical values of the angles $\gamma$ and $\varphi$, are not equal to each other. They have opposite signs. The validity of effect 1.5 follows from the lack of identity of the expressions for the error (10) and correction (11).

**Thesis 2**

In order to compensate for the error of the cross slope $\Delta \gamma$ of the surface, graded by the EM (for values of the moldboard angle $\varphi \neq 90^\circ$), the value of the blade tilt angle to the horizontal plane should be changed by $\Delta \gamma_k$:

$$
\Delta \gamma_k = \Delta \gamma + \Delta \gamma_n,
$$

where $\Delta \gamma_n$ is the correction, characterizing the difference in the error of the cross profile $\Delta \gamma$ and the magnitude of the compensating change in the blade tilt angle to the horizontal plane.
Proof
From (10) and (11) we can write
\[ \Delta \gamma_k = \Delta \gamma + \arctg \left( \frac{\tan \gamma}{\sin \varphi} \right) - \arctg (\sin \varphi \cdot \tan \gamma), \]  
whence
\[ \Delta \gamma_k = \Delta \gamma + \arctg (0.5 \cdot \sin 2\gamma \cdot \cot \varphi \cdot \cos \varphi) \]  
or
\[ \Delta \gamma_k = \Delta \gamma + \Delta \gamma'_n, \]  
where
\[ \Delta \gamma'_n = \arctg (0.5 \cdot \sin 2\gamma \cdot \cot \varphi \cdot \cos \varphi). \]  

Effect 2.1
The value of the correction \( \Delta \gamma'_n \) does not depend on the size of the moldboard, the type of the EM, its geometric parameters, the magnitude of the cross profile error \( \Delta \gamma \), and is determined only by the values of the angles of the cross slope \( \gamma \) and moldboard \( \varphi \). The validity of effect 2.1 follows directly from (15).

Thesis 3
If there is an error in the cross slope of the surface \( \Delta \gamma \) (at the moldboard angle \( \varphi \neq 90^\circ \)), in order to compensate for the error, it is necessary to change the blade tilt angle relative to the horizontal plane by \( \Delta \gamma_k \):
\[ \Delta \gamma_k = K'_\gamma \cdot \Delta \gamma, \]  
where \( K'_\gamma \) is the coefficient of compensation of the moldboard angular position:
\[ K'_\gamma = \frac{\gamma - \arctg (\sin \varphi \cdot \tan \gamma)}{\gamma - \arctg \left( \frac{\tan \gamma}{\sin \varphi} \right)}. \]  

Proof
From (10) and (11) we can write
\[ \frac{\Delta \gamma_k}{\Delta \gamma} = \frac{\gamma - \arctg (\sin \varphi \cdot \tan \gamma)}{\gamma - \arctg \left( \frac{\tan \gamma}{\sin \varphi} \right)} = K'_\gamma, \]  
from which expression (16) is directly obtained.

Effect 3.1
The coefficient of compensation of the moldboard angular position \( K'_\gamma \) does not depend on the size of the moldboard, the type of the EM, its geometric parameters, the magnitude of the cross profile error \( \Delta \gamma \), and is determined only by the values of the angles of the cross slope \( \gamma \) and moldboard \( \varphi \). The validity of effect 3.1 follows from the expression (17).

Effect 3.2
The values of the compensation coefficient \( K'_\gamma \) are not affected by the signs of the angle \( \gamma \) and the change in the value of \( \Delta \varphi \) with respect to \( \varphi = 90^\circ \). This coefficient always takes negative values.
The validity of effect 3.2 follows from the symmetry of the function (17) with respect to the values of the angles of the cross slope and moldboard $\gamma=0^\circ$ and $\varphi=90^\circ$, respectively.

3. The experimental results

In figure 2, as an example, the functional dependences of $\gamma_{po}$ and $\gamma_r$, obtained in the range $-30^\circ \leq \gamma \leq 30^\circ$ for fixed values of $\varphi$ are given.

![Figure 2](image1)

Figure 2. Functional dependencies of the parameters from the given angle of the cross slope: $a$ – the blade tilt angle to the horizontal plane; $b$ – the actual angle of the cross slope

In figure 3, as an example, the functional dependences of $\Delta \gamma_k$ and $\Delta \gamma$, obtained in the moldboard angle range $30^\circ \leq \varphi \leq 150^\circ$ for fixed values of $\gamma$, are given.

![Figure 3](image2)

Figure 3. Functional dependencies of the correction parameters and the error from the moldboard angle: $a$ – correction values; $b$ – cross profile errors

In figure 4, as an example, the functional dependences of the correction $\Delta \gamma_n$, constructed for the angles of cross slope $-30^\circ \leq \gamma \leq 30^\circ$, and moldboard angles $30^\circ \leq \varphi \leq 150^\circ$, are given.

![Figure 4](image3)
4. The discussion of the results

The resulting graphical dependences (see figure 2) are fairly close to linear. Therefore, when finding the angles of cross slope and moldboard in the ranges $-30^\circ \leq \gamma \leq 30^\circ$, $30^\circ \leq \phi \leq 150^\circ$, respectively, in engineering calculations a simplified formula $\gamma_{po}$ can be recommended for use:

$$\gamma_{po} \approx \gamma \cdot \sin \varphi .$$

From the dependences, presented in figure 3, and constructed for the angles of cross slope and moldboard $-30^\circ \leq \gamma \leq 30^\circ$, $30^\circ \leq \phi \leq 150^\circ$, respectively, the obviousness of effect 1.2 follows. Figure 3, b illustrates the validity of effect 1.4 due to the symmetry of the function (11) with respect to $\varphi=90^\circ$. The validity of effect 1.5 is also confirmed and illustrated in figure 3.

5. Conclusions

The analysis of theoretical theses and effects, as well as analysis of graphical representation of functional dependencies, was carried out. This made it possible to draw the following conclusions:
1. The cross slope $\gamma_f$ of the roadbed surface being graded, does not depend on the size of the moldboard and the construction of the EM, and is determined only by the installation angles of the moldboard: $\gamma$ and $\varphi$ (9).
2. To ensure the angle of the roadbed surface cross slope $\gamma$, it is necessary to set the blade tilt angle to the horizontal plane $\gamma_{po}$, according to (5).
3. To compensate for the error in the cross slope $\Delta \gamma$ of the roadbed surface to be graded, it is necessary to change the blade tilt angle to the horizontal plane by $\Delta \gamma_k$, according to (15), (17).

The formulated conclusions are recommended to be taken into account when creating and improving control systems for the EM of motor graders type.

References

[1] Zhulai V, Tyunin V and Krestnikov A 2016 Estimation of fuel efficiency of self-propelled wheeled earth-moving machines *Mechanization of construction* Vol 77 8 27–31
[2] Song Q, Wand W and Jia C 2016 Research on fuel consumption of hybrid bulldozer under typical duty cycle *The 2015 Int. Conf. on Mechanical Engineering and Control Systems (MECS2015)* (Singapore: World Scientific Publishing Co Pte Ltd) pp 54–57
[3] Ignatov S and Portnova A 2013 Methods for solving the problem of controllability of road machinery *Materials of Int. Congr. SibADI Architecture. Construction. Transportation. Technology. Innovations* Vol 1 (Omsk: SibADI) pp 51–57
[4] Shcherbakov V and Belov I 2016 Analysis of the mathematical model of interaction between the working element of the motor grader and the micro relief *Engineering and technology of construction* 4 60–66
[5] Agarkov A and Chekhovskoy E 2016 Analysis of the design of the working equipment of the motor grader in order to improve reliability *Innovative science* 12–2 9–11
[6] Mukushev Sh and Philippi V 2016 Overview of the construction of the moldboards of motor graders *Engineering and technology of construction* 4 50–54
[7] Skoptsov M 2016 Analysis of tendencies of perfection of motor graders with the purpose of increasing productivity in planning works *Velez* 6–1 101–105
[8] Bulgakov A, Emelianov S, Bock T and Tokmakov G 2016 Adaptive control of bulldozer's workflows *Proc. of the 33rd Int. Symp. on Automation and Robotics in Construction and Mining (ISARC 2016)* (New York City: Curran Associates, Inc.) pp 90–97
[9] Hayashi K and Shimada K 2013 Development of D61EXi/PXi-23 bulldozer with automatic control system of work equipment *Komatsu Technical Report* Vol 59 166
[10] Mikhailovskay V 2016 Kinematic analysis of the working equipment of the motor grader *Mechanization of construction* Vol 77 9 59–61
[11] Shevchenko V and Ragulin V 2016 Analysis of the suspension of the working equipment of the motor grader by computer simulation *Bulletin of the Kharkiv National Automobile and Highway University* 73 234–8