Synthesis of multifunctional composite coatings with improved anti-friction properties for agricultural machinery

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Abstract. The article is devoted to the synthesis of multifunctional composite coatings with improved antifriction properties in a complex acoustic field realized by means of two quasi-coherent sources of ultrasonic vibrations. The developed device for acoustic synthesis, which is based on the cavitation effect, allows developing high effective pressure values from 100 to 1000 bar in the shock wave, when the cavitation cavity collapses. The highly concentrated effect of the device on the composition ingredients synthesizes new compounds, are impossible to obtain under ordinary conditions. The process is fully controllable and allows imparting unique properties to the finished product, among which a special place should be given to the variable value of the friction coefficient. It depends on the external load and the high wear resistance value of the surface layer of the multifunctional composite protective coating. There is a problem of improving the energy efficiency of agricultural machinery and equipment. The solution to this problem is associated with the use of innovative technologies based on implementing the highly concentrated energy sources. The aim of the research is to optimize the process of obtaining multifunctional composite coatings with improved antifriction properties based on mass transfer of the electrode material and the subsequent formation of structures with predicted physical and mechanical properties. In order to achieve this goal, a generalized model of applying multifunctional composite coatings using the electro-acoustic spraying method has been developed.

1. Introduction

Acoustic synthesis is an energy-intensive and complex stage of obtaining multifunctional composite materials. As a result of synthesis, an aggregative and stable system should be obtained. It may not have kinetic stability. Selecting the equipment for the acoustic synthesis of reagents and determining the optimal modes of its operation require knowledge of the features of complex colloidal chemical processes that occur at the interface between the surface of the particles and a dispersion medium [1]. The synthesis production process for multifunctional composite materials is implemented by forming a complex acoustic field with two quasi-coherent PMS6-22 transducers with a resonant frequency of 22 kHz and an ultrasonic generator UZG-3-4M.
The formation of nanoparticles of ingredients occurs during the general technological synthesis process of multifunctional composite materials. This process takes place in an acoustic synthesis device, the diagram of which is shown in Figure 1. In order to forecast the main quality parameters of machine parts, the forming tool and the executive equipment of agricultural machinery products, the methodology of designing the experiment was used. The methodology lies in the general context of synthesizing the mathematical model in the form of Cauchy and uses Jacobi matrices with the goal of optimizing the production process of multifunctional composite materials by the criterion of minimizing reduced costs [2].

Under the assumptions of the heat loss absence of ideal solution synthesis by an intense complex ultrasonic field, this object will be described by the following balance control system:

\[
\begin{align*}
\frac{dM}{dt} &= (Gl + Gf + Gy - G); \\
\frac{d(M*c)}{dt} &= (Gf*c_f - G*c); \\
\frac{d(M*\lambda*Q)}{dt} &= (Gf*\lambda_f*Qo + Gl*\lambda_i*Qo + Gy*e - G*\lambda*Q)
\end{align*}
\]

Let us mathematically transform the resulting system of equations, since this can lead to new forms or reveal the effect on the objects condition.

The time derivatives are written down based on the equations in the system

\[
\begin{align*}
\frac{dM}{dt} &= (Gl + Gf + Gy - G); \\
\frac{dM}{dt}c + \frac{dc}{dt}M &= (Gl*c_f - G*c); \\
\frac{dM}{dt}Q + \frac{dQ}{dt}\lambda M &= (Gf*\lambda_f*Qo + Gf*\lambda_f*Qo + Gy*e - G*\lambda*Q)
\end{align*}
\]
The system has the form that does not directly correspond to the Cauchy form, so the next stage of transformations is necessary. The equation system (3) is substituted for \( \frac{dM}{dt} \) into the right-hand side and everything is transferred to the right-hand sides, leaving only time derivatives in the left-hand sides.

\[
\begin{align*}
\frac{dM}{dt} &= (G_f + G_c + G_e - G_l) \\
\frac{dc}{dt} &= \frac{1}{M} (G_f c - G_l c - G_e - G_y y) \\
\frac{dQ}{dt} &= \frac{1}{\lambda M} (G_f \lambda f Q_0 + G_l \lambda l Q_0 + G_e \lambda e Q_0 + G_y \lambda y Q_0 - G_l \lambda l Q - G_f \lambda f Q - G_y \lambda y Q)
\end{align*}
\]

It is obvious that the control variables are \( M, s \) and \( Q \). Input actions are \( G_f, G_l, G_e \). \( G \) is perturbation. Assuming that \( M=x_1, c=x_2, Q=x_3, G_f=U_1, G_l=U_2, G_e=U_3, G=V \), the system of equations was rewritten as follows:

\[
\begin{align*}
\frac{dx_1}{dt} &= U_1 + U_2 + U_3 - V \\
\frac{dx_2}{dt} &= \frac{1}{x_1} (U_1 c_p - U_2 x_2 - U_1 x_2 - U_3 x_2) \\
\frac{dx_3}{dt} &= \frac{1}{\lambda x_1} (U_1 \lambda p Q_0 + U_2 \lambda p Q_0 + U_3 e - U_2 \lambda x_3 - U_1 \lambda x_3 - U_3 \lambda x_3)
\end{align*}
\]

The resulting system of nonlinear differential equations structurally describes the dynamic properties of the object exactly up to the assumptions made [3] in the selected variable conditions. Further study of the model assumes studying the technological operating conditions of the device, namely, the variation range of the disturbance \( G=V \), and the necessary range of control actions associated with it. In addition, a significant role is played by the nature of the technology of changing state variables, namely, the stability of the variables \( x_1, x_2, x_3 \).

Let’s assume that the considered device will operate in the rigid stability of the outgoing variables \( M, s, Q \) according to the technology. Then its mathematical model within the narrow range \( \pm \Delta M, \pm \Delta c, \pm \Delta Q \), as well as with small changes in disturbing and controlling influences can be described by an approximate linear mathematical model [4].

The algorithm used is based on expanding the nonlinear function of several variables in a Taylor series in increments relative to some point of the PS taken as the nominal value and as the center (pole) of the PS. This method requires the fulfillment of two following conditions [5]:

- the right parts of the nonlinear DE (\( \psi \)) are differentiable functions, i.e. do not have discontinuities of the first and second kinds;
- the deviation of the controls \( \Delta u \) and the deviation of the perturbed motion \( x(t) \) from the unperturbed \( x^0(t) \) are small for all \( t \geq t_0 \), i.e.

\[
\begin{align*}
x(t) &= x^0(t) + \Delta x(t), |\Delta x(t)| \leq \delta_1, \quad t=1...n; \\
u(t) &= u^0(t) + \Delta u(t), |\Delta u(t)| \leq \delta_2, \quad t = 1...k,
\end{align*}
\]

where \( \delta_1, \delta_2 \) are sufficiently small numbers.

Let us linearize the system using this method. The rule of expanding the function of several variables in a Taylor series is applied.
\[ \psi_i(x(t), u(t)) = \psi_i(x^0(t), u^0(t)) + \sum_{k=1}^n \frac{\partial \psi_i}{\partial x_k} \bigg|_0 \Delta x_k + \sum_{j=1}^n \frac{\partial \psi_i}{\partial u_j} \bigg|_0 \Delta u_j + R_i, i = 1...n. \]

The expression \( \bigg|_0 \) points at the calculating the partial derivative in the vicinity of the unperturbed motion. The remainder term \( R \) contains the deviation degrees \( \Delta x, \Delta u \), starting from the second and higher. Due to the smallness of these deviations, these terms can be neglected [5]. Considering the (7), the following is obtained

\[ \Delta \chi_i(t) = \sum_{k=1}^n \frac{\partial \psi_i}{\partial x_k} \bigg|_0 \Delta x_k + \sum_{j=1}^n \frac{\partial \psi_i}{\partial u_j} \bigg|_0 \Delta u_j, i = 1...n. \]  

The obtained equations (8) are linear. Using the vector-matrix symbols, the equation (8) can be written as follows [6]:

\[ \Delta \chi = \left[ A \right] \Delta \chi + \left[ B \right] \Delta u, \]  

where matrices \( A \) and \( B \) are called Jacobi matrices.

For system (7), the Jacobi matrices are obtained after expanding into a Taylor series:

\[ A = \begin{bmatrix} 0 & 0 & 0 \\ -U_{10} - U_{20} - U_{30} & 0 & 0 \\ 0 & 0 & -U_{10} - U_{20} - U_{30} \end{bmatrix}, \]

\[ B = \begin{bmatrix} 1 & 1 & 1 \\ \frac{c_p \cdot x_{20}}{x_{10}} & \frac{-x_{20}}{x_{10}} & \frac{-x_{20}}{x_{10}} \\ \frac{Q_0 - \lambda \cdot x_{30}}{\lambda x_{10}} & \frac{Q_0 \lambda x_{10}}{\lambda x_{10}} & \frac{e - \lambda \cdot x_{30}}{\lambda x_{10}} \end{bmatrix}, \]

\[ H = \begin{bmatrix} -1 \\ 0 \\ 0 \end{bmatrix}. \]  

Let us linearize the system using this method. The rule of expanding the function of several variables in a Taylor series is applied.

The mathematical model in continuous time is obtained by omitting the increment sign \( \Delta \) [7].

\[ \begin{aligned} \frac{dx_1}{dt} &= U_1 + U_2 + U_3 - V; \\
\frac{dx_2}{dt} &= \frac{1}{x_{10}} \cdot \left( (-U_{10} - U_{20} - U_{30}) \cdot x_1 + (c_p - x_{20}) \cdot U_1 - U_2 \cdot x_{20} - U_3 \cdot x_{20} \right); \\
\frac{dx_3}{dt} &= \frac{1}{\lambda x_{10}} \cdot \left( (-U_{10} - U_{20} - U_{30}) \cdot x_1 + (Q_0 \cdot \lambda \cdot x_{30} - x_{30} \cdot \lambda \cdot \frac{e - \lambda \cdot x_{30}}{\lambda}) \cdot \frac{U_1 + Q_0 \cdot \lambda x_{10}}{\lambda} \cdot \frac{U_1}{\lambda} \cdot \frac{U_1}{\lambda} \cdot U_3 \right). \end{aligned} \]  

The numerical substitution of the known variables and nominal values into the system of equations was performed (11).

\( X_{10} = M_n = 1800 \text{g} \) is the nominal value of the solution mass in the device;
\( X_{20} = c_n = 0.3 \) is the nominal value of the solution concentration in the device;
\( X_{30} = Q_n = 55^\circ C \) is the nominal value of the solution temperature in the device.
We supplemented the resulting system (12) with the observation equations [8]. Since the output variables in our case are \( M, c, \) and \( Q, \) i.e., \( x_1, x_2, x_3, \) it was particularly them that were observed. The correlation between the mass of the material and its level in the device was used, and through monitoring the level of material the mass will be observed. The expression of the correlation between the mass and the level has the following form:

\[
M = S \cdot p \cdot H
\]

where \( s \) is the surface area of the solution in the device, \( p \) is the density. The following expression for the level of the material will be obtained:

\[
H = \frac{M}{\rho \cdot S} = \frac{X_1}{260.57 \cdot 3.14} = \frac{X_1}{818.2} = 0.00122 \cdot X_1
\]

Now the object’s MM can be supplemented with the observation equations, then the MM will take the following form:

\[
\begin{align*}
\frac{dx_1}{dt} &= U_1 + U_2 + U_3 - V; \\
\frac{dx_2}{dt} &= -0.0056x_2 + 0.000112U_1 - 0.000168U_2 - 0.000168U_3; \\
\frac{dx_3}{dt} &= -0.0056x_3 - 0.01862U_1 - 0.01755U_2 + 0.401U_3.
\end{align*}
\]

(12)

(15)

In this case, the Jacobi matrix will take the following form:

\[
A = \begin{bmatrix}
0 & 0 & 0 \\
0 & -0.0056 & 0 \\
0 & 0 & -0.0056
\end{bmatrix};
\]

\[
B = \begin{bmatrix}
1 & 1 & 1 \\
0.000112 & -0.000168 & -0.000168 \\
-0.01862 & -0.01755 & 0.401
\end{bmatrix}; H = \begin{bmatrix}
-1 \\
0
\end{bmatrix}.
\]

(16)

The output matrix will be as follows:

\[
C = \begin{bmatrix}
0.00122 & 0 & 0 \\
0 & 1 & 0 \\
0 & 0 & 1
\end{bmatrix}.
\]

(17)
As can be seen from the structure of the matrices, in particular from the structure of the system $A$ matrix, the obtained system is reduced to a diagonal basis, in which eigenvalues (roots of the system) are placed diagonally in the matrix [9].

The controllability was evaluated by analyzing the mathematical model of the dissolver system as an object of control.

In order to assess controllability, it is necessary to compose a controllability matrix according to the following formula and determine its rank:

$$M_y = \left[ B | AB | A^2 B | ... | A^{n-1} B \right];$$

(18)

According to the Kalman criterion, if the controllability matrix was calculated by formula (8.1) has a rank equal to the order of the system, then the system is completely controllable. The controllability of the system is determined.

In order to assess the controllability, the controllability matrix is obtained:

$$M_y = \begin{bmatrix} 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0.000112 & -0.000168 & -0.000168 & 0 & 0 & 0 & 0 & 0 \\ -0.01862 & -0.01755 & 0.401 & -0.0001 & -0.0001 & 0.0022 & 0 & 0 \end{bmatrix};$$

(19)

$\text{rang} (M_y) = 3$.

The rank of the matrix $M_y$ is equal to the order of the system ($n = 3$), so it is concluded that the object is fully controllable [10].

The block diagram of the control system in matrix form is synthesized, which is shown in Figure 2.

In order to assess observability, it is necessary to compose an observability matrix using the following formula:

$$M_n = \left[ C^T | A^T C^T | (A^T)^2 C^T | ... | (A^T)^{n-1} C^T \right].$$

(20)

According to the observability criterion, if the observability matrix calculated by formula 20 has a rank equal to the order of the system, then the system is completely observable. The observability of the system is determined [11].

The observability matrix $M_n$ is composed according to formula 20 and the MATLAB package is used to calculate its rank.

$$M_n = \begin{bmatrix} 0.00122 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & 0 \\ 0 & -0.0056 & 0 \\ 0 & 0 & -0.0056 \\ 0 & 0 & 0 \\ 0 & 0 & 0.00003136 \\ 0 & 0 & 0.00003136 \end{bmatrix};$$

(21)

$\text{rang} (M_n) = 3$.

Since the rank of the matrix $M_n$ is equal to the order of the system ($n = 3$), it is concluded that the object is completely observable.

According to the above mentioned conclusions stating that the object is fully observable and fully controllable, it can be concluded that the object is complete [12].

The dependences for calculating the matrices $K$ and $R$ are expressed using relation (21).
Thus, the problem of synthesizing the control law has been reduced to calculating the matrices \( K \) and \( R \). Using the MATLAB package, the following can be obtained:

\[
K = B^{-1} (Ac - A); \quad R = B^{-1} F.
\]

Using MATLAB, the following can be obtained:

\[
K = \begin{bmatrix}
-0.012 & -15.7143 & 0 \\
-0.0071 & 15.7545 & 0.001 \\
-0.0009 & -0.0402 & -0.001
\end{bmatrix};
\]

\[
R = \begin{bmatrix}
0.012 & 35.7143 & 0 \\
0.0071 & -35.8056 & -0.0143 \\
0.0009 & 0.0913 & 0.0143
\end{bmatrix}.
\]

A block diagram of the resulting control system is composed in matrix form:

\[
\begin{array}{c}
\begin{array}{c}
N \\
\rightarrow
\end{array}
\end{array}
\begin{array}{c}
\begin{array}{c}
\rightarrow \\
\uparrow \\
R \\
\rightarrow \\
B \\
\rightarrow \\
\int \\
\rightarrow \\
K \\
\rightarrow \\
C
\end{array}
\end{array}
\]

**Figure 2.** Structural diagram of the CS in matrix form.

2. **Analyzing the results and overall conclusions**

As a result of theoretical and experimental studies related to the synthesis of multifunctional composite coatings with improved anti-friction properties, the following qualitative and quantitative conclusions were obtained:

1. An acoustic synthesis device was developed using a complex acoustic field, which made it possible to obtain an aggregative and stable composition system.

2. A mathematical model of the dissolver system was obtained, which made it possible to analyze the controllability of the system. Thus, the calculated value \( M_y =3 \) indicates that the system is fully controllable.

3. The structural diagram of the control system for the acoustic synthesis of multifunctional composite coatings with improved antifriction properties has been synthesized. The system allows forming the resulting oscillation vector of the acoustic field in such a way that by an order more cavities will collapse than if only longitudinal ultrasonic vibrations are used.

4. The multi-loop feedbacks in the block diagram of the automatic control system allow reducing the static error, which favorably affects the transient process having an exponential form.

5. Multifunctional composite coatings produced by an acoustic synthesis device by using a complex acoustic field made it possible to create unique operational properties of the surfaces of the processed agricultural machinery. The properties consist in the formation of a variable friction coefficient at the interface depending on external pressure.
6. The acoustic synthesis of multifunctional composite coatings with improved antifriction properties, implemented through the use of two quasi-coherent sources of ultrasonic vibrations, does not have an overshoot, which leads to high quality of the products with sufficiently large stability margins both in amplitude and phase of oscillations.

7. The use of magnetostrictive ultrasonic transducers makes it possible to obtain large amplitudes of acoustic vibrations over a wide range of effective values, up to 15 μm. The high acoustic power supplied to the processed medium makes the active control possible depending on the given reference transient characteristics with the subsequent possibility of applying complex standard laws of controlling the dynamic systems in order to obtain stable output parameters.

The problem of obtaining multifunctional composite coatings and materials with unique physical and mechanical properties is most acute for transnational manufacturers in the general context of the development of modern high technologies. The solution to this problem is inherently associated with the use of new highly efficient processes for the synthesis of paints and varnishes.

Modern technology for producing high-quality paint and varnish products using a complex ultrasonic field is one of the most progressive in the world for the moment. The technology basis is the integrated effect of a complex highly concentrated acoustic and electromagnetic fields on the processes of cold physical and chemical synthesis of paints and varnishes. The complex effect exerted on the elements of the composite compound of liquid and solid phases leads to the appearance of new quasi-ordered stable nanocrystalline structures in solutions.

The presence of quasi-ordered nanocrystalline structures in the compositions made it possible to significantly improve the texotropic and penetrating properties of the multifunctional paint coating. The sufficiently large value of the adhesion strength ensures good adhesion of the applied layer to the substrate.

Such state of the resulting composition leads to an optimal distribution of elements among the entire volume of manufactured products. This elemental distribution during drying makes it possible to obtain several layers that not only increase the drying speed of the multifunctional paint and varnish composite coating, but also simultaneously increase their surface hardness. The increase leading to a sharp improvement in such quality parameters as mechanical abrasion, chemical resistance and heat transfer, which is an important factor in the conditions of modern operation of all kinds of ships and marine structures.

The elasticity of the inner layers makes it possible to sharply increase not only the adaptive resistance of the coating to external mechanical loads, but also to form a variable value of the friction coefficient of the coating. As the coating wears, it improves its antifriction properties and the wetting angle, which ultimately leads to an improvement in the antifouling properties of the surface for epibiosis and other biological organisms in the water. This fact will reduce friction during the movement of the vessel, fuel consumption and increase speed, which, ultimately, will positively affect the technical and operational characteristics and economic efficiency of its use.

The layered self-organizing drying structure of a multifunctional composite paint coating indicates the presence of unique physical and mechanical properties of the layers. The layers have different heat transfer coefficients that form a heat shield, and high moisture resistance and frost resistance allow them to be used in a fairly wide temperature range.

Obtaining self-organizing layer-by-layer structures with a large nomenclature of elemental composition made it possible to obtain excellent values of such a quality parameter as coverage rate. As a result, the multifunctional composite paint coating has a lower specific consumption per unit area than analogues, which will lead to a sharp improvement in the economic efficiency of production while increasing the quality of the protective properties of paint coatings.

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