The Operation of a Tillage Tool Smart Control System

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Abstract. Studying control systems is associated with a number of problems related to the operation of the system components and the dynamics of links between the components. The development of control systems is required to interact with the changing controlled object. Some continuous processes involve products or media that are significantly longer than the machine used, which has to move to operate. In such cases, it is quite difficult to ensure the proper operation of the control system because of the stochastic properties of the medium and the high movement rate of the mechanism. The problem lies in the lack of knowledge about the content, structure, and operating algorithms of smart control systems for the working tools interacting with the soil as a polyphase medium. The creation of a mathematical model for a smart control system for the tool interacting with the soil marks the employment of innovative digital and smart technologies for cultivation. The tool and soil parameters can be recorded both before and after tillage.

1. Introduction
Soil cultivation is the most energy-consuming field operation. There exist various profile tools that help tear away, deform, and crumble soil layers [1–4]. However, the changes in the soil parameters within a single field lead to the inefficient operation of such tools [5]. The wedge reaction direction does not correspond with the soil layer cleaving direction, which leads to the increased resistance to the movement of the tool [6–8]. There are tools designed to cultivate various types of soils [9]. The problem of plow draft, however, remains with the fluctuation of soil parameters. This problem can be solved by vibrating the tool. This requires the adjustment of vibration frequency and amplitude, as well as the vibration direction. Besides, there must be a tool vibration control system in place that would feature a database on the best vibration parameters and their control algorithms to achieve the best reduction of plow draft possible [10].

2. Research methods
The structure and fineness of the soil are measured using various deformers. A classic deformor has a form of a dihedral wedge with a profiled active face that determines the fineness of the destructured soil layer [1].
Figure 1. The interaction of dihedral and trihedral wedges with the soil: a – with crumbling angle $\alpha$; b – with displacement angle $\gamma$; c – with backset angle $\beta_0$; d – trihedral wedge [1].

A significant proportion of the energy required to move the deformer is spent on tearing out the medium from its main body. To reduce the tear-out force, the deformer is vibrated along with the shifting of the dihedral wedge position and angle [2]. When a polyphase medium is deformed, the stochastic changes of its phase proportions and mechanical properties do not allow to reduce the amounts of energy used for deformation. The problem is the lack of knowledge on the composition and structure of a smart deformer control system that does not allow to control the energy inputs required to deform a polyphase medium if its properties change. To solve this problem, it is necessary to develop a mathematical model for a smart control system for a polyphase medium deformer. This solution will present a mathematical description of controlling energy inputs required to restructure a polyphase medium (soil). It will also help differentiate the energy inputs required to restructure a polyphase medium and develop a management model for energy consumption.

Figure 2. Soil cleaving with a wedge [11].

$\alpha$ is the wedge angle; N is the normal to the wedge plane; $\varphi$ is the friction angle between the wedge and the soil; R is the direction of the soil layer reaction to the wedge; $\omega$ is the internal friction angle of the soil; $K$ is the cleaving path of the soil layer.

3. Research results
Let us consider the interaction of the wedge and the soil and assume that the tool will vibrate along its vertical and long axes so that the aggregate vibration went in the direction of soil cleaving.
Figure 3. Tool movement patterns to determine vibration parameters.

The cleaving micromotion of the tool must go along the soil cleaving direction with a twist of $\omega/2$ (half of the internal soil friction angle).

First of all, let us set the vibration amplitude $A$. Let us resolve it into the vertical and horizontal components.

The first type of vibration direction changes.

Let us set the $A_z$ value. The maximum $A_x$, corresponding with the movement of the tool in the cleaving direction, can be determined as:

$$A_x = \frac{A_z}{\tan(\pi/2 - \alpha - \varphi)} = A_z \tan(\alpha + \varphi)$$

(1)

The minimum $A_x$ value is determined using the following expression:

$$A_x^l = A_z \tan(\alpha + \varphi + \omega / 2)$$

(2)

Thus, to ensure that the micromotions of the tool are within the angle $A_1B_A$, it is necessary that $A_x$ for the set $A_z$ changed within the following range:

$$A_z \tan(\alpha + \varphi) \leq A_x \leq A_z \tan(\alpha + \varphi + \omega / 2)$$

(3)

We can see that the resulting movement reduces from $A$ to $A_1$. If we need to maintain the same vibration amplitude $A_1 = A$ for varying micromovement angle, we should not reduce $A_x$ to $A_1A_x$, but rather to an intermediary value:

$$A_x^l = A_z \cos(\alpha + \varphi + \omega / 2)$$

(4)

The vertical component must equal

$$A_z^2 = A_z \sin(\alpha + \varphi + \omega / 2)$$

(5)

The second type of vibration direction changes.

Let us set the $A_x$ value. The maximum $A_z$, corresponding with the movement of the tool in the cleaving direction, can be determined as:

$$A_z = A_x \cot(\alpha + \varphi)$$

(6)

The minimum $A_z$ value is determined using the following expression:

$$A_z^l = A_x \cot(\alpha + \varphi - \omega / 2)$$

(7)
Thus, to ensure that the micromovements of the tool are within the angle $\angle ABA_2$, it is necessary that $A_z$ for the set $Ax$ changed within the following range:

$$A_c \cdot \tan(\alpha + \varphi - \omega / 2) \leq A_z \leq A_c \cdot \tan(\alpha + \varphi)$$  \hspace{1cm} (8)

Simultaneously, we can see that the resulting movement reduces from $A$ to $A_2$. If we need to maintain the same vibration amplitude $A' = A$ for varying micromovement angle, we should not reduce $A_z$ to $A'z$, but rather to an intermediary value:

$$A_z^2 = A \sin(\alpha + \varphi - \omega / 2)$$  \hspace{1cm} (9)

The horizontal component must equal

$$A_z^2 = A \cos(\alpha + \varphi - \omega / 2)$$  \hspace{1cm} (10)

The presented algorithm helps maintain the wedge reaction to the soil within the internal friction angle $\omega$, the bisecting line of which corresponds with the cleaving direction $A$ determined by the wedge angle and the wedge-and-soil friction angle.

The best angle for tool vibrations must be selected by determining the minimum wedge movement resistance, which corresponds to the minimum energy inputs required for cultivation. The resistance of a real tool can be determined through the plastic deformation value of the tool stilt measured by a strain gauge. Thermoresistive sensors must be located on the front of the stilt, next to its attachment point on the frame.

The smart control system algorithm for a tilling machine tool will look as follows.

\[\text{Figure 4. Tool control system algorithm.}\]
The mathematical model of a smart tool control system that can reduce energy consumption includes:
- a mathematical description of the database with operation quality criteria for the tool,
- an evaluation unit model for soil properties before and after deformation,
- a model of the tool vibration parameter control unit that can also store implemented change algorithms.
- a model of the decision-making unit.

The core of the implemented control process remains unchanged. It consists of selecting sets of simple tasks to change (for soil and tools) and measure (soil properties and tool conditions), as well as the selection of goal achievement algorithms requiring the least resources.

4. Conclusions
The operation of a process control system is linked with the operation of tools and the shifting parameters and properties of the processed object. This link is especially relevant for some continuous processes that involve products or media that are significantly longer than the machine used, which has to move to operate. These processes include tillage and agricultural cultivation technologies. The problems associated with controlling tillage tools have not been extensively studied by the academic community. For example, we can find research works dealing with control system synthesis [12–16], information system efficiency assessment [17], models, and methods for the development of fail-proof control systems [18]. We reviewed the analysis and synthesis of control systems and various management methods. Apart from generic theoretical management problems, we studied control systems for specific industrial processes and machines (energy systems, traffic control, robot control, execution devices). We have to point out that the problem stated above was not analyzed in the context of all problems in question. Besides, the research of control systems designed for such business processes helps create a smart control system for tilling tools based on the mathematical model of tool operation optimization management and the adjustment algorithms for the smart control system itself.

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