Mathematical modeling of pneumatic installations for transportation of solid domestic waste

R Yusupov\(^1\) and S Andreev\(^*\)

\(^1\)Russian State Agrarian University-Moscow Agricultural Academy named after K.A. Timiryazev Institute of Mechanics and Energy named after V.P. Goryachkin, 127550, Moscow, St. Timiryazevskaya, 49, Russia

\(^*\) Corresponding author: jusupow@mail.ru

Abstract. The article is devoted to the consideration of the method of mathematical modeling of a pneumatic transport installation. The peculiarity of the approach is that it is aimed at studying low-frequency processes in a simulated object, i.e. those processes that affect its energy. This will allow you to get a mathematical model of small dimension. For this purpose, the model is decomposed into subsystems separated from each other by weak elastic relations. A method for estimating the numerical value of the dynamic compliance of these bonds is proposed.

1. Introduction

In a number of industrially developed countries of Europe, people faced an exacerbation of the problem of shortage of space for municipal waste in large cities much earlier than Russia. Practically the only way to solve it radically now is the thermal neutralization of municipal solid waste with the generation of thermal and / or electrical energy [1-6].

The process of incineration of solid waste not only provides sanitary and hygienic treatment of waste, but also reduces the amount of disposal of residues from the processing of solid waste to 10% of the original. Waste incineration is a thermal oxidation process to reduce waste, extract valuable materials, ash, or generate energy from it. The lowest calorific value per working mass for Moscow wastes is, on average, 7500–8000 kJ / kg, humidity is about 30–40%, ash content is 25–30% [1,2].

Due to changes in the morphological composition (increasing the share of packaging, plastic, paper, reducing food waste), there is a tendency to increase the heat of combustion of MSW (in Western European countries, this value reaches 10,500–12,500 kJ / kg). Using solid waste as a fuel for generating heat and electricity as opposed to dumping them saves traditional fuels (coal, gas, fuel oil).

The calorific value of household waste roughly corresponds to brown coal. On average, the calorific value of household waste ranges from 1000 to 3000 kcal / kg. It was also revealed that the calorific value of 10,500 kg of municipal solid waste is equivalent to 1000 kg of oil; calorific content of household waste is only 2 times lower than that of coal; about 5000 kg of garbage emit as much heat when burning as 2000 kg of coal or 1 ton of liquid fuel.

Currently, the level of household waste incineration varies from one country to another. From the total volumes of household garbage, the share of burning varies in such countries as Austria, Italy, France, Germany, from 20 to 40%; Belgium, Sweden - 48-50%; Japan - 70%; Denmark, Switzerland 80%; England and the United States - 10% [7-9]. In our country, only about 2% of household garbage is incinerated so far, and in Moscow - about 10% [1,2,9].

According to foreign data, it is advisable to use waste incineration in cities with a population of at least about 15 thousand. About 300-400 kWh of electricity can be generated from each ton of waste. Each city resident gives out, approximately, from 500 to 800 kg of waste per year.

The experience of industrial operation of TPPs operating on solid waste in Moscow showed that the installations operate in compliance with the environmental requirements adopted in Russia and the EU for the process of thermal disposal of solid waste. The equipment of new power plants on alternative fuel meets modern requirements and allows to solve both the problems of sanitary cleaning of solid waste and the problem of energy supply to the adjacent areas of the city.

One of the important conditions for improving the efficiency of equipment and solving environmental problems in waste recycling enterprises is the use of pneumatic transport in production processes.

Pneumatic transport has a number of significant advantages over mechanical. Therefore, during the construction of new and reconstruction of existing enterprises, it becomes necessary to design and implement pneumatic conveying units (PTU). When designing pneumatic installations, it should be taken into account that air is used in installations other than transportation and for technological purposes, which allows reducing the number of pieces of process equipment (for cleaning, surface treatment), as well as ventilation costs [10-14].

Pneumatic transport installations are a complex of devices that ensure the movement of bulk materials (powdered, granular, crushed, etc.) or special vehicles (capsules, containers with raw materials, finished products, etc.) using compressed air or discharged gas.

Pneumatic transport is widely used to move materials due to their significant performance and large radius of operation in the most cramped working conditions, i.e., using areas unsuitable for other transportation methods, saving production space, complete absence of residues and losses of the product being moved in lines sanitary and hygienic conditions of its transportation; with the exception of violations of technological and hygienic modes of air in industrial premises due to the absence of dust; ease of installation, reduction of staff and simplified maintenance; flexibility in operation and the possibility of full automation control. To move solid household waste (MSW) through pipelines, it is the most advisable to use a method of pneumatic transportation in suspension. At the same time the speed of the transporting air in the pipeline must be quite high - 25 - 35 m / s.

There are disadvantages of pneumatic transport: the relatively high specific energy consumption per unit mass of the transported product, the complexity of manufacturing and operating equipment for cleaning the transporting and exhaust air, significant wear. However, the correct choice of the method and equipment for pneumatic conveying of this product allows to eliminate them partially or completely. Of interest to specialists is the question of mathematical modeling of the elements of a pneumatic transport installation when solving the problem of synthesizing an automatic control system (ACS) for the process of transporting solid waste. (Figure 1).
2. Method

Associated with the use of an equivalent circuit for replacing elements of a pneumatic conveying installation method is proposed. The essence of the method lies in the fact that the dynamic system of a real installation can be modeled as a definitely connected set of parameters of the following elements:

- An element that has the property to accumulate kinetic energy. In a mechanical system, it is an inertial element (mass), in an electrical one, inductance.
- An element with the property of accumulating potential energy. In a mechanical system, it is a spring; in an electrical system, a capacitor (capacitance).
- An element with the property of irreversibly dissipating energy. In a mechanical system, it is a mechanical resistance, it characterizes irreversible energy losses, friction losses, in an electric system, electrical resistance, and it characterizes irreversible energy losses due to heating.

Here one can also consider such a concept as mechanical conductivity, which characterizes irreversible energy losses due to slipping. If we consider the electrical system, then it is characterized by electrical conductivity, which characterizes the loss of energy leakage.

Figure 2 shows the replacement pattern of the dynamic system of a pneumatic conveying installation for solid waste transportation.

The tasks of designing complex mechanical systems, predicting their dynamic and energy characteristics require the creation of mathematical models. Special software systems have been developed in our country and in some countries abroad to automate the process of forming mathematical models of complex objects. They are based on the use of methods of electromechanical analogy, matrix-topological and tabular methods. In turn, the task of saving machine time when performing calculations of complex dynamic systems with a large scatter of time constants, ensuring clarity and simplicity of formalizing mathematical models determines the search for ways to reduce the dimensions of the latter. This is evident because there is a class of tasks that do not require drawing the high-frequency components of dynamic processes. This is especially true for mechanical systems of traction and
transport vehicles, the efficiency of which is largely determined by the influence of low-frequency components of the oscillations [15, 16].

However, despite the progress achieved in this direction, models often have too much detail, and therefore a higher dimension. A way of reducing the dimension of a mathematical model is proposed by introducing into it an integral parameter reflecting the action of a set of elements and functional units of the system. Analysis of the dynamic systems of real mechanisms and machines shows that in the low-frequency range of oscillations, this parameter can be the compliance of quasi-elastic bonds through media of different physical nature: electric, hydraulic, pneumatic, etc. Thus, in an internal combustion engine, such a connection implies a fuel mixture in a piston system, in hydraulic machines - a hydraulic connection, in electric machines - a connection through an electromagnetic field, in a pneumatic conveying installation - airflow in the pipeline [15, 16].

In the process of modeling a complex dynamic system are based on the proposed approach, it is important to identify quasi-elastic constraints. In some cases, this task can be solved heuristically with a focus on the experience of the researcher. In addition, theoretical methods described in [17–22] can be used here.

Much attention is paid to the methods of studying dynamic systems that are based on equivalent replacement schemes by foreign authors. In works [23-25] some terms are clarified, sufficient and necessary conditions for the similarity of mechanical and electrical systems are identified. Some methods for the formation of equivalent schemes are specified. For example, the concepts “loop method”, the node method, by analogy with the methods known in electrical engineering, the method of loop currents, the method of node potentials, are introduced.

A common drawback of all the theoretical works discussed above is that they do not reveal at all or weakly reveal the issues of studying the dynamic properties of systems composed of components of different physical nature (electrical, hydraulic, mechanical).

In general, according to the review of analytical methods for studying the dynamic properties of power transmissions, it can be concluded that the scope of application of existing methods is limited to one specific physical nature (mechanical, hydraulic, electrical).

\[ e_1 \text{ – compliance of a weak elastic electromagnetic coupling in a dynamic system of an asynchronous electric motor of a blower, } (N m)^{-1}; \]
\[ \gamma_1 \text{ – the mechanical conductivity, which characterizes the losses in terms of the velocity factor ibid, } (N m)^{-1}; \]
\[ \gamma_2 \text{ – mechanical conductivity, the reciprocal of the mechanical resistance } \beta_2, \text{ characterizes the power factor losses in the same place, } (N m s)^{-1}; \]
\[ J_1 \text{ – the moment of inertia of the rotor of an electric motor, kg } m^2; \]
\[ \gamma_3 \text{ – mechanical conductivity, characterizes leakage losses in a dynamic system in a pneumatic conveying installation, } (N m s)^{-1}; \]
\[ e_2 \text{ – compliance of weak elastic coupling in the dynamic system of the pneumatic conveying installation, } (N m)^{-1}; \]
\[ J_2 \text{ – the mass of the transported medium in the pneumatic conduit, reduced to rotor speed, kg } m^2 \]
$e_t$ - mechanical conductivity, the reciprocal of the mechanical resistance $\beta$, characterizes the friction losses in the dynamic system of pneumatic conveying installation, $N m s^{-1}$; $W(t)$ – the source of angular velocity, $s^{-1}$.

3. Results

Let us consider the transition process occurring in the subsystem (Figure 3). Suppose it is oscillatory in nature. In this case, there is a periodic conversion of the potential energy of the elastic element into the kinetic energy of the inertial element. At the same time, some of the energy is irreversibly lost in dissipative elements (friction loss and leakage). Moreover, friction losses cause a decrease in torque, which means potential energy, and leakage losses cause a decrease in speed and, consequently, kinetic energy. Hence, the energy balance equation for the part of the transition process corresponding to a certain time $\Delta t / 2$

$$\Delta W_p = \Delta W_k + \Delta W_{\Omega 1} + \Delta W_{M1},$$

where: $\Delta W_p$ – the potential energy stored in the elastic element at the initial moment of the considered time interval; $\Delta W_k$ – the increment of the kinetic energy of the inertial element over time $\Delta t / 2$; $\Delta W_{\Omega 1}$ – the increment of dissipation losses by the speed factor for the same time; $\Delta W_{M1}$ – the increment of dissipation losses by the garden factor for the same time.

Further, we note that $\Delta W_{\Omega 1}$ affects the kinetic energy of the inertial element, and $\Delta W_{M1}$ affects the potential energy of the elastic element. Thus, $\Delta W_{\Omega 1}$ and $\Delta W_{M1}$ can be expressed as ratios:

$$\Delta W_{\Omega 1} = n \Delta W_k, \quad \Delta W_{M1} = m \Delta W_p,$$

where: $n$ and $m$ are coefficients. Then equation (1) can be rewritten:

$$\Delta W_p = \Delta W_k + n \Delta W_k + m \Delta W_p.$$  

Hence, $\Delta W_p = \Delta W_k \frac{1+e^n}{1-m}$. 

Since $\Delta W_p = e\Delta M_2^2/2$, $\Delta W_k = J\Delta \Omega_2^2/2$.

where: $\Delta \Omega_1 / \Delta M_1$ – the steepness of the mechanical characteristics of the subsystem.

Thus, the calculation of compliance is possible if the slope of the characteristic $M = f(\Omega)$ and the coefficients $n$ and $m$ are known.

To determine the latter, we first find their connection with the decrement of the oscillations in the subsystem. The ratio is known

$$d = \exp(\alpha T),$$

where: $\alpha$ is the attenuation coefficient of free oscillations; $T$ – the period of free oscillations.

Consider the equivalent circuit of the subsystem (Figure 3). The analysis of the scheme suggests that, under the assumption of linearity of its parameters, the transition process in it can be represented as the superposition of two transient processes: one in speed, the other in torque. Moreover, the transient process in the speed factor is implemented on the circuit section with the series-connected elements $y_1$, $J_1$, $e_1$, and on the force factor - on the section with the parallel-included elements $J_1$, $\beta_1$, $e_1$. Greater visibility is achieved if the replacement scheme of the subsystem is brought into conformity with the preceding arguments and present it in the form of a set of two simplified schemes. The first one is...
constructed from parallel-connected \( 2\beta, e, J \), and the other is built from the successively inserted \( 2\gamma, e, J \) (Figure 4).

Let us verify the validity of the statement that the real transient process in the mechanical circuit of a subsystem that can be represented as the result of the superposition of two transients. We use the operator equations describing the circuit in Figure 4. For the circuit in Figure 46, we can write

\[
p\epsilon M (p) + 2\gamma M (p) + M (p)/ (pJ) = \Omega (p)
\]

The parameters of the transient process (rate of attenuation \( \alpha\Omega \) and the frequency of free oscillations \( \omega\Omega \)) are determined from the characteristic equation.

\[
p^2 + 2\gamma p/e + 1/ (eJ) = 0
\]

\[
\alpha\gamma = -\gamma/e,
\]

\[
\omega\gamma = \sqrt{\frac{1}{e}} - (\frac{\gamma}{e})^2. \tag{3}
\]

Similarly for the circuit in Figure 4a

\[
P\epsilon\Omega (p) + 2\beta\Omega (p) + \Omega (p)/ (pJ) = M (p)
\]

\[
p^2 + 2\beta p/J + 1/ (eJ) = 0,
\]

\[
\alpha\beta = -\beta/J,
\]

\[
\omega\beta = \sqrt{\frac{1}{eJ}} - (\frac{\beta}{J})^2. \tag{4}
\]

Finally, for the equivalent circuit of a dynamic link system (Figure 3)

\[
p\epsilon M_1 (p) + \gamma M_1 (p) + \gamma M_2 (p) - \gamma M_1 (p) - \gamma M_2 (p) = \Omega (p)
\]

\[
p^2 + p(J\gamma_1 + e)/ (Je\gamma) + (\gamma_1 + \gamma)/ (Je\gamma) = 0
\]

\[
\alpha = (J\gamma_1 + e)/(2Je\gamma),
\]

\[
\omega = \sqrt{[((\gamma_1 + \gamma_2)}/ (e\gamma_2)] - ((\gamma_1 + \gamma + e)/ (2Je\gamma_2))^2. \tag{5}
\]

Let's compare the characteristic equation (5) with the equation obtained after adding (3) and (4)

\[
p^2 + p(J\gamma_1 + e)/ (Je\gamma) + (\gamma_1 + \gamma_2)/ (Je\gamma_2) = 0
\]

\[
\alpha = (\alpha\Omega + \alpha\Omega)/2,
\]

\[
\omega = (\omega\Omega + \omega\Omega)/2.
\]
If the first relation is obvious, then the second is proved as follows:

\[(\omega_\Omega + \omega_M)^2/4 = [\frac{1}{\epsilon J} - \left(\frac{\beta}{\gamma}\right)^2/4 = [\frac{1}{\epsilon J} - \left(\frac{\beta}{\gamma}\right)^2/4]. \tag{7}\]

Taking into account the fact that for dynamic systems with weak dissipation, the proximity of the frequencies \(\omega_\Omega\) and \(\omega_M\) is characterized, we can assume that the arithmetic mean and geometric mean of these frequencies are equal;

\[\omega_{sa} = \omega_{sr} \quad \text{or} \quad (\omega_\Omega + \omega_M)/2 = \sqrt[4]{\omega_\Omega \omega_M}. \]

Then in expression (7)

\[\frac{1}{\epsilon J} - \left(\frac{\beta}{\gamma}\right)^2/4 = \omega_{sa}^2 \approx \omega_{sr}^2. \]

After substitution of the obtained relation in (7), the transformations take the following form:

\[2\omega_{sa}^2 = 2(\epsilon J\gamma \omega / 2)^2 - (\beta J)^2/4 = [2(\epsilon J\gamma \omega / 2)^2 - (\beta J)^2/4]. \tag{8}\]

As we see, relations (8) and (5) practically are coincided. This is confirmed by concrete calculations. The insignificant discrepancy between the calculated data and the expressions (8) and (5) themselves is explained by the accepted assumption about the equality of \(\omega_{sa}\) and \(\omega_{sr}\). We note that the result obtained agrees well with the well-known propositions from the theory of oscillations on the superposition of oscillations with similar frequencies [26]. Another feature that confirms the connectedness of transients in the studied circuits is interesting. To do this, we define relations for calculating the resonant frequencies in terms of speed and moment in the subsystem (Figure 3) by transforming the expressions for the complex mechanical conductivities \(Y\) and the resistances \(Z\).

Expression for mechanical conductivity \(Y\):

\[Y = \gamma_1 + \gamma_2 / (1 + \gamma_2 \omega^2 J^2) + j\omega [e \gamma_2 J / (1 + \gamma_2 \omega^2 J^2)].\]
Equating to zero, the coefficient at the imaginary part of the complex mechanical conductivity will find the resonant frequency of the moment [27]

\[ \Omega_{rez.m} = \sqrt{1/\epsilon J} - (\beta/\epsilon)^2 \]  

(9)

As we can see, the obtained relation coincides with expression (4) for calculating the natural oscillation frequency in the simplified subsystem (Figure 4a).

Similarly, we write the expression for the mechanical resistance \( Z \):

\[ Z = 1/\gamma_2 + \gamma_1/ (\gamma_2 + \omega^2 e^2) + j\omega (J - e/(\gamma_2 + \omega^2 e^2)). \]

Hence the resonant frequency in speed:

\[ \Omega_{rez.\Omega} = \sqrt{1/\epsilon J} - (\gamma_1/\epsilon)^2 \]  

(10)

From a comparison of the obtained relation with (3), it follows that they coincide.

Thus, in accordance with the known theoretical principles [26], the resonant frequencies are \( \Omega_{rez.m} \) and \( \Omega_{rez.\Omega} \) can be considered the partial frequencies of the subsystem (Figure 3), and the simplified subsystems (Figure 4a, b) - as partial systems.

Now let us return to the further presentation of the procedure for deriving a formula for calculating the dynamic compliance of a quasi-elastic connection in a subsystem.

The speed transition observed in the scheme in Figure 4b will be characterized by the decrement of the oscillation \( d_\Omega \), the attenuation coefficient \( \alpha_\Omega \), the free oscillation period \( T_\Omega \). Accordingly, the torque transient process is \( d_M, \alpha_M, T_M \). A graphical representation of transients is presented in Figure 5.

For further reasoning, it is advisable to use the decrement of vibration to understand the ratio of the magnitudes of factors (torque, speed) changing in the transient process at times \( t_1 + \Delta t \), not \( t_1 + T \) [27].

Then:

\[ d_M = \exp (\alpha_M \Delta t), d_\Omega = \exp (\alpha_\Omega \Delta t). \]

(11)

Taking into account the decrement \( d_\Omega \), we find the dissipative losses in speed over the segment \( \Delta t \) as the difference of the increments of the kinetic energies in the regions \((t_1, t_0)\) and \((t_0, t_2)\):

\[ W''_\Omega = \Delta W_k1 - \Delta W_k2 = J \Delta \Omega_1^2/2 - J \Delta \Omega_2^2/2 = J \Delta \Omega_1^2/2 - J (\Delta \Omega_1 d_\Omega)^2/2 = (1 - d_\Omega^2) J \Delta \Omega_1^2/2, \]

(12)

where: \( \Delta W_k1 \) – the increment of kinetic energy in the area \((t_1, t_0)\), \( \Delta W_k2 \) – the same at the site \((t_0, t_2)\), \( \Delta \Omega_1 \) – the increment of the velocity factor in the segment \((t_1, t_0)\), \( \Delta \Omega_2 \) – the same on the segment \((t_0, t_2)\).

Similarly, we define the dissipative losses by the force factor as the difference between the increments of potential energies in the \((t_1, t_0)\) and \((t_0, t_2)\) sections:
\[ W'_{M} = \Delta W_{P1} - \Delta W_{P2} = J\Delta M_{1}^{2}/2 - J\Delta M_{2}^{2}/2 = e (\Delta M_{1})^{2} / (2d_{M}^{2}) = (1 - 1/d_{M}^{2}) e\Delta M_{1}^{2}/2, \]

where: \( \Delta W_{P1} \) - the increment of kinetic energy in the area \((t_{0}, t_{1})\),
\( \Delta W_{P2} \) - the same at the site \((t_{1}, t_{2})\),
\( \Delta M \) is the increment of the speed factor at the site \((t_{1}, t_{2})\).

Denote by \( \Delta W_{Q1} \) - dissipative energy loss by the speed factor in the area \((t_{1}, t_{0})\), \( \Delta W_{Q2} \) – in the area \((t_{0}, t_{2})\), then
\[ W''_{M} = \Delta W_{Q1} - \Delta W_{Q2} . \]

Similarly, for dissipative losses by the force factor:
\[ W''_{M} = \Delta W_{M1} - \Delta W_{M2} \]

Express the ratio of dissipative losses in the areas \((t_{1}, t_{0})\) and \((t_{0}, t_{2})\) through decrements:
\[ \begin{align*}
W_{Q1}/\Delta W_{Q2} &= (\Delta\Omega_{1}^{2})\gamma / (\Delta\Omega_{2}^{2})\gamma = d_{1}^{2}, \\
W_{M1}/\Delta W_{M2} &= (\Delta M_{1}^{2})/\beta \gamma = d_{2}^{2},
\end{align*} \]

where: \( \Delta\Omega_{1}^{2}, \Delta\Omega_{2}^{2}, \Delta M_{1}^{2}, \Delta M_{2}^{2} \) - average values of increments of speed and power factors in the areas \((t_{1}, t_{0})\) and \((t_{0}, t_{2})\).

Taking into account relations (14), (15), we get:
\[ \Delta W_{Q1} = W''_{M}/(1 + d_{1}^{2}). \Delta W_{M} = W''_{M}d_{2}^{2}/(1 + d_{2}^{2}). \]

After substitution in (18) of expressions (12), (13):
\[ \Delta W_{Q1} = (1 - d_{2}^{2}) J\Delta\Omega_{1}^{2}/(2(1 + d_{2}^{2})). \]

Comparing (19) and (20) with (1), we find
\[ n = (1 - d_{2}^{2})/(1 + d_{2}^{2}), \quad m = (d_{1}^{2} - 1)/(d_{1}^{2} + 1) \]

Taking into account relation (2), we obtain the final expression for calculating the dynamic compliance of the elastic connection in the pneumatic duct:
\[ e = J(1 + d_{2}^{2})\gamma (\Delta\Omega_{1}/\Delta M_{1})^{2}. \]

In practical calculations, compliance is calculated by successive approximation. The first approximate value is found from the assumption that the oscillatory process is continuous, i.e. decrements \( d_{2} = d_{M} = 1 \). At the same time
\[ e = J(\Delta\Omega_{1}/\Delta M_{1}) \]

Then, the approximate values of the attenuation coefficients \( \alpha_{Q1}, \alpha_{M} \) from (3) and (4) are calculated. Based on them, for a given period \( \Delta t \), the refined values of decrements and compliance are determined by (11). The cycle is repeated until the value of duration is not satisfied with the desired accuracy. Dynamic elasticity constraint. Above is a method for calculating compliance in the subsystem of a pneumatic conveying installation (PTU), based on the assumption that the steepness of the static and dynamic characteristics \( \Omega = f(M) \) coincide.

Here we propose a technique that allows to take into account the deformation of the steepness of the characteristic depending on the oscillation frequency of the variable component of the external load. An expression characterizing the relationship between the slope and frequency can be obtained from the equation describing the replacement circuit of the mechanical chain of the subsystem (Figure 3). As is known, the expression of the total mechanical conductivity of the equivalent circuit of a mechanical chain simultaneously corresponds to the steepness of the dynamic characteristic:
\[ (j\omega) = d\omega/d\Omega = \gamma_{1} + j\omega_{1} + j\gamma_{2}/(1 - j\omega T_{1}T_{2}) = (j\gamma_{1} + j\gamma_{2}/(1 - j\omega T_{1}T_{2})), \]

For the module of complex mechanical conductivity, we have:
\[ Y (\omega) = (\gamma_{1} + \gamma_{2})/(1 - \omega^{2}T_{1}T_{2})^{2} + (\omega T_{12} + \omega T_{1})^{2}/(1 + \omega^{2}T_{2}^{2}). \]

This expression corresponds to the unregulated subsystem. The influence of the regulator on the formation of the slope of the characteristic \( f_{S} = f(M) \) is taken into account by the coefficient \( K \) [192].
\[ Y (\omega)_{reg} = Y (\omega) = K (\gamma_{1} + \gamma_{2})/(1 - \omega^{2}T_{1}T_{2})^{2} + (\omega T_{12} + \omega T_{1})^{2}/(1 + \omega^{2}T_{2}^{2}). \]

Here: \( \gamma_{1}, \gamma_{2} \) - coefficients (mechanical conductivities), characterizing dissipative losses; \( T_{1} = c_{1}/(\gamma_{1} + \gamma_{2}) \), \( T_{2} = J_{1}/\gamma_{2} \), \( T_{12} = J_{1}/\gamma_{2}/(\gamma_{1} + \gamma_{2}) \) are time constants;
\[ e_s = \frac{(y_1 + y_2)^2(1 + T_2^2 - 2(y_1 + y_2)e_s \omega^2)}{2e_s \omega^2(1 + \omega^2 T_2^2)} - \frac{\sqrt{(y_1 + y_2)^2(1 + \omega^2 T_2^2 - 2(y_1 + y_2)e_s \omega^2)}}{4e_s \omega^2(1 + \omega^2 T_2^2)} \]  

\[ J_i = J_i^2 \frac{(y_1 + y_2)^2(1 + \omega^2 T_2^2 - 2(y_1 + y_2)e_s \omega^2)}{2e_s \omega^2(1 + \omega^2 T_2^2)} - \frac{\sqrt{(y_1 + y_2)^2(1 + \omega^2 T_2^2 - 2(y_1 + y_2)e_s \omega^2)}}{4e_s \omega^2(1 + \omega^2 T_2^2)} \]  

4. Conclusions

1. Practically the only way to solve the problem of the shortage of space for municipal waste in large cities is currently the thermal neutralization of solid household waste with the generation of heat and/or electric energy.

2. The equipment of new power plants on alternative fuel meets modern requirements and allows to solve both the problems of sanitary cleaning of solid waste and the problem of energy supply to the adjacent areas of the city.

3. One of the important conditions for improving the efficiency of the equipment and solving environmental problems in waste recycling enterprises is the use of pneumatic transport in production processes. In pneumatic installations, air is used, besides transportation, and for technological purposes, reduces the number of pieces of process equipment, as well as the cost of ventilation.

4. It is of interest to specialists the question of mathematical modeling of the elements of a pneumatic transport installation when solving the problem of synthesizing an automatic control system (ACS) in the process of transporting solid waste.

5. Analysis of published analytical methods for studying the dynamic properties of complex systems shows that the scope of existing methods is limited to one specific physical nature: mechanical, hydraulic, electrical.

6. A universal method is proposed associated with the use of an equivalent circuit for replacing elements of a pneumatic conveying installation. A feature of the method is that in order to reduce the dimension of the model, the ability to assess the energy performance of the system, an integral parameter is introduced into the mathematical model - the compliance of a weak elastic connection.

7. An energy method has been developed for determining the numerical value of the dynamic compliance of a weak elastic connection in inhomogeneous elements of a complex system.
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