Mathematical model for studying the operation of a machine-tractor unit with a tractor «DT-175S» with an elastic element in the linkage system

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Abstract. The increase in engine power and the speed of movement of the machine-tractor unit leads to an increase in the amplitude and frequency of oscillations of the hook force. At the same time, the magnitude of these effects depends on fluctuations in the hook load, the nature of the work process, the dynamics of operating modes and the frequency properties of the transmission. Reducing the nature of transient dynamic loads can be achieved by using elastic connections in the tractor structure. The issues of a rational combination of increased operating power of the engine with a simultaneous decrease in dynamic loads in the transmission exacerbate the problem of choosing rational modes of operation of the machine-tractor unit. Uneven hook load causes fluctuations in the engine crankshaft rotation speed, an increase in the load on the transmission parts and, consequently, a decrease in power and an increase in engine fuel consumption. Therefore, to protect the transmission from vibrations that occur in the engine-transmission system, special damping devices are used. A characteristic feature of the device, which is the possibility of using elastic - damping elements, allowing to reduce the frequency of natural vibrations of the transmission.

1. Introduction
Currently, when improving the performance of a machine-tractor unit through structural and technological modeling, a low level of theorization of technological processes of interaction between a machine and a locality and functional interactions of its intrastructural elements causes particular difficulty. The most effective measures for the modernization of mobile machines in agricultural production is a machine imitation of the process of interaction of the working parts of agricultural machines with the processed surface.

Numerous studies reveal the negative effect of the amplitude of forced vibrations from the resistance forces on the hook on the effective operation of the machine-tractor unit [1, 2, 3, 4]. Among the ways to reduce these vibrations, we propose the installation of an elastic connection between the tractor and the agricultural machine [5, 6, 7]. The installation of elastic elements in different places of the power drive and the attachment is not to reduce the fluctuations of the input signal (Pkr), but to ensure the conditions for optimal interaction of the working parts of agricultural machines with the processed material, determined by the decrease in the average load on the tractor hook and their dispersion [5, 6, 8].
For this, a mathematical model has been developed that allows one to study the influence of the location of the elastic element in the hitch of the tractor and the working parts of the tillage machines. The use of modeling will allow at the design stage to study the dynamics of complex systems, determine operating modes, select rational design parameters, and optimize elastic elements.

2. Materials and methods

The study of a mathematical model describing the transformation of the input signal \((P_{in})\) of a random nature is fully based on the classical theory of random processes. The probabilistic characteristics of realizations of a random loading process (spectral densities) were obtained by processing experimental data on machine-tractor units with serial attachments and shafting under the assumption of their stationarity in the broad sense of their ergodicity [9].

3. Results and discussions

Calculations of the stiffness of elastic elements in the hitch system of various machine-tractor units with the tractor «DT-175S – Volgar» will be presented in the form of a table.

| Indicators                          | Arable | Cultivating | Sowing                 |
|------------------------------------|--------|-------------|------------------------|
| \(M_{in}, \text{kg}\)              | 8000   | 8000        | 8000                   |
| \(m, \text{kg}\)                   | 1150\(+370\) | 2638\(+370\) | 5370\(+370\)          |
| \(\Delta\)                         | 1.3    | 1.3         | 1.3                    |
| \(\lambda\) calculated, 1/s        | 13.2   | 15.7        | 18.2                   |
| \(v, 1/c\)                         | 22.9   | 15.5        | 11.5                   |
| \(C_r, \text{kN/m calculated}\)   | 798    | 726         | 749                    |
| \(C_r, \text{kN/m experiment}\)   | 800-980| 730-800     | 730-800                |

To reduce the energy level of the spectral density at lower frequencies, it is necessary to select a damper that excludes an increase in the dynamic gain of the oscillatory system.

The data in the table indicate the possibility of using in all three cases a hitch with the same rigidity (730-800 kN/m). Tractors have to work in zones with different soil characteristics, according to statistical estimates, therefore, the design of the elastic element, as necessary, or even better, should automatically adapt to the changing operating conditions of the machine-tractor unit.

From expression (1) it can be seen that to a large extent the calculated stiffness of elastic elements depends on the coefficient of accounting for rotating masses \(\delta\).

\[
v = \sqrt{\frac{2}{\sqrt{\pi}}} \frac{\delta \cdot m_{in} + m}{m} \cdot \lambda^2\,.
\]

When the torque converter is blocked, the shafting from the drive sprocket to the engine becomes transparent and the flywheel inertia increases \(\delta\) (up to about 1.8), which increases \(v\), and hence \(C_r\) of the elastic hinge, designed to damp the oscillations of the hook force of a given frequency \(\lambda\) calculated. But with an increase in the frequencies of natural vibrations, they leave the zone of the frequency of oscillations of the tractive effort and allow to somewhat reduce \(\lambda\) calculated, which means, to exclude
a noticeable difference in the rigidity of the tractor attachment when working with a torque converter and blocking it.

The analysis of the spectral densities of the machine-tractor unit based on the tractor «DT-175S» with elastic elements of different stiffness makes it possible to draw the following conclusions based on the considered physical picture of the interaction of a spring-loaded agricultural machine with obstacles (Figure 1, 2):

1) the type and numerical characteristics of spectral densities for different machine and tractor units with tractor «DT-175S» when working with a torque converter and its blocking are practically the same (the exception is an arable machine-tractor unit with a blocked torque converter): each of them has an energy surge at frequencies, approximately equal to 2 Hz;

2) the reason for the appearance of the named burst is most likely associated with the frequency of natural longitudinal angular oscillations (it corresponds to the named frequency);
3) the installation of elastic elements, as a rule, reduces the energy level of low-frequency (up to 0.8-1.0 Hz) oscillations, which corresponds to the previously given conclusion about the influence of the difference on it

\[ \left( \frac{2\pi}{\lambda} \cdot \frac{m_{MTU}}{m \cdot \nu} - \sqrt{2} \right). \]  

(2)

This correspondence is fully observed in the arable machine-tractor unit (Figure 1), deviations are noticeable in other machine-tractor units, mainly with elastic elements of low rigidity. This tendency can be explained by the intensification of fluctuations due to a decrease in the \( \lambda/\nu \) ratio;

4) an increase in the energy level at a different frequency with a non-optimal stiffness of the elastic element is associated with an increase in the residual frequencies of the spectrum as a result of the approach of the natural frequency to the spectrum of operating frequencies and the obtaining of resonances at frequencies that are multiples of \( \nu \).

The obtained criterion according to the formula (1) makes it possible to evaluate the peculiarities of the operation of elastic elements located in different nodes of the machine-tractor unit: on the shaft of the driving sprocket, in the hinged system or on the working parts of the machine-tool.

**Elastic elements on the drive sprocket shaft.** In this case, the sprung mass consists of the mass of the machine and the mass of the tractor \( m_{tr} + m \) dependence (1) will take the form

\[ \nu = \sqrt{2} \cdot \frac{\delta \cdot m_{tr} + m}{2\pi \cdot m_{tr} + m} \cdot \lambda. \]  

(3)

For a plowed machine-tractor unit with tractor «DT-175S»: \( \nu = 0.25 \lambda \).

Hence it follows that \( \lambda/\nu = 4.0 \) and the oscillation mode turns out to be over resonant. At the same time, not only the dynamic components of the average hook force are reduced, but also the amplitude of its oscillation. The latter fact creates more favorable conditions for the transmission and engine loading [10].

The disadvantage of the elastic element on the drive sprocket shaft is its reduced rigidity in the optimal version. Indeed, recalculation of the reduced horizontal stiffness \( C_{r} = (m_{tr} + m) \nu^2 \) into circular gives the following value at \( \lambda = 2 \) Hz:

\[ C_{r} = \frac{1}{2\pi^2} \cdot \frac{(\delta \cdot m_{tr} + m)^2 \cdot \lambda^2 \cdot r^2_{zv}}{m_{tr} + m} = 14.47 \text{kN} \cdot \text{m rad}. \]  

(4)

With such stiffness at the nominal tractor load (30 kN), the twist of the elastic element will be approximately 0.7 rad, which corresponds to the horizontal movement of the tractor relative to the equilibrium position by 20 ... 25 cm. With the maximum possible deviations of the hook load and its 30% oscillation, this movement will be within 15 ... 30 cm that, of course, is unsafe when the machine and tractor unit stops. However, the execution of such an elastic element is possible when using elements of variable stiffness, the load characteristic of which has the form shown in (Figure 3) (\( M_{zv} \) is the moment of the asterisk).
Such elastic elements, operating on machines loaded according to the laws of random processes, require the installation of special shock absorbers, which provide damping of resonance amplitudes falling into the working zone of the frequency spectrum [5]. The influence of the dissipative properties of shock absorbers on the reduction of the dynamic components of the hook force requires a separate study.

**Elastic elements in the hinge.** According to expression (1) for elastic elements in the suspension system, the required stiffness for damping the dynamic components of the hook force with a frequency $\lambda$ corresponds to the pre-resonant vibration zone ($\lambda/\nu = 0.5$). But a further decrease in the stiffness of elastic elements, even with a decrease in the influence of individual obstacles, which correspond to collisions with a frequency $\lambda$, can lead to: an increase in $\lambda/\nu$ oscillations, and, consequently, an increase in the dynamic amplification coefficient of residual oscillations.

In case of random vibrations, an attempt to damp the vibrations of a lower frequency $\lambda$ allows you to transfer the natural frequency to the operating frequency spectrum, increasing the energy level of vibrations at frequencies close to $\nu$. The use of elastic elements with an optimal ratio of dissipative properties and natural frequencies. Allows the designer to ignore the tail parts of the spectrum when designing the optimal stiffness of the elastic element.

**The use of elastic elements on the working parts of agricultural machines.** The total weight of the five parts $m_{we}$ of the plow «PLN-5 X35» is 260 kg. Then, according to expression (1) for the arable unit

$$\nu = \frac{\sqrt{2}}{2\pi} \cdot \frac{\delta \cdot m_{tr} + m}{m_{we}} \cdot \lambda = 9.9 \lambda$$

The large difference in the proportionality coefficient between $\nu$ and $\lambda$ and the limited spectrum of the frequencies of the hook force with high energy levels - 3 - 4 Hz - enable the elastic elements located on the working parts of the machines to reduce the dynamic effect of lower frequencies than in the previously presented cases. Even with a calculated $\lambda = 1$Hz, the operating vibration zone of 2Hz lies at $\lambda/\nu \leq 0.25$ (the vibration amplification coefficient is always less than 1.05), and for low frequencies of the spectrum with a small energy level $\lambda/\nu \leq 0.5$ (the gain is less than 1.3). Considering this, it should be noted that the design of fastening the working parts of tillage machines becomes more complicated.
4. Conclusions

Based on theoretical reasoning and analysis of the mathematical model, the following conclusions can be drawn.

1. The condition for choosing the optimal stiffness of the elastic element to reduce the influence of the nature of the impact of the working parts of agricultural machines with the processed material can be considered the ratio of the frequencies of natural and forced vibrations

\[ \nu = \frac{\sqrt{2}}{2\pi} \cdot \frac{\delta \cdot m_{\mu} + m}{m_{gs}} \cdot \lambda, \]  

(6)

where \( m_{gs} \) - the mass of the spring-loaded parts of the machine-tractor unit.

2. The place of installation of elastic elements in the traction force generation system determines their functionality:
   a) On the drive shaft of the drive sprocket, they reduce not only the dynamic components of shock effects of a certain frequency, but also the amplitude of the remaining impact. The location of natural frequencies in the frequency range of the vibration components of the hook force requires sufficient resistance in the damper (shock absorber) to damp the vibrations that have fallen into the resonance zone. Due to the low rigidity of these elements, their design is complicated;
   b) In the hitch system, they are able to extinguish the most dangerous frequencies (2.0-2.5 Hz) without using special damping devices. The horizontal displacement of the machine within 3-5 cm depends on the value of the stiffness of the elastic elements; this is a safe condition for the operation of the machine-tractor unit;
   c) On the working parts of the machine, it is possible to eliminate the dynamic components of lower frequencies, reduce horizontal displacements, but complicate the design of agricultural machines.

3. Due to the fact that tractors have to work in zones with different, according to statistical estimates, soil characteristics, the design of the elastic element should allow changing the rigidity of the elastic element as needed, and even better - automatically adapt to the operating conditions of the machine-tractor unit.

References

[1] Polivaev O I, Pankov A V, Ivanov V P etc. 2011 Reduction of dynamic loads in the transmission of tractors Tractors and agricultural machinery 3 43-45

[2] Gapich D S, Eviev V A, Kosulnikov R A, Chumakov S A 2018 Problematic issues of increasing the energy efficiency of the machine-tractor unit with elastically fixed working parts. Proc. of the Nizhnevolszky agro-university complex: science and higher professional education 1 (49) 312-318.

[3] Polivaev O I, Polukhin A P 2000 Reduction of dynamic loads in machine and tractor units Voronezh: VGAU 197.

[4] Fomin S D 2012 Assessment of the influence of the transmission rigidity on the stability of the uncontrolled movement of the machine-tractor unit with different types of kinematic connection of the driving wheels Proc. of the Nizhnevolszky agro-university complex: science and higher professional education 1 (25) 155-160.

[5] Kuznetsov N G Nekhoroshev D A, Nekhoroshev D D 2012 Influence of the gear ratio of the planetary clutch on the stiffness of the pneumohydraulic elastic element. Tractors and agricultural machinery 1 28-29.

[6] Gapich, D S, Shiryaeva E V, Denisova O A 2015 Fourier analysis of experimental oscillograms of the traction resistance of the working part of the cultivator of the machine-tractor unit. Proc. of the Nizhnevolszky agro-university complex: science and higher professional education 3
(39) 151-154.

[7] Fomin S D 2012 Modeling the dynamics of interaction of masses of the «tractor-traile» subsystem for unsteady curvilinear motion. Proc. of the Nizhnevolzhsky agro-university complex: science and higher professional education 4 (28) 202-207.

[8] Nekhoroshev D D, Konovalov P V, Popov A Yu, Nekhoroshev D A 2019 Features of improving the operation of a machine-tractor unit by reducing load fluctuations Proc. of the Nizhnevolzhsky agro-university complex: science and higher professional education 1 (53) 345-351.

[9] Lurie A B 1970 Statistical dynamics of agricultural aggregates Kolos L 194.

[10] Ovchinnikov A S, Kuznetsov N G, Nekhoroshev D D et al. 2018 Some ways to reduce the dynamic loads of agricultural machine-tractor aggregates. ARPN Journal of Engineering and Applied Sciences 13 (22) 8776-8779.