Reliability improvement of heavy machineries friction units

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Abstracts. The demand for more sustainable agriculture promotes the need for friction parts and components with a high durability and better performance. Widely known that absence of the constant and smooth lubricant supply into the working system is the main cause of the decline in reliability. As a result, most of the time the machines work in conditions of a lubricant deficiency. Thus, the development and implementation of the direct adaptive control methods into the friction nodes could be of great importance. Moreover, this approach increases reliability and simplifies the industrial application of the similar systems.

1. Introduction
The main factor of the agriculture complex reliability in the Russian Federation is the performance of heavy loaded friction units. The wear in machine units causes safety and functional losses, as it affects the speed, traction, efficiency, maneuverability and handling of the machinery. Thus, the methodology of the safe use and fast repair is in high demand especially among manufacturers and service companies. Constant supply of the lubricant into the friction nodes leads indirectly to a diversity in agricultural machinery and technology. The necessity of the regular improvement in agricultural equipment results in a more sustainable and cost-efficient cultivation. However, the constant load on the machinery, difficulties in operational conditions and high demand of the fast requires a change of the lubricant supply process in general.

2. Methods and results
One of the prominent methods to solve the current durability problem is the application of the adaptive lubricant supply system based on the friction [1-10]. However, in such a way the issue usually is not discussed and studied [11-20]. The solution for the proposed objective implies input and output parameters evaluation in general. The mentioned above evaluation includes discussion of the 3 subtopics:
1. to identify control parameters;
2. to unify the controller operation algorithm using system quality variables;
3. to design the regulator.

It is well known that the main parameters of the working units are constantly changing under the workload and in time. Thus, the main algorithm should be adapted to the newly formed variables [1-5].

Consider the use of state-space representation in order to solve the adaptive mechanical system:
\[ \dot{X} = \varphi(x, u, t), \]  

(1)

where \( x(t) - n \) – state vector; \( u(t) - m \) – input (control) vector.

The state and input vectors are time-variant (i.e. depend on time). Thus, the variables could be evaluated using the following equations (2), where \( x^{(0)} \) is the initial conditions and \( x^{(1)} \) is the final conditions.

\[ x(t_0) = x^{(0)}; \quad x(t_1) = x^{(1)}. \]  

(2)

where \( t_0, t_1 \) – is the time of start and end of the process.

The management efficiency would be estimated using integral equation:

\[ \gamma = \int_{t_0}^{t_1} \varphi_0(x, u, t) dt. \]  

(3)

where \( \varphi_0(x, u, t) dt \) – continuous function of the arguments.

Thus, the smaller the integral value is the higher efficiency would be. In accordance with the design features of the object and its properties the bounded set lies within \( u_1, ... u_m \). A set (\( u \)) is called bounded if it has an upper and a lower bound, i.e. \( u_1 = u^*_1 \).

Perturbation is ambiguous for the following reasons: inaccurate implementation of the initial conditions (2); incomplete information on external disturbances acting on the system; inaccurate implementation of the management process. As a result, it is necessary to obtain an equation of real motion, which takes into account the deviation from the equation of unperturbed (theoretical) motion. The similar objectives were studied previously [4, 5, 6].

Consider the unperturbed motion equation is known, i.e. the following function has a solution \( u^*(t) = u^{(0)}_k(t) \) (\( k = 1, m \)). Thus, using it in the equation (1) and solving it with initial arguments (2), the results would be \( x^*_i(t) \) (\( i = 1, n \)). Consider to use the functions of perturbation as were calculated in the previous papers [6, 7, 8].

If \( \delta_{xi}(t) \) (\( i = 1, n \)) and \( \delta_{uk}(t) \) (\( k = 1, m \)) are deviation of the real movement from theoretical, then the perturbed movement is described by the following functions (4):

\[ x^*_i(t) = x^*_i(t) + \delta_{xi}(t); \quad u^*_k(t) = u^*_k(t) + \delta_{uk}(t); \quad (i = 1, n; \quad k = 1, m). \]  

(4)

Numbers \( \delta_{xi}(t) \) (\( i = 1, n \)) are random small values so that their values are not bigger than \( \varepsilon \) i.e. satisfy the equation:

\[ \sum_{i=1}^{n} \delta_{xi}^2(t_0) \leq \varepsilon^2 \]  

(5)

Thus, continuing the calculations, the management efficiency would be described as a state variable function:
\[
\gamma = \int_{t_0}^{t_1} \left[ x_i(t) + u_k(t) \right] \cdot dt = \int_{t_0}^{t_1} \left[ x_i^* (t) + \delta x_i (t) \right] + \left[ u_k^* (t) + \delta u_k (t) \right] \cdot dt .
\] (6)

The solution to the equation is to bound the set within \((t_1, t_0)\) variables:

\[
\gamma = \lim_{t_1 \to \max t_1 - t_0} \frac{1}{t_1 - t_0} \int_{t_0}^{t_1} \left[ x_i^* (t) + \delta x_i (t) \right] + \left[ u_k^* (t) + \delta u_k (t) \right] \cdot dt .
\] (7)

Define the matrix \((m \times n)\) of the sustainable movement:

\[
u = c \cdot x .
\] (8)

Consider the valuables of the set to be functions of the arguments and controls that are independent from the initial conditions (4) and have the form [4, 5, 6, 7]:

\[
x_i^* (t) + \delta x_i (t) = \varphi_1 \cdot \left[(x_1 \ldots x_i), (\delta x_1 \ldots \delta x_i)\right];
\] (9)

\[
u_k^* (t) + \delta u_k (t) = \varphi_2 \cdot \left[(u_1 \ldots u_k), (\delta u_1 \ldots \delta u_k)\right].
\] (10)

The control function includes undefined values for which only restrictions are known. The structure of adaptive systems assumes a function that includes a criterion for changing uncertain parameters:

\[
\beta(t) = \varphi_3 (\beta, u).
\] (11)

The equations (9), (10) describe the regulator operation and the formula (11) is evaluated the process of adaptation. Where \(\beta(t)\) is adapter [5, 6, 7, 8, 9]. As a result, the adaptive regulator consists of the adapter and regulator. The design of the system is shown at the figure 1 [5, 6, 7, 8, 9].

![Figure 1. The design of the adaptive system.](image)

The functional \(\gamma\) (7) is described by the equations (9) and (10) and when taking into account the minimal conditions should have the following properties:

\[
\gamma = \lim \{ \varphi_1 \cdot \left[(x_1 \ldots x_i), (\delta x_1 \ldots \delta x_i)\right] + \varphi_2 \cdot \left[(u_1 \ldots u_i), (\delta u_1 \ldots \delta u_i)\right] \} \to \min.
\] (12)

The solution to the first objective is to identify the main arguments in the form of input-output. The evaluation parameters describe the process of lubricant supply, where \(h\) is the lubricant layer thickness and \(\nu\) is the wear:

\[
U = \varphi(h),
\] (13)
So the wear rate \( J \) would be a function of time based on the lubricant layer thickness \( h \):

\[
J = \varphi(h_1, \ldots, h_i).
\] (14)

On the other side, the wear coefficient \( J \) depends on the load-speed regime, type \( \mu \) and hardness \( HB \) of the material, roughness \( R \), contaminants \( q \), the type \( \rho \) of lubricant and its layer thickness \( h \) \[8, 9\].

\[
f = \varphi(\mu, \ HB, \ R, \ \rho, \ h, \ q).
\] (15)

Since \( \mu, \ HB, \ R, \ \rho, \ h, \ q \) are the constant parameters and \( R \) is uncontrollable variable the \( f \) could be considered as a function of \( h \). Thus, the lubricant layer thickness \( h \) is an adapter and parameters \( f \) and \( J \) are the state and control variables.

\[
\beta = h, \ x = f, \ u = J.
\] (16)

Summarizing the results of the equation (16) the following equation could be written:

\[
X = \varphi(f, \ J, \ t).
\] (17)

limitations (2):

\[
x(t_0) = f^0; \ x(t_1) = f'.
\] (18)

and equation (11):

\[
\beta(t) = \varphi(h, \ J).
\] (19)

Then the clarification of the second objective lays in the transformation of the equations (9) and (10) taking into account equation (16):

\[
x_i(t) + \delta x_i(t) = \varphi_1[(f_1, \ldots, f_i), (\delta f_1, \ldots, \delta f_i)];
\] (20)

\[
u_k(t) + \delta u_k(t) = \varphi_2[(J_1, \ldots, J_i), (\delta J_1, \ldots, \delta J_i)].
\] (21)

The solution to the second problem reduces to minimizing the functional (21), and the third problem is to determining the adaptation and regulation algorithm according to the equation (20).

The connection between external parameters \( P, V \) and control adaptation arguments allows to solve the studied topic. The main parameters of the friction unit with an adaptive controller are shown in table 1 and figure 2.

| System      | Mode       | Control terms      |
|-------------|------------|--------------------|
| Adapter     | Turn on    | \( h \to h_{\text{min}} \to 0 \) |
|             | Turn off   | \( h \to h_{\text{max}} \) |
|             | Stable     |                    |
3. Conclusion
The research of the adaptive regulator components has shown that the thickness of the lubricant layer is the key factor of the machinery reliability. Moreover, the results of study are implemented in the method of analytical construction of the frictional nodes. Proposed approach could be advantageous for similar systems and horticulture machines.

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