The object of this study is the material flow incoming the conveyor. The actual problem of calculating the stochastic characteristics of the input material flow of a transport system, based on the typification of the input material flow, is being solved. When constructing a model of the input material flow, methods of similarity theory were used. A criterion has developed for dividing the realization of the input material flow into a deterministic and stochastic component, which makes it possible to represent the stochastic component of the input flow in the form of an realization of a centered ergodic process. A method is presented for calculating amplitude and phase frequency spectra for the components of the input material flow, based on specified types of theoretical correlation functions. The calculating accuracy of the normalized correlation function values is ε ~0.05. Distinctive features of the obtained results are that the typification method of the input material flow is based on the use of the amplitude spectrum for the input material flow. A special feature of the results obtained is that a single realization of the input material flow was used to model the input material flow. The scope of application of the obtained results is the mining industry. The developed methodology for calculating the statistical characteristics of the input material flow allow to improve the accuracy of algorithms for optimal control of the flow parameters of the transport system for a mining enterprise. The condition for the practical application of the obtained results is the presence in the sections of the transport conveyor of measuring sensors that determine the speed of the belt and the amount of material in the bunker

Keywords: transport conveyor, similarity criteria, statistical characteristics, correlation function, material flow typification

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DEVELOPMENT OF A METHOD FOR CALCULATING STATISTICAL CHARACTERISTICS OF THE INPUT MATERIAL FLOW OF A TRANSPORT CONVEYOR

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1. Introduction

The transport conveyor, used to move bulk materials, is a complex dynamic distributed system with a transport delay [1] and consists of a large number of separate long belt conveyors [2] and bunkers between them [3, 4]. The belt conveyor is the most important link in the transport system of a mining enterprise, characterized by versatility, ease of automation and high productivity. Increasing the efficiency of a belt conveyor is directly related to reducing the cost of transporting bulk material, which constitutes a significant part of the cost of material extraction [5]. A common way to reduce transport costs is to increase the loading factor of a belt conveyor with bulk material, based on the use of belt speed control systems [6, 7] and the amount of material flow coming from the accumulating bunker [8–10]. When designing control systems for the flow parameters of a transport system, one of the problems is the calculation of the statistical characteristics of the input material flow. A common approach to solving the problem is to use the assumption of stationarity of the input material flow with an approximated exponential correlation function $\exp(-t/t_{cor})$ and a normal distribution law for minute values of the input material flow. However, this assumption often does not hold for operating conveyors. In real transport systems, the distribution law of minute values of the input material flow can differ significantly from the normal distribution law and has the form of a multimodal distribution. The correlation function, which characterizes the input flow of material for existing transport systems, can be represented by a periodic function that decays with increasing correlation time. In this regard, to synthesize optimal control algorithms, it is necessary to build models that take into account the statistical characteristics of the input material flow, which allow to reduce the unit costs of material transportation, reduce wear and increase the service life of equipment. Determination of the statistical characteristics of the input material flow is based, as a rule, on measuring the minute values of the input flow. For this purpose, belt weighers, volumetric ultrasonic or ultrasonic, laser or optical sensors are used, transmitting the measurement results to the control system.

Thus, the study of the statistical characteristics of the input material flow in belt conveyors is an important and relevant area of practical importance for further optimization of specific transport costs when using belt conveyors in the mining industry.

2. Analysis of literature data and problem statement

The material flow $\lambda(t)$, incoming the belt conveyor is a random process. Statistical characteristics are determined from realizations of a random process obtained as a result of an experiment. As a rule, works devoted to the study of the characteristics of the input material flow of the analyzed transport system contain a single realization for the input material flow, observed over a fixed time interval.

The paper [11] presents the results of studies of the input flow of material for a brown coal quarry (Bełchatów, Poland). The results of experimental measurements for the volumetric productivity of the SRs 2000 excavator are presented. The realization studied in this work for a continuous input flow of material emphasizes the unevenness of the material flow formed at the material extraction site. The amplitude of the oscillation is one third of the maximum value of the material flow with a quasi-constant period of oscillation. The main focus of the work is on the problem of energy recuperation for inclined conveyors. The realization obtained as a result of measuring the values of the input material flow is presented. However, the statistical characteristics of the input material flow are not taken into account in the proposed energy recuperation model. The reason is explained by objective difficulties associated with determining statistical characteristics based on available experimental data. An option to overcome these difficulties may be the use of techniques that determine both the type of input material flow and its statistical characteristics. Paper [12] presents the results of a practical study of real-time monitoring of material flows at a solid fuel production plant. For the realization represented by experimental values, a periodic nature of fluctuations in the values of the input material flow is observed. As in the previous paper [12], the realization of the input material flow contains clearly long-wave oscillations of the material flow values. The study assumes that the amplitude and length of the oscillation period depend on the operating conditions of the technological equipment. The paper [13] presents the results of a study of the input material flow on the 2LU120 belt conveyor of the eastern conveyor line of the Dolzhanskaya-Kapitalnaya Mine (Ukraine). The paper discusses the issue of the relationship between strong uneven material flow, which is random in nature, and the amount of unproductive energy spent on moving the moving parts of the conveyor. The presented realization for the input material flow is fairly well approximated by the periodic function. As an effective technical solution that ensures adaptation of the conveyor belt speed to a random flow of material, the use of belt speed control systems is proposed. Despite the fact that the study presents realizations for the input material flow, the proposed methodology for determining the power reserve of a belt conveyor does not take into account such statistical characteristics of the input material flow as the standard deviation and the correlation function. The reason lies in the objective difficulties associated with determining the statistical characteristics of the realization obtained as a result of experimental measurements of the values of the input material flow. The type of distribution law and correlation function for minute values of the input material flow can significantly change the upper and lower limits of belt speed control. To overcome the problems associated with determining the limits of belt speed control, a technique is required for calculating the statistical characteristics of the input material flow based on an experimentally determined implementation of the input material flow. In [14], the realization of the material flow incoming the input of a conveyor section (NCC Industry, Uddevalle, Sweden) is analyzed. To measure the amount of material flow, mass measuring devices connected to a cloud solution for processing information about the input material flow were used. The collected data was recorded to cloud storage at a frequency of 0.1–0.2 Hz. The realization of a random process allows to conclude that the material flow is a continuous flow with periodic, rarely repeating sharp decreases in material flow values. In [15] presents a realization for an input stream of material with interruptions. The realization for the material flow entering the transport conveyor has significant time intervals during which there was no material flow. In [16], an implementation for a material flow formed by a Takrafs wheel excavator bucket SRs 2000.32/5s is considered. It is emphasized that the flow of material incoming the input of the conveyor section is a continuous flow, the average value of which can be specified by a periodic function. The presented analysis of realizations for input material flows allows to assert that at most mining enterprises the input flow of material arriving at the entrance of the transport system is a continuous flow. The analysis of the realization for the material flow [11], carried out in [17], does not confirm the assumption that the minute values for the input material flow have a normal distribution law with an exponential correlation function $\exp(-t/t_{cor})$.

All this allows to assert that it is advisable to conduct a study devoted to the typification of input material flows. There is a need to develop methods that allow, from a small number of realizations for a flow of input material, to determine the type of correlation function and the law of distribution of minute values. This allow to make it possible to characterize the input flow of material with a sufficient degree of accuracy and, accordingly, reduce the error in modeling the process of moving material in the transport system.

3. The aim and objectives of the study

The aim of the study is to develop a methodology for calculating the stochastic characteristics of the input material flow, based on the typification of the input material flow. This allows improve the accuracy of analytical models used to synthesize algorithms for optimal control of flow parameters of the transport system in order to reduce unit transport costs.

To achieve the goal, the following tasks have been set:

– develop an analytical model of the input material flow $\lambda(t)$, based on the analysis of the density distribution $f_{\lambda s}(\lambda)$ of material flow values and significant statistical characteristics, such as the mathematical expectation $m_{\lambda s}$, standard deviation $\sigma_{\lambda s}$ and correlation function $k_{\lambda s}(\eta)$;

– develop a typification method of the input material flow $\lambda(t)$, based on the analysis of its correlation function $k_{\lambda s}(\eta)$ for the implementation of a random process.

4. Materials and methods of research

The object of this study is the flow of material incoming the transport conveyor. The flow of material is understood as a stochastic sequence of values of the mass of material arriving at the input of the conveyor in a given unit of time. This unique set of material flow values, as a result of carrying out only one measurement experiment over a sufficiently extended period of time, forms a single realization of material flow.

It is assumed that the results obtained, based on the analysis of the statistical characteristics of the flow of material incoming the transport conveyor, allow make it possible to clarify the values of the flow parameters of the transport system. This, in turn, makes it possible to increase the accuracy of the mathematical model of the conveyor and, as a consequence, the accuracy of the algorithm for controlling the flow parameters of the transport system. Improved material flow control ultimately leads to lower unit transportation costs for the conveyor belt.

The foundation of the conducted research is the general provisions of the statistical theory of flow production control systems [18]. To describe the flow parameters of a section of a transport conveyor, methods of the theory of random processes were used. The use of similarity theory methods for technological processes [19] makes it possible to present a model of the input material flow in a universal form, expanding the scope of application of the research results.

5. Results of the study of the input material flow of the transport conveyor

5. 1. Analytical model of input material flow

The input material flow $\lambda(t)$ is represented as a superposition of a deterministic process $\lambda_d(t)$ and a stationary centered ergodic process $\lambda_d(t)$

$$\lambda(t)=\lambda_d(t)+\lambda_s(t). \tag{1}$$

With a limited set of sample data specified by a single realization of a random process on the experimental measurement interval $t\in[0,T]$, time averaging for a stationary process $\lambda_s(t)$ can be replaced by averaging over the aggregate:

$$m_{\lambda s}=\frac{1}{T}\int_0^T\lambda_s(t)\mathrm{d}t=\int_{-\infty}^{\infty}\lambda f_{\lambda s}(t)\mathrm{d}\lambda=0,$$

$$\sigma_{\lambda s}{}^2=\frac{1}{T}\int_0^T\lambda_s(t)^2\,\mathrm{d}t=\int_{-\infty}^{\infty}\lambda^2 f_{\lambda s}(\lambda)\mathrm{d}\lambda, \tag{2}$$

where $m_{\lambda s}$ is the mathematical expectation; $\sigma_{\lambda s}$ is standard deviation; $f_{\lambda s}(\lambda)$ is distribution density of a random variable of the input material flow:

$$1=\int_{-\infty}^{\infty}f_{\lambda s}(\lambda)\mathrm{d}\lambda. \tag{3}$$

The correlation function of a stationary ergodic process $\lambda_s(t)$ is given by the expression:

$$k_{\lambda s}(\eta)=k_{\lambda s}(-\eta). \tag{4}$$

A sufficient condition for the fulfillment of equalities (2), (4) is the limit equality:

$$\lim_{\eta\to\infty}k_{\lambda s}(\eta)\to 0. \tag{5}$$

To describe the flow of material incoming at the input of the transport conveyor, dimensionless parameters have been introduced:

$$\gamma(\tau)=\frac{\lambda(t)}{m_d},\quad \gamma_d(\tau)=\frac{\lambda_d(t)}{m_d},$$

$$\gamma_s(\tau)=\frac{\lambda_s(t)}{m_d},\quad t\in[t_{\min},t_{\max}],\quad \tau\in[-1,1], \tag{6}$$

$$\tau=2\frac{t-t_{\min}}{t_{\max}-t_{\min}}-1,$$

$$\eta=t_i-t_j=\frac{t_{\max}-t_{\min}}{2}(\tau_i-\tau_j)=\frac{t_{\max}-t_{\min}}{2}\vartheta,$$

$$\vartheta=\frac{2\eta}{t_{\max}-t_{\min}}, \tag{7}$$

$$m_s=\frac{m_{\lambda s}}{m_d}=0,\quad \sigma_s=\frac{\sigma_{\lambda s}}{m_d},\quad k_s(\eta)=\frac{k_{\lambda s}(\vartheta)}{m_d{}^2}, \tag{8}$$

$$\gamma_s=\frac{\lambda_s}{m_d},\quad 1=\int_{-\infty}^{\infty}f_s(\gamma_s)\mathrm{d}\gamma_s, \tag{9}$$

where the value m_d is calculated as the average value of the material flow for its realization $\lambda_s(t)$ at the interval $t\in[t_{\min}, t_{\max}]$:

$$m_d=\frac{1}{t_{\max}-t_{\min}}\int_{t_{\min}}^{t_{\max}}\lambda(t)\mathrm{d}t=\frac{1}{N+1}\sum_0^N\lambda(t_n), \tag{10}$$

$$t_n=t_{\min}+n\Delta t,\quad \Delta t=\frac{(t_{\max}-t_{\min})}{N},\quad n=0,N. \tag{11}$$

Taking into account the entered parameters, the material flow and its statistical characteristics are presented in dimensionless form:

$$\gamma(\tau)=\gamma_d(\tau)+\gamma_s(\tau), \tag{12}$$

$$1=\frac{1}{2}\int_{-1}^{1}\gamma(\tau)\mathrm{d}\tau=\frac{1}{N+1}\sum_0^N\gamma(\tau_n),\quad \tau_n=\frac{n}{N},\quad n=0,N, \tag{13}$$

$$0=\int_{-\infty}^{\infty}\gamma f_s(\gamma)\mathrm{d}\gamma=\frac{1}{2}\int_{-1}^{1}\gamma_s(\tau)\mathrm{d}\tau=\frac{1}{N+1}\sum_0^N\gamma_s(\tau_n), \tag{14}$$

$$\sigma_s{}^2=\int_{-\infty}^{\infty}\gamma^2 f_s(\gamma)\mathrm{d}\gamma=\frac{1}{2}\int_{-1}^{1}\gamma_s^2(\tau)\mathrm{d}\tau=\frac{1}{N+1}\sum_0^N\gamma_s^2(\tau_n). \tag{15}$$

For the correlation function $k_s(\vartheta)$ of the ergodic random process $\lambda_s(t)$ the following expression is used:

$$k_s(\vartheta_m)=\frac{1}{2}\int_{-1}^{1}\gamma_s(\tau)\gamma_s(\tau+\vartheta_m)\mathrm{d}\tau=$$
$$=\int_0^1\gamma_s(\tau)\gamma_s(\tau-\vartheta_m)\mathrm{d}\tau=$$
$$=\frac{2}{N+1}\sum_{n=N/2}^{N}\gamma_s(\tau_n)\gamma_s(\tau_n-\vartheta_m)=$$
$$=\frac{2}{N+1}\sum_{n=0}^{N/2}\gamma_s(\tau_n)\gamma_s(\tau_n+\vartheta_m), \tag{16}$$

$$\vartheta_m=2\frac{m}{N},\quad m=0,\frac{N}{2}.$$

The correlation function $k_s(\vartheta)$ of the ergodic random process $\lambda_s(t)$ is an even function of the argument ϑ:

$$k_s(\vartheta)=k_s(-\vartheta). \quad (17)$$

A sufficient condition for the fulfillment of equality (16), which determines the ergodicity of the random process $\lambda_s(t)$ with respect to the correlation function, is the limit relation:

$$\lim_{\vartheta\to\infty} k_s(\vartheta)\to 0. \quad (18)$$

The distribution density $f_{\lambda s}(\lambda)$ is an approximation of the distribution series of material flow values $\gamma_{sn}=\gamma_s(\tau)$ for the interval $t\in[-1,1]$.

5. 2. The typification method of the input material flow

If the deterministic flow of material on the interval $t\in[-1,1]$ is represented as a Fourier series expansion

$$\gamma_d(\tau)=\frac{a_{d0}}{2}+\sum_{n=1}^{\infty}a_{dn}\cos(\pi n\tau)+\sum_{n=1}^{\infty}b_{dn}\sin(\pi n\tau), \quad (19)$$

$$a_{d0}=\int_{-1}^{1}\gamma_d(\tau)\mathrm{d}\tau,\ \ a_{dn}=\int_{-1}^{1}\gamma_d(\tau)\cos(\pi n\tau)\mathrm{d}\tau,$$

$$b_{dn}=\int_{-1}^{1}\gamma_d(\tau)\sin(\pi n\tau)\mathrm{d}\tau, \quad (20)$$

then the stochastic process $\gamma_s(\tau)$ for the interval $t\in[-1,1]$ can be written as a Fourier series expansion as follows:

$$\gamma_s(\tau)=\gamma(\tau)-\gamma_d(\tau)=$$
$$=\gamma(\tau)-\frac{a_{d0}}{2}-\sum_{n=1}^{\infty}a_{dn}\cos(\pi n\tau)-\sum_{n=1}^{\infty}b_{dn}\sin(\pi n\tau), \quad (21)$$

with unknown coefficients a_{d0}, a_{dn}, b_{dn}. The coefficient a_{d0} is determined from equation (13). The stochastic process $\gamma_s(\tau)$ is centered, which implies a_{d0}=2. If the correlation function $k_s(\vartheta)$ for the stochastic process $\gamma_s(\tau)$ on the interval $t\in[-1,1]$ is known, then the coefficients a_{dn}, b_{dn} can be calculated from the equation (17):

$$k_s(\vartheta)=\frac{1}{2}\int_{-1}^{1}\gamma_s(\tau)\gamma_s(\tau+\vartheta)\mathrm{d}\tau=$$
$$=\frac{1}{2}\int_{-1}^{1}(\gamma(\tau)-\gamma_d(\tau))(\gamma(\tau+\vartheta)-\gamma_d(\tau+\vartheta))\mathrm{d}\tau=$$
$$=\frac{1}{2}\int_{-1}^{1}\gamma(\tau)\gamma(\tau+\vartheta)\mathrm{d}\tau-\frac{1}{2}\int_{-1}^{1}\gamma(\tau)\gamma_d(\tau+\vartheta)\mathrm{d}\tau-$$
$$-\frac{1}{2}\int_{-1}^{1}\gamma(\tau+\vartheta)\gamma_d(\tau)\mathrm{d}\tau+\frac{1}{2}\int_{-1}^{1}\gamma_d(\tau)\gamma_d(\tau+\vartheta)\mathrm{d}\tau \quad (22)$$

Since the material flow $\gamma_d(\tau)$ is a deterministic process, and the material flow $\gamma_s(\tau)$ is a stochastic centered process, taking into account the fact that for an ergodic process the equality:

$$\int_{-1}^{1}\gamma_s(\tau)\gamma_d(\tau+\vartheta)\mathrm{d}\tau=0, \quad (23)$$

the expression for the correlation function $k_s(\vartheta)$ (22) is transformed to the form:

$$k_s(\vartheta)=\frac{1}{2}\int_{-1}^{1}\gamma(\tau)\gamma(\tau+\vartheta)\mathrm{d}\tau-\frac{1}{2}\int_{-1}^{1}\gamma_d(\tau)\gamma_d(\tau+\vartheta)\mathrm{d}\tau. \quad (24)$$

The deterministic material flow $\gamma_d(\tau)$ is represented in the following form:

$$\gamma_d(\tau)=\frac{A_0}{2}+\sum_{n=1}^{\infty}A_n\cos(\pi n\tau+\phi_n). \quad (25)$$

The amplitudes A_n and phases φ_n of the harmonic components are calculated using the formulas:

$$A_0=a_{d0}=2,\ \ A_n=\sqrt{a_{dn}^2+b_{dn}^2},$$
$$\phi_n=\arg(a_{dn}-ib_{dn}),\ \ i=\sqrt{-1}. \quad (26)$$

The sets of quantities A_n and ϑ are, respectively, the amplitude and phase frequency spectra of the material flow (amplitude spectrum and phase spectrum). Frequency spectra are functions that depend on the harmonic number n as an independent variable. Taking into account the identical equality:

$$\cos(\pi n(\tau+\vartheta)+\phi_n)=$$
$$=\cos(\pi n\tau+\phi_n)\cos(\pi n\vartheta)-\sin(\pi n\tau+\phi_n)\sin(\pi n\vartheta), \quad (27)$$

the material flow correlation function can be represented as follows:

$$k_s(\vartheta)=\frac{1}{2}\int_{-1}^{1}\gamma(\tau)\gamma(\tau+\vartheta)\mathrm{d}\tau-1-\sum_{n=1}^{\infty}\frac{A_n^2}{2}\cos(\pi n\vartheta). \quad (28)$$

Substituting ϑ=0 into the correlation function $k_s(\vartheta)$, the dispersion value for the stochastic process are obtained $\gamma_s(\tau)$:

$$k_s(0)=\sigma_s^2=\frac{1}{2}\int_{-1}^{1}\gamma^2(\tau)\mathrm{d}\tau-1-\sum_{n=1}^{\infty}\frac{A_n^2}{2}. \quad (29)$$

The stochastic component of the input material flow $\gamma_s(\tau)$ (21) is presented in the form of a Fourier series expansion with unknown amplitudes A_n and phases $\gamma_s(\tau)$ of the harmonic components. The amplitude values can be determined if the correlation function $k_s(\vartheta)$ for the random process $\gamma_s(\tau)$ is known, which is approximated with a sufficient degree of accuracy by the theoretical correlation function $k_s(\vartheta)$:

$$k_a(\vartheta)=\sigma_s^2\varphi_s(\vartheta), \quad (30)$$

where $\phi_s(\tau)$ is the normalized correlation function; $\sigma_s(\tau)$ is standard deviation of the studied random process $\gamma_s(\tau)$. The normalized correlation function $\phi_s(\tau)$ is an even function that can be represented on the interval $\vartheta\in[-1,1]$, let's expand it into even harmonics:

$$\varphi_s(\vartheta)=\frac{D_0}{2}+\sum_{n=1}^{\infty}D_n\cos(\pi n\vartheta), \quad (31)$$

$$D_0=2\int_{0}^{1}\varphi_s(\vartheta)\mathrm{d}\vartheta,\ \ D_n=2\int_{0}^{1}\varphi_s(\vartheta)\cos(\pi n\vartheta)\mathrm{d}\vartheta. \quad (32)$$

To determine the amplitudes A_n standard models of normalized correlation functions $\phi_s(\tau)$, were used, satisfying condition (18):

$$\varphi_s(\vartheta)=\exp(-\vartheta/\vartheta_{cor}), \tag{33}$$

$$D_0=2\vartheta_{cor}\left(1-e^{\frac{-1}{\vartheta_{cor}}}\right),$$

$$D_n=2\frac{\vartheta_{cor}}{\pi^2n^2\vartheta_{cor}^{\ 2}+1}\left(1-(-1)^n e^{\frac{-1}{\vartheta_{cor}}}\right),$$

$$\varphi_s(\vartheta)=\exp(-\vartheta/\vartheta_{cor})(1+\vartheta/\vartheta_{cor}), \tag{34}$$

$$D_0=4\vartheta_{cor}\left(1-e^{\frac{-1}{\vartheta_{cor}}}\right)-2e^{\frac{-1}{\vartheta_{cor}}},$$

$$D_n=4\vartheta_{cor}\frac{1-(-1)^n e^{\frac{-1}{\vartheta_{cor}}}}{\left(\pi^2n^2\vartheta_{cor}^{\ 2}+1\right)^2}-\frac{2(-1)^n e^{\frac{-1}{\vartheta_{cor}}}}{\pi^2n^2\vartheta_{cor}^{\ 2}+1},$$

$$\varphi_s(\vartheta)=\exp(-\vartheta/\vartheta_{cor})(1-\vartheta/\vartheta_{cor}), \tag{35}$$

$$D_0=2e^{\frac{-1}{\vartheta_{cor}}},$$

$$D_n=\frac{2(-1)^n e^{\frac{-1}{\vartheta_{cor}}}}{\left(\pi^2n^2\vartheta_{cor}^{\ 2}+1\right)^2}-\frac{2\pi^2n^2\vartheta_{cor}^{\ 2}\left(2\vartheta_{cor}(-1)^n e^{\frac{-1}{\vartheta_{cor}}}-2\vartheta_{cor}-(-1)^n e^{\frac{-1}{\vartheta_{cor}}}\right)}{\left(\pi^2n^2\vartheta_{cor}^{\ 2}+1\right)^2},$$

$$\varphi_s\ \ \vartheta\ =\exp\ -|\vartheta|/\vartheta_{cor}\ \ \cos\ \ \beta\vartheta\ . \tag{36}$$

For small values of the parameter ϑ_{cor} the limiting relation $\exp(-1/\vartheta_{cor})\to 0$, is valid, the use of which allows to present typical models of normalized correlation functions $\phi_s(\vartheta)$ in the following form:

$$\varphi_s(\vartheta)=e^{-\frac{\vartheta}{\vartheta_{cor}}}\approx\vartheta_{cor}+\sum_{n=1}^{\infty}\frac{2\vartheta_{cor}}{\pi^2n^2\vartheta_{cor}^2+1}\cos(\pi n\vartheta)=$$
$$=\frac{1}{\alpha}+\sum_{n=1}^{\infty}\frac{2\alpha}{\pi^2n^2+\alpha^2}\cos(\pi n\vartheta), \tag{37}$$

$$\varphi_s(\vartheta)=e^{-\frac{\vartheta}{\vartheta_{cor}}}\left(1+\frac{\vartheta}{\vartheta_{cor}}\right)\approx$$
$$\approx 2\vartheta_{cor}+\sum_{n=1}^{\infty}\frac{4\vartheta_{cor}}{\left(\pi^2n^2\vartheta_{cor}^2+1\right)^2}\cos(\pi n\vartheta)=$$
$$=\frac{2}{\alpha}+\sum_{n=1}^{\infty}\frac{4\alpha^3}{\left(\pi^2n^2+\alpha^2\right)^2}\cos(\pi n\vartheta), \tag{38}$$

$$\varphi_s(\vartheta)=e^{-\frac{\vartheta}{\vartheta_{cor}}}\left(1-\frac{\vartheta}{\vartheta_{cor}}\right)\approx$$
$$\approx\sum_{n=1}^{\infty}\frac{4\pi^2n^2\vartheta_{cor}^3}{\left(\pi^2n^2\vartheta_{cor}^2+1\right)^2}\cos(\pi n\vartheta)=$$
$$=\sum_{n=1}^{\infty}\frac{4\alpha}{\left(\pi^2n^2+\alpha^2\right)^2}\cos(\pi n\vartheta), \tag{39}$$

$$\varphi_s(\vartheta)=e^{-\frac{\vartheta}{\vartheta_{cor}}}\cos(\beta\vartheta)\approx$$
$$\approx\sum_{n=1}^{\infty}2\frac{\alpha^2+\beta^2+\pi^2n^2}{\left(\alpha^2+(\beta-\pi n)^2\right)\left(\alpha^2+(\beta+\pi n)^2\right)}\cos(\pi n\vartheta), \tag{40}$$

where $\alpha=1/\vartheta_{cor}$ is the attenuation parameter. Let's represent the correlation function $k_s(\vartheta)$ (28) of the material flow $\gamma_s(\tau)$ in the form of a Fourier series expansion:

$$k_s(\vartheta)=\frac{B_0}{2}+\sum_{n=1}^{\infty}B_n\cos(\pi n\vartheta)=$$
$$=\frac{C_0}{2}+\sum_{n=1}^{\infty}C_n\cos(\pi n\vartheta)-1-$$
$$-\sum_{n=1}^{\infty}\frac{A_n^{\ 2}}{2}\cos(\pi n\vartheta)=\sum_{n=1}^{\infty}\left(C_n-\frac{A_n^{\ 2}}{2}\right)\cos(\pi n\vartheta), \tag{41}$$

with expansion coefficients:

$$C_0=2\int_0^1 z_s(\vartheta)\mathrm{d}\vartheta=2,\quad C_n=2\int_0^1 z_s(\vartheta)\cos(\pi n\vartheta)\mathrm{d}\vartheta,$$

$$z_s(\vartheta)=\int_{-1}^{1}\gamma(\tau)\gamma(\tau+\vartheta)\mathrm{d}\tau. \tag{42}$$

Indeed, if to represent the material flow $\gamma(\tau)$ in the form of a Fourier series expansion, similarly as for the material flow $\gamma_d(\tau)$:

$$\gamma(\tau)=\frac{G_0}{2}+\sum_{n=1}^{\infty}G_n\cos(\pi n\tau+\phi_n),$$

$$G_0=\int_{-1}^{1}\gamma(\tau)\mathrm{d}\tau=A_0=2, \tag{43}$$

then the expansion of the function $z_s(\vartheta)$ can be approximated as a series:

$$z_s\ \ \vartheta\ =\int_{-1}^{1}\gamma(\tau)\gamma(\tau+\vartheta)\mathrm{d}\tau=$$
$$=\frac{G_0^{\ 2}}{4}+\sum_{n=1}^{\infty}\frac{G_n^{\ 2}}{2}\cos\ \ \pi n\vartheta\ . \tag{44}$$

The correlation function $k_s(\vartheta)$ (37), constructed on the basis of experimental data, is equated to the theoretical correlation function $k_s(\vartheta)$ (30). The resulting equation is used to calculate the unknown coefficients A_n for given values of the standard deviation σ_s and the correlation time ϑ_{cor} of the realization of the stochastic material flow $\gamma_s(\tau)$:

$$A_0=2,$$

$$A_n^2=2\left(C_n-\sigma_s^2D_n\right),$$

$$C_n>\sigma_s^2D_n,$$

and

$$A_n^2=0,\quad C_n\le\sigma_s^{\ 2}D_n,\quad n=1,2,3,\ldots \tag{45}$$

To assess the accuracy of approximation, the criterion was used

$$\int_0^1 \left(k_s(\vartheta)-k_a(\vartheta)\right)^2 \mathrm{d}\vartheta =$$

$$=\int_0^1 \left(\begin{array}{l} \sum_{n=1}^{\infty} B_n \cos(\pi n\vartheta) - \sigma_s^2 \frac{D_0}{2} - \\ -\sigma_s^2 \sum_{n=1}^{\infty} D_n \cos(\pi n\vartheta) \end{array} \right)^2 \mathrm{d}\vartheta =$$

$$=\frac{\sigma_s^4 D_0^4}{4}+\frac{1}{2}\sum_{n=1}^{\infty}\left(B_n-\sigma_s^2 D_n\right)^2 =$$

$$=\frac{\sigma_s^4 D_0^4}{4}+\frac{1}{2}\sum_{n=1}^{\infty}\left(C_n-\frac{A_n^2}{2}-\sigma_s^2 D_n\right)^2 \to \min. \quad (46)$$

This criterion determines the values of the coefficients A_n for each type of theoretical correlation function represented by the values of the coefficients D_n. From the existing options for approximating the correlation function of the input material flow with theoretical correlation functions, a variant of the theoretical function is selected for which the power of the deterministic process is minimal:

$$P_d=\frac{A_0^2}{4}+\frac{1}{2}\sum_{n=1}^{\infty}A_n^2=1+\frac{1}{2}\sum_{n=1}^{\infty}A_n^2 \to \min. \quad (47)$$

Thus, typification of the input material flow comes down to analyzing the power of the deterministic component of the material flow in accordance with the approximation criterion (46). The type of input flow is determined by the type of function of the theoretical correlation function, which, when approximating the input flow of material, gives the least power of the deterministic component. The ideal option is an input material flow for which the power of the deterministic component is equal to P_d=1. In this case, the input material flow is a stationary flow, which can be represented by an ergodic process.

Typical models of normalized correlation functions $\phi_s(\vartheta)$ for the value ϑ_{cor}=0.3 (33)–(36) and their approximation by a Fourier series are presented in Fig. 1. Graphical analysis of the obtained results shows that to approximate the normalized correlation functions $\phi_s(\vartheta)$ a Fourier series containing up to 10 terms can be used. For small values of the correlation time ϑ_{cor} approximate formulas (37)–(40) can be used when calculating the Fourier series expansion coefficients (37)–(40). This approach simplifies computational procedures and makes it possible to present research results in a visual representation. A comparative analysis of the error in calculating the values of the correlation function $\phi_s(\vartheta)$ (Fig. 1, *a*) when replacing the exact values of the expansion coefficients (33) with approximate values (37) for the correlation time ϑ_{cor}=0.3 is shown in Fig. 2, *a*. As the correlation time ϑ_{cor} decreases, the accuracy of calculating the correlation function values increases. When using an approximate expression for calculating expansion coefficients (38), the accuracy of calculating the value of the correlation function decreases with increasing value of the correlation time ϑ between cross sections of the random process realization. In Fig. 2 shows the error in calculating the values of the correlation function depending on the number of terms of the Fourier series used to approximate the function $\phi_s(\vartheta)$ (Fig. 1, *a*). For cases where analytical dependencies that allow calculating the values of expansion coefficients have not been determined, numerical integration methods are used.

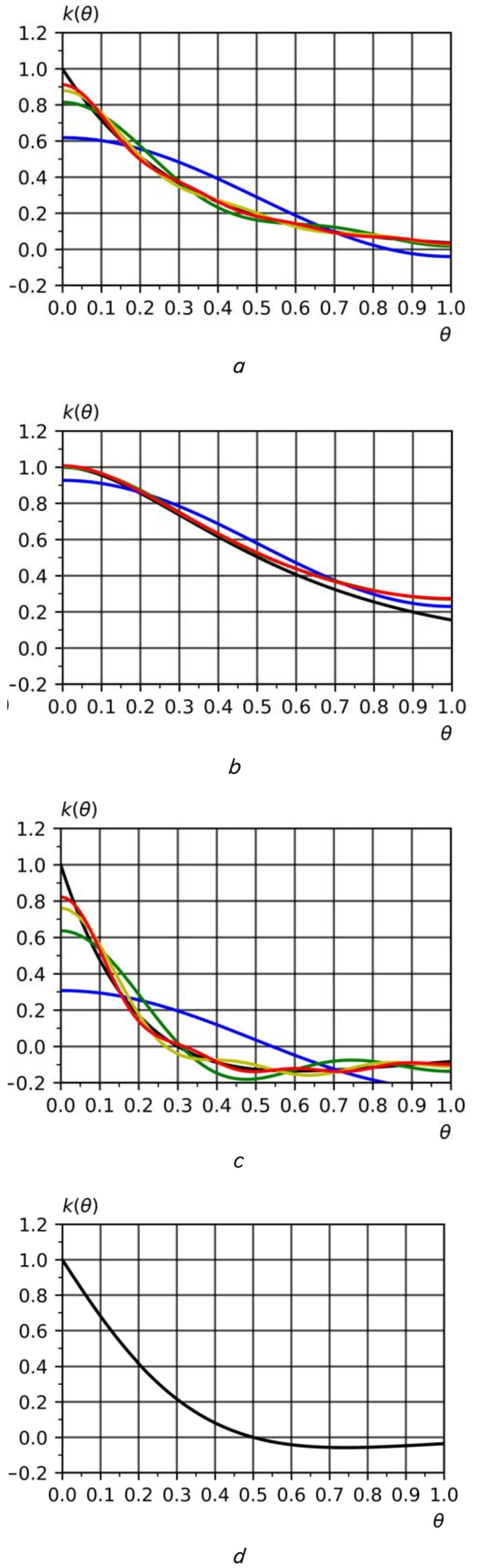

Fig. 1. Typical models of normalized correlation functions $\phi_s(\vartheta)$ and their approximation by a Fourier series (blue: 2 member of the series; green: 4 member of the series; yellow: 8 member of the series; red: 16 member of the series; black: theoretical function): *a* – $\phi_s(\vartheta)=\exp(-\vartheta/\vartheta_{cor})$; *b* – $\phi_s(\vartheta)=\exp(-\vartheta/\vartheta_{cor})(1+\vartheta/\vartheta_{cor})$; *c* – $\phi_s(\vartheta)=\exp(-\vartheta/\vartheta_{cor})(1-\vartheta/\vartheta_{cor})$; *d* – $\phi_s(\vartheta)=\exp(-\vartheta/\vartheta_{cor})\cos(\beta)$

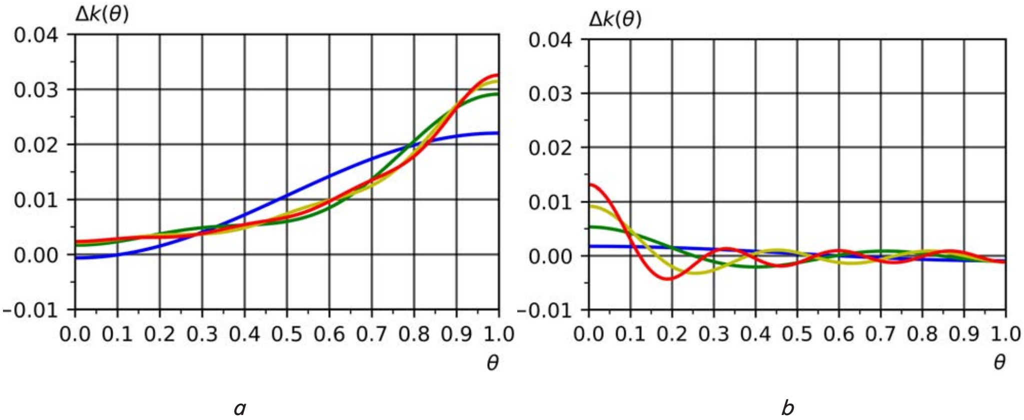

Fig. 2. Calculating error of the values of the normalized correlation function $\phi_s(\vartheta)=\exp(-\vartheta/\vartheta_{cor})$ when using to calculate expansion coefficients: *a* — approximate value (38); *b* — numerical integration methods

Using the theoretical studies presented above, the type of input material flow was determined based on experimental measurements [11], presented in the form of a separate implementation of the input material flow (Fig. 3). The characteristics of the input material flow are calculated using dimensionless parameters (6)–(9). Analysis of the characteristics of the input material flow (Fig. 3, *c*, *d*) suggests that the correlation time ϑ_{cor} is small. In this regard, when calculating the coefficients of expansion of the correlation function into a Fourier series, approximate expressions (37)–(40) are used. To construct the correlation function $k_s(\vartheta)$, the reliazation of the input material flow $\gamma_s(\tau)$, is used, based on the values of the known coefficients A_n (46). For the zero approximation of the deterministic material flow $\gamma_d(\tau)=1$ (25) the correlation function $k_s(\vartheta)$ of the input material flow $\gamma(\tau)$ is shown in Fig. 4, *d*. The presented correlation function is used as an initial approximation to determine what type of input material flow is.

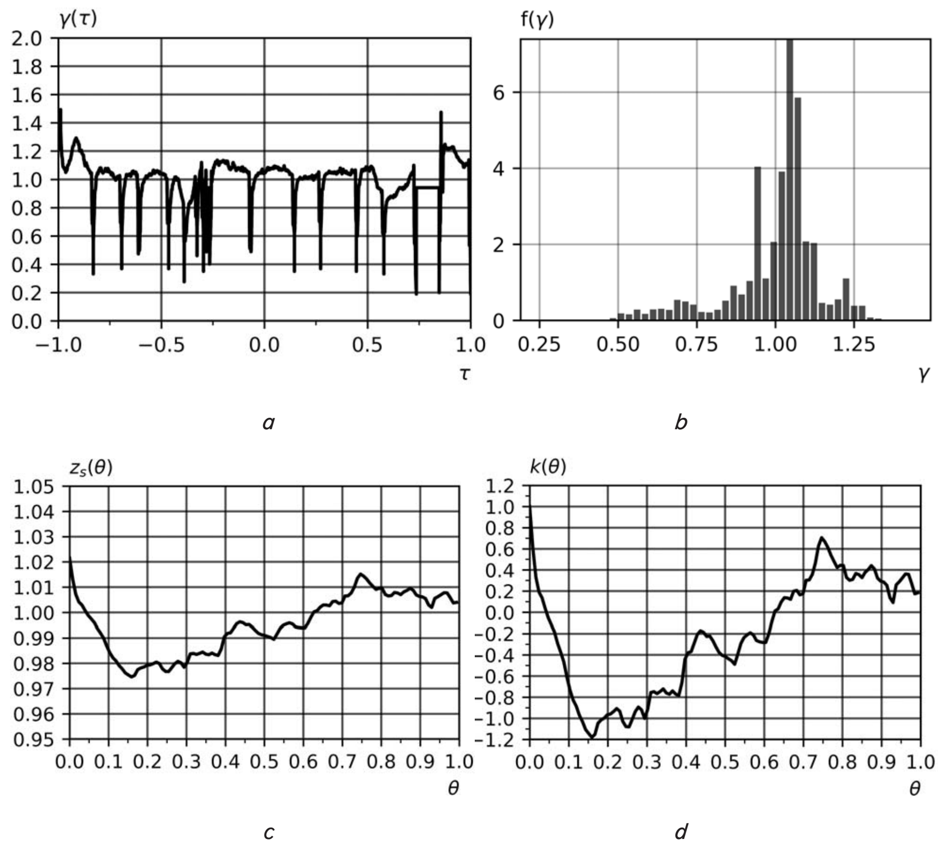

Fig. 3. Dimensionless characteristic of the input material flow $\gamma(\tau)$ [11]: *a* — realization of input material flow $\gamma(\tau)$; *b* — histogram of input material flow values $\gamma(\tau)$; *c* — function $z_s(\vartheta)$ for the realization $\gamma(\tau)$ input material flow; *d* — correlation function $k_s(\vartheta)$ for zero approximation $\gamma_d(\tau)=A_0/2$

The accuracy of approximation of the correlation function of the input material flow by theoretical correlation functions (33)–(36) is determined in accordance with the approximation quality criterion (46). The lowest power of the deterministic component of the input flow in accordance with criterion (47) corresponds to the type of theoretical correlation function (35) presented in Fig. 1, *c*. The realization $\gamma_s(\tau)$ or the input material flow and the histogram of the values of $\gamma_s(\tau)$ under the assumption of the type of input material flow in the form (35) are presented in Fig. 4.

To approximate the input material flow, 20 terms of the Fourier series expansion are used. The amplitude spectrum for the deterministic component of the material flow is shown in Fig. 4, *c*. In accordance with the approximation criterion (46), this spectrum corresponds to the correlation function of the stochastic component of the input material flow, Fig. 4, *d*. The resulting correlation function is qualitattively different from the correlation function for the zero approximation (Fig. 1, *d*) and allows to consider the stochastic component of the input material flow as a centered ergodic process. This is the rationale for using formulas (13)–(16) to calculate the statistical characteristics of the input material flow. The histogram of the values of the random process $\gamma_s(\tau)$ is transformed to a form that qualitatively corresponds to the normal distribution law, Fig. 4, *b*. The modulus of the correlation function of the stochastic component of the input material flow is a decreasing function of the correlation time, which tends to zero at large values of the correlation time. This confirms that the process $\gamma_s(\tau)$ in accordance with the sufficient condition (5) is an ergodic process, and the type of process $\gamma_s(\tau)$ in accordance with the given criteria for the quality of approximation (46) and the minimum power of the deterministic component (47) is uniquely determined.

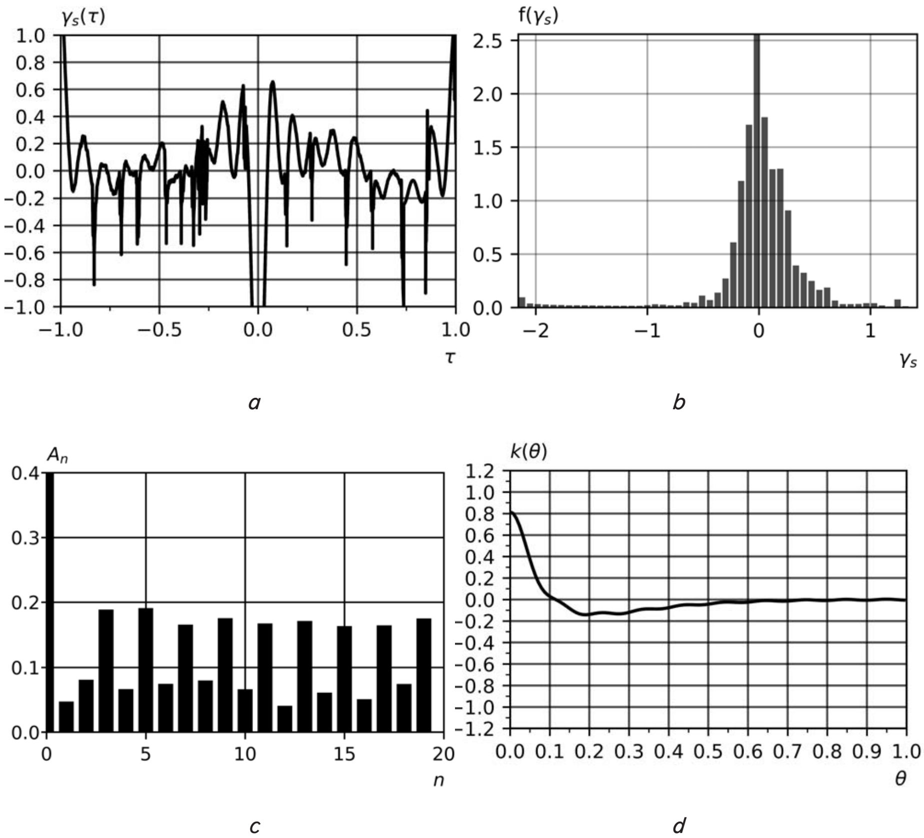

Fig. 4. Dimensionless characteristic of the input material flow $\gamma_s(\tau)$ [11] with a deterministic flow $\gamma_d(\tau)$ (approximation of 20 terms of the Fourier series): *a* — realization of input material flow $\gamma_d(\tau)$; *b* — histogram of input material flow values $\gamma_d(\tau)$; *c* — Fourier coefficients A_n; *г* — correlation function $k_s(\vartheta)$

6. Discussion of the results of modeling the input material flow

Belt conveyor systems are a type of production systems with a flow method of organizing production. A distinctive feature of conveyor systems is that elements move along the transportation route at the same speed, equal to the speed of the conveyor belt. Models of belt conveyors [5–10] refer to models of macro-description of the transport system. Macroparameters of the transport system, such as flow and density of the material are averaged values. Input material flow models based on individual realizations of the material flow incoming the input of a conveyor section is referred to as microdescription models. Averaging the values of the input material flow over an ensemble of realizations makes it possible to determine statistical characteristics and make the transition from a micro-description model of the input material flow to a macro-description model, providing the possibility of joint use of two classes of models.

In this study, a model of the input material flow of a transport conveyor (1)–(9) is proposed, taking into account the peculiarities of the functioning of the studied conveyor-type transport systems. In contrast well-known models of the input material flow of a transport conveyor [17], the model takes into account the following fundamental features of the material flow of existing conveyor-type transport systems:

– firstly, the input flow of material is presented as a combination of deterministic and stochastic components, which makes it possible to use analytical PDE models [5] of the transport conveyor to synthesize optimal controls for the flow parameters of the transport system;

– secondly, the distribution law and the correlation function of the minute values of the input material flow are determined from the experimental reaization for the input material flow, and are not based on the accepted theoretical assumption about the distribution law and the form of the correlation function, which makes it possible to increase the accuracy of calculating the statistical characteristics of the input material flow;

– thirdly, the justification and subsequent use of the ergodicity condition for a random process of material flow, such as the mathematical expectation, standard deviation and correlation function, since averaging over multiple realizations is replaced by time averaging for one realization.

This approach allows to take into account:

a) initial distribution of material along the transportation route, which, unlike existing models, makes it possible to obtain the value of flow parameters and, accordingly, to form optimal control during the initial movement of the belt;

b) variable transport delay for the synthesis of optimal controls under transient unsteady conditions, which is impossible when using the assumption of stationarity of the input material flow;

c) the influence of uneven distribution of material along the transportation route on the flow characteristics of the transport system.

The ergodicity conditions (18) of the random process $\gamma_s(\tau)$ imply that the random process is a stationary process with a mathematical expectation equal to zero (14) and variance (15), which characterizes the power of the fluctuation component of the implementation of the random process.

The typification method of the input material flow proposed in this work is based on the fact that for the analysis of a random process, observation is available only, as a rule, of one realization of the material flow, and not the entire ensemble. In this case, if it is justified that the process under study $\gamma_s(\tau)$ is ergodic, then the realization of a random process $\gamma_s(\tau)$ of sufficient length is a typical representative of the statistical ensemble. Using a single realization for the input material flow, the statistical characteristics (14)–(16) of the random process can be calculated. The use of periodic functions in the analysis of the statistical characteristics of the random process $\gamma_s(\tau)$ made it possible to simplify the calculations of numerical characteristics by replacing averaging over an infinite (in the limit) time interval with averaging over the period $T=(t_{\max}-t_{\min})$. Thus, the typification problem of the input material flow comes down to determining the type of theoretical correlation function $\gamma_s(\tau)$, most suitable for approximating the correlation function $k_s(\vartheta)$ in accordance with the criteria for the quality of approximation and the minimum power of the deterministic component of the input material flow.

A limitation of this study is the requirement that the length of the interval during which the input material flow is measured must be significantly greater than the characteristic correlation time of the stochastic input material flow. To ensure the effective functioning of the control system for the flow parameters of the transport system, one more important condition is necessary: the use of high-precision measuring sensors. The use of ultrasonic, laser or optical sensors that can accurately determine the volume of the moved material on a conveyor plays a critical role in generating data on the speed and density of material flow. This is necessary for the correct calculation of minute values of material flow, and, accordingly, for determining its statistical characteristics, which makes it possible to increase the efficiency of control and management of the transport system. The error in calculating numerical characteristics is determined by the length of the interval over which the experimental implementation of the input material flow is presented, and directly by the error of the measuring sensors.

To demonstrate the method of typing the input material flow, experimental measurements of the input material flow, presented in the work, were selected [11]. Analysis of papers [13–16] made it possible to justify the division of the input material flow into deterministic and stochastic components of the material flow. When calculating the correlation function for the experimental implementation of the input material flow [11], the results of work [17] are used. The use of a technique based on the analysis of the power of the deterministic component of the material flow in accordance with the approximation criterion (46) made it possible to synthesize a material flow corresponding to the stochastic component, the correlation function of which can be approximated by an exponential function. In this case, the distribution of values of the stochastic component of the input material flow is quite close to the normal distribution law.

The practical importance of the results obtained lies in the fact that the distribution law, statistical characteristics and correlation function of the input material flow are determined on the basis of experiment, rather than theoretical assumptions, which makes it possible to increase the accuracy of modeling. The practical use of the proposed model is the possibility of synthesizing algorithms for optimal control of the speed of a transport conveyor belt, taking into account the statistical characteristics of the input material flow.

One of the promising methods for modeling the movement of material on a transport conveyor is based on an analytical model containing a partial differential equation. This method has successfully used for transport systems with a small number of conveyor belts. However, for transport systems containing several dozen belt conveyors, the use of this method is difficult due to the increase in the number of partial differential equations. As an alternative, a transport system model using a neural network can be considered. A limitation of using a neural network-based model is that training a neural network requires a data set containing a large number of realizations of the input material flow. In this regard, the prospect of further research is to improve the method proposed in this work for designing a generator of input material flow values with a given correlation function and the distribution law of minute material flow values. Such a generator will allow, based on the experimental implementation of the input material flow, to generate a training data set consisting of the required number of implementations of the input material flow with specified statistical characteristics. This opens up new possibilities for modeling transport systems with a large number of conveyor belts.

7. Conclusions

1. An analytical model of the flow of material entering the entrance of the transport conveyor is developed. A distinctive feature of this model is the representation of the input material flow as a combination of deterministic and stochastic components. The advantage of this approach over existing modeling methods is that to calculate the statistical characteristics of the input material flow, a stochastic component is used, which is represented as a process with ergodic properties. This made it possible to calculate the statistical characteristics of the input material flow using the correlation function and the distribution law of minute values, determined on the basis of experimental measurements. The use of experimentally obtained realizations of the input material flow instead of theoretical assumptions about the correlation function and the distribution law of minute values of the material flow helps to increase the accuracy of modeling the movement of material along the transport route.

2. The analytical model of the input material flow is used to develop a typification method for input material flows, based on the analysis of the correlation function calculated from a single implementation of a random process. The algorithm for using the typification method of the input material flow consists of the following steps:

a) select the deterministic component of the material flow;

b) for each type of theoretical correlation function, in accordance with the criterion of approximation accuracy, determine the expansion coefficients A_n;

c) select a set of expansion coefficients A_n of minimum power;

d) determine the statistical characteristics and distribution law of the values of the stochastic component of the material flow for a selected set of decomposition coefficients.

To form a criterion that determines the type of correlation function of the input material flow, standards of common theoretical correlation functions for a random process represented by the stochastic component of the material flow model are introduced. The quality criterion determines the theoretical correlation function, which is used to approximate the correlation function constructed based on the experimental implementation for the input material flow. The input parameters of the simulation are sets of material flow realizations based on experimental measurements.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, including financial, personal, authorship, or any other nature that could affect the research and its results presented in this paper.

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Availability of data

The manuscript has no associated data.

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