INCREASING ACCURACY OF MEASURING FUNCTIONING PARAMETERS OF AGRICULTURAL UNITS

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Abstract. The paper substantiates the ways of increasing the accuracy of measuring the parameters of agricultural units (AU) functioning. It has been noted that agricultural machines and units work in conditions of vibrations and noises created by the environment and technological tools. Features of the movement of these systems and their compliance with their functional purpose are factors that determine the degree of perfection of AU. The study of the dynamics of AU operation requires new research methods and means, therefore a measuring system of the dynamics and energy of mobile machines was created. Increasing the accuracy of measuring parameters of AU operation is achieved by substantiating the data processing algorithm of the sensors of the measuring system. The main component of the measurement system is an inertial measurement unit (IMU), which consists of an accelerometer, a gyroscope, and a magnetometer. It was established that the signal measured by IMU consists of four components: real acceleration; angles of inclination of the AU element relative to the horizon; vibration and inherent noise of the sensor. The IMU installed on the tractor frame determined that the main spectrum of oscillations is in the range from 0 to 3 Hz. The maximum vibration energy corresponds to a frequency of 0.4 Hz. The second harmonic of the oscillations is at a frequency of 25 Hz for the three axes of the accelerometer. An algorithm for data processing by the measuring system has been developed, including processing with the Butterworth filter, compensation of centrifugal velocities, tilt angles, free fall acceleration. The Butterworth low-pass filter with a cut-off frequency of 3 Hz was used to compensate for the real acceleration. The speed and position data of the GPS receiver included in the measuring system must be processed by the Butterworth frequency filter with a cut-off frequency of 1 Hz. It was determined that the maximum traction power of the tractor is 108.0 kW. It was established that the power determined by the measuring system due to acceleration and data processing by the developed method is 101.3 kW. The error of measuring the traction power of the tractor is 6.2%.

Keywords: vibration, oscillations, dynamics, measuring system, agricultural unit.

Introduction

Agricultural units (AU) being a coupling of a power unit (tractor) and an agricultural machine operate in conditions of vibrations and noises created by the environment and the tools themselves. The peculiarities of the functioning of these systems and their compliance with their functional purpose are the factors the degree of perfection of AU depends on. Further expansion of technological capabilities and the scope of their application require in-depth study of the functioning process [1].

The study of the dynamics of AU operation requires new research methods and tools, therefore a measuring system of the dynamics and energy of mobile machinery was created [2; 3].

Currently, the number of studies of the dynamics of AU elements using acceleration sensors are increasing [4-6]. Nevertheless, these and other papers pay not enough attention to the processing of data obtained from sensors during tests. In [7; 8], the measurement errors introduced by sensors are substantiated. Thus, the task of improving the accuracy of measuring the parameters of AU functioning remains relevant.

Materials and methods

The main component of the measuring system (MS) is an inertial measuring unit, consisting of an accelerometer, a gyroscope, and a magnetometer.

Let us consider the signal measured by the acceleration sensor (accelerometer). From an analytical point of view, it consists of four components.

1. Effective acceleration (this is the acceleration acting along the corresponding axis of the AU element and created by it).
2. The angle of inclination of the AU element relative to the horizon.
3. Vibrations created by the environment when moving, in stationary mode or by a process machine.
4. Intrinsic noise of the sensor.

During experimental studies, IMU can be located in an arbitrary location of AU relative to the center of mass.

The first stage of processing the data coming from the gyroscope and accelerometer should be the correction of their values:

$$\mathbf{a_c} = \begin{bmatrix} a_x c \\ a_y c \\ a_z c \end{bmatrix}; \begin{bmatrix} a_x c \\ a_y c \\ a_z c \\ 1 \end{bmatrix} = \begin{bmatrix} \mathbf{a_r} \\ 1 \end{bmatrix} \cdot \mathbf{A} = \begin{bmatrix} a_x r \\ a_y r \\ a_z r \\ 1 \end{bmatrix} \cdot \begin{bmatrix} a_{11} & a_{12} & a_{13} & b_1 \\ a_{21} & a_{22} & a_{23} & b_2 \\ a_{31} & a_{32} & a_{33} & b_3 \\ 0 & 0 & 0 & 1 \end{bmatrix};$$
$$\boldsymbol{\omega}_\mathbf{c} = \begin{bmatrix} \omega_x c \\ \omega_y c \\ \omega_z c \end{bmatrix}; \begin{bmatrix} \omega_x c \\ \omega_y c \\ \omega_z c \\ 1 \end{bmatrix} = \begin{bmatrix} \boldsymbol{\omega}_\mathbf{r} \\ 1 \end{bmatrix} \cdot \mathbf{G} = \begin{bmatrix} \omega_x r \\ \omega_y r \\ \omega_z r \\ 1 \end{bmatrix} \cdot \begin{bmatrix} g_{11} & g_{12} & g_{13} & c_1 \\ g_{21} & g_{22} & g_{23} & c_2 \\ g_{31} & g_{32} & g_{33} & c_3 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \quad (1)$$

where $\mathbf{a_r} = [a_x r\ a_y r\ a_z r]^T$ – input signal of the accelerometer;
$\boldsymbol{\omega}_\mathbf{r} = [\omega_x r\ \omega_y r\ \omega_z r]^T$ – output signal of the accelerometer;
$\mathbf{a_c} = [a_x c\ a_y c\ a_z c]^T$ – adjusted signal of the accelerometer;
$\boldsymbol{\omega}_\mathbf{c} = [\omega_x c\ \omega_y c\ \omega_z c]^T$ – adjusted signal of the gyroscope;
$\mathbf{G}$ – gyroscope adjustment matrix;
a_{ij}, b_i, g_{ij}, c_i – coefficients of adjustment matrices.

The coefficients of the adjustment matrices are determined during the calibration of IMU according to the method given in [1]. IMU is placed four times, when the force of gravity of the Earth relative to the body of the device will be known, parallel to one axis and perpendicular to the other two. Having determined the value of the actual gravity, the coefficients of the correction matrices are calculated.

The adjusted signal of the accelerometer $\mathbf{a_c}$ and gyroscope $\boldsymbol{\omega}_\mathbf{c}$ is processed using the Butterworth filter:

$$\mathbf{a_f} = filter(\mathbf{a_c}), \boldsymbol{\omega} = filter(\boldsymbol{\omega}_\mathbf{c}), \quad (2)$$

where $\mathbf{a_f} = [a_x f\ a_y f\ a_z f]^T$ – matrix-vector of the filtered signal of the accelerometer;
$\boldsymbol{\omega} = [\omega_x\ \omega_y\ \omega_z]^T$ – matrix-vector of the filtered signal of the gyroscope.

After filtering the gyroscope signal (2), we will get the actual value of the angular velocity of rotation ω_x, ω_y, ω_z of the AU element around the *x*, *y*, *z*-axes.

The vector matrix $\boldsymbol{\theta}$ of sensor rotation angles α, β, γ around the *x*, *y*, *z*-axes can be found by solving the following system of differential equations:

$$\boldsymbol{\theta} = \begin{bmatrix} \alpha \\ \beta \\ \gamma \end{bmatrix}, \begin{bmatrix} \dot{\alpha} \\ \dot{\beta} \\ \dot{\gamma} \end{bmatrix} = \begin{bmatrix} 1 & \frac{\sin\beta \cdot \sin\alpha}{\cos\beta} & \frac{\sin\beta \cdot \cos\alpha}{\cos\beta} \\ 0 & \cos\alpha & -\sin\alpha \\ 0 & \frac{\sin\beta}{\cos\beta} & \frac{\cos\alpha}{\cos\beta} \end{bmatrix} \cdot \begin{bmatrix} \omega_x \\ \omega_y \\ \omega_z \end{bmatrix}. \quad (3)$$

In the case when IMU is not installed in the center of mass of the mobile machine or its element, it is necessary to subtract the centrifugal force from the acceleration:

$$\mathbf{a_b} = \begin{bmatrix} a_x b \\ a_y b \\ a_z b \end{bmatrix} = \mathbf{a_f} - \boldsymbol{\omega} \cdot \boldsymbol{\upsilon} = \begin{bmatrix} a_x f \\ a_y f \\ a_z f \end{bmatrix} - \begin{bmatrix} \omega_x \\ \omega_y \\ \omega_z \end{bmatrix} \cdot \begin{bmatrix} \upsilon_x \\ \upsilon_y \\ \upsilon_z \end{bmatrix}^T, \quad (4)$$

where $\boldsymbol{\upsilon} = [\upsilon_x\ \upsilon_y\ \upsilon_z]^T$ – speed of movement of the mobile machine along the corresponding *x*, *y* and *z*-axes.

After subtracting the centrifugal force from the acceleration, it is necessary to subtract the gravitational component and thus obtain its real value:

$$\mathbf{a} = \begin{bmatrix} a_x \\ a_y \\ a_z \end{bmatrix} = \mathbf{a_b} + g \cdot \begin{bmatrix} -\sin\beta \\ \cos\beta \cdot \sin\alpha \\ \cos\beta \cdot \cos\alpha \end{bmatrix} = \begin{bmatrix} a_x b \\ a_y b \\ a_z b \end{bmatrix} + g \cdot \begin{bmatrix} -\sin\beta \\ \cos\beta \cdot \sin\alpha \\ \cos\beta \cdot \cos\alpha \end{bmatrix}, \quad (5)$$

where g – acceleration of gravity.

The speed of movement of the AU element can be obtained by integrating the acceleration:

$$\boldsymbol{\upsilon} = \begin{bmatrix} \upsilon_x \\ \upsilon_y \\ \upsilon_z \end{bmatrix} = \begin{bmatrix} \int_0^t a_x dt + \upsilon_x\big|_{t=0} & \int_0^t a_y dt + \upsilon_y\big|_{t=0} & \int_0^t a_z dt + \upsilon_z\big|_{t=0} \end{bmatrix}^T, \quad (6)$$

where $\upsilon_x|_{t=0}$, $\upsilon_y|_{t=0}$, $\upsilon_z|_{t=0}$ – initial value of the velocities.

The effectiveness of the developed method is evaluated by the spectral density determined from the formula [9]:

$$S_{xx}(f) = \int_{-\infty}^{\infty} R_{xx}(\tau) e^{-2j\pi f\tau} d\tau, \quad (7)$$

where $R_{xx}(\tau)$ – correlation function of a random process.

Thus, the actual angular velocities of the mobile machine (2), acceleration (5) and velocity (6) were obtained. The developed IMU data processing method compensates for the angle of inclination of the AU element at stage (5), vibrations and noise are removed by the Butterworth filter (2).

Results and discussion

Experimental research was carried out on a combined tillage and seeding unit consisting of the tractor John Deer 8345R, the seed hopper John Deer 1910 and the direct seeding planter John Deer 1895. The research was carried out on a farm in the Kharkiv region, during which the dynamic and energy indicators of AU were determined. The dependence of the acceleration of the tractor frame on time (along the longitudinal axis x) was determined (Fig. 1).

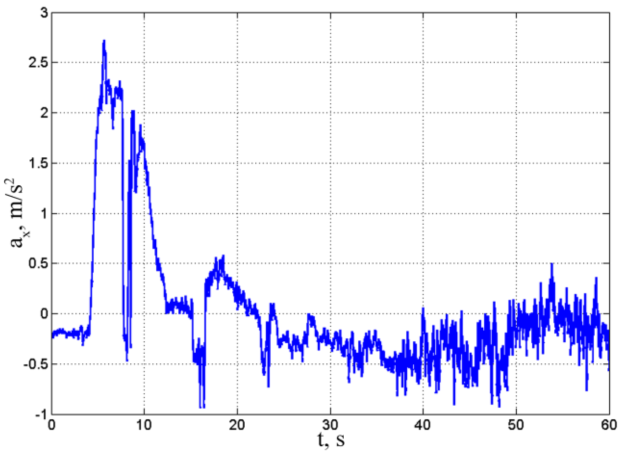

Fig. 1. **Dependence of acceleration of the tractor frame on time (along the *x*-axis)**

All the four components listed above occur during the measurements (Fig. 1). The tractor is tilted, and therefore the graph does not start from “0”. The longer is the time of the experiment, the more speed of movement increases and so does the amplitude of vibrations.

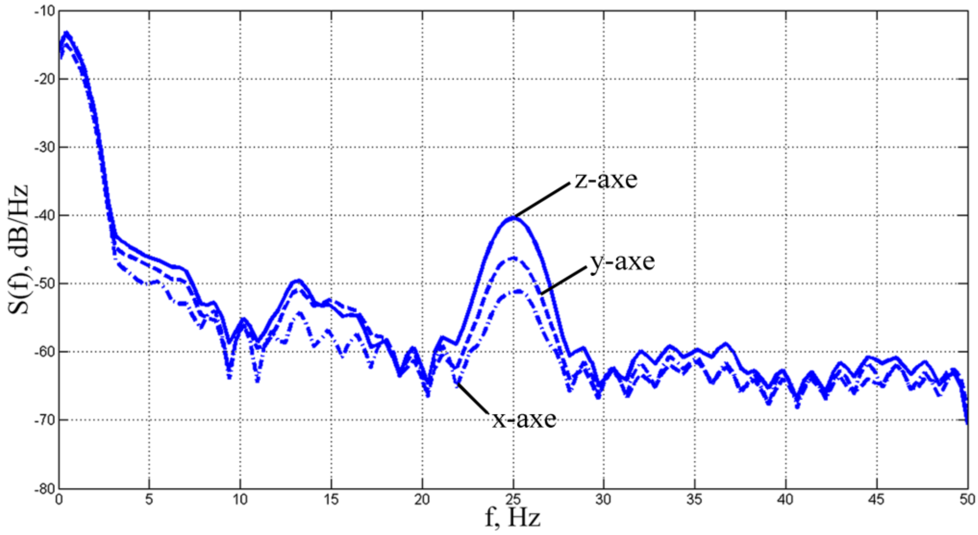

Fig. 2. **Spectral density of accelerations of the tractor frame along the *x*, *y* and *z-axes***

The main spectrum of oscillations lies in the range from 0 to 3 Hz (Fig. 2). The maximum vibration energy corresponds to a frequency of 0.4 Hz. The second harmonic of the oscillation is at 25 Hz for the three axes of the accelerometer. The Butterworth low-pass filter with a cutoff frequency of 3 Hz was used to extract the true acceleration.

To process the data of the GPS receiver and the data of the traction force sensor, we will similarly use a Butterworth filter with a cutoff frequency of 3 Hz.

Let us consider the acceleration of the tractor frame during straight-line movement and compare the raw data from the sensor and the filtered data (Fig. 3).

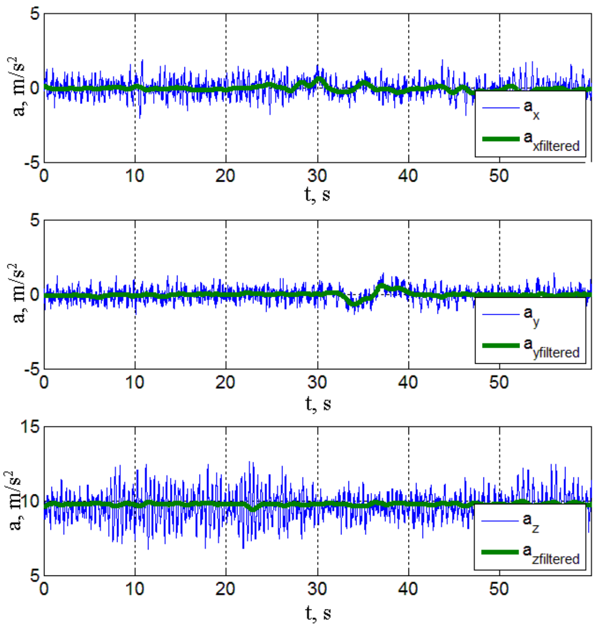

Fig. 3. **Dependences of accelerations of the John Deere 8345R tractor frame on the time during rectilinear movement: a_x, a_y a_z – acceleration of the element along the *x*, *y*, and z-*axes***

The analysis of the statistical data of the John Deere 8345R tractor acceleration signals allows to draw a conclusion about the effectiveness of the proposed data processing algorithm by the measuring system. The decrease in the standard deviation of the accelerations was observed from $\sigma_{ax} = 0.543$, $\sigma_{ay} = 0.424$ and $\sigma_{az} = 0.157$ (for the "raw" data) to $\sigma_{axf} = 0.157$, $\sigma_{ayf} = 0.153$ and $\sigma_{azf} = 0.080$ (for the data processed by the developed technique); sample variance $D_{ax} = 0.295$, $D_{ay} = 0.180$ and $D_{az} = 0.917$

(for the "raw" data) to D_{axf} = 0.025, D_{ayf} = 0.024 and D_{azf} = 0.006 (for the data processed by the developed technique). The reduction of the standard deviation and dispersion of the accelerations of the tractor frame indicates the effectiveness of the developed method.

Studies of AU were carried out during which a measuring system with inertial measuring devices was applied and a method of increasing the accuracy of parameter measurement was developed [8]. The measuring system determined the acceleration of the tractor, which was converted into the tractor's traction and energy indicators. Traction power of the tractor, which is determined by the classical method through the traction force of the tractor, is 108.0 kW [1]. The power determined by the measuring system due to acceleration and data processing by the developed method is 101.3 kW. The error of measuring the traction power of the tractor is 6.2%. The power determined by the measurement system due to acceleration without data processing is 98.6 kW. In this case, the error of measuring the traction power of the tractor is 8.7%.

Thus, increasing the accuracy of measuring the parameters of AU operation is achieved by substantiating the method of data processing of sensor signals of the measuring system (1)–(7). Data from IMU are used during various studies and calculations of the operation of AU, therefore, increasing the accuracy of measuring parameters leads to a justified increase in the accuracy of studies and calculations [10].

Conclusions

1. A method of data processing by a measuring system has been developed, which excludes the influence of indicators of the location of sensors, acceleration of free fall, unevenness of fields and inclination. It was established that the signals from IMU from an analytical point of view consist of four components: real acceleration; angle of inclination of the element; environmental vibrations and the intrinsic noise of the sensor.
2. It was determined that the main vibration spectrum of AU elements lies in the range from 0 to 3 Hz. The maximum vibration energy corresponds to a frequency of 0.4 Hz. The second harmonic of the oscillation is at 25 Hz for the three axes of the accelerometer. The Butterworth low-pass filter with a cutoff frequency of 3 Hz was used to extract the true acceleration. The Butterworth filter was also used to process GPS receiver data and traction sensor data.
3. The analysis of the statistical data of the John Deere 8345R tractor acceleration signals allows to draw a conclusion about the effectiveness of the proposed data processing algorithm by the measuring system. The decrease in the standard deviation of the accelerations was observed from σ_{ax} = 0.543, σ_{ay} = 0.424 and σ_{az} = 0.157 (for the "raw" data) to σ_{axf} = 0.157, σ_{ayf} = 0.153 and σ_{azf} = 0.080 (for the data processed by the developed technique); sample variance D_{ax} = 0.295, D_{ay} = 0.180 and D_{az} = 0.917 (for the "raw" data) to D_{axf} = 0.025, D_{ayf} = 0.024 and D_{azf} = 0.006 (for the data processed by the developed technique). The reduction of the standard deviation and dispersion of the accelerations of the tractor frame indicates the effectiveness of the developed method.
4. It was determined that the maximum traction power of the tractor is 108.0 kW. It was established that the power determined by the measuring system due to acceleration and data processing by the developed method is 101.3 kW. The error of measuring the traction power of the tractor is 6.2%.

Author contributions

Conceptualization, R. Antoshchenkov; methodology, V. Antoshchenkova; software, D. Smitskov; validation, D. Smitskov and V. Kis; formal analysis, R. Antoshchenkov and V. Antoshchenkova; investigation, V. Kis; data curation, D. Smitskov; writing – original draft preparation, R. Antoshchenkov; writing – review and editing, V. Antoshchenkova and V. Kis; visualization, D. Smitskov. All authors have read and agreed to the published version of the manuscript.

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