Synthesis of energy-efficient control methods of the electromechanical disintegrator operating modes

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Abstract: *The present trend in the development of highly efficient technological equipment for the production of nanomaterials is being analysed. It is associated with the synthesis of energy-efficient control methods for the operating modes of electromechanical disintegrator of multifactorial action. As a result of genetic modelling, the deterministic relationship between the genetic information of generative electromechanical chromosomes, structure of the resulting magnetic flux in the active zone of electromechanical disintegrator and its functional operating modes has been established. According to the results of structural synthesis, methods for technical implementation of energy-efficient modes of material processing, which ensure the increase of productivity of the electromechanical disintegrator, have been optimized and developed. The credibility of theoretical results was confirmed by experimental studies.*

Keywords: *GENETIC MODELING, STRUCTURAL SYNTHESIS, CONTROL METHODS, OPERATING MODES, ELECTROMECHANICAL DISINTEGRATOR, ACTIVE ZONE, DISCRETE FERROMAGNETIC PARTICLES, NANOMATERIALS, ENERGY-EFFICIENCY, PRODUCTIVITY.*

1. Introduction

The creation of highly efficient technological equipment for the production of powder materials and homogeneous mixtures of the nanoscale range is one of the priority areas of modern science and technology. The importance of such research is determined by the widespread use of nanopowder materials and technologies in such important fields as electronics, pharmaceuticals, chemical industry, materials science, and others. This indicates the relevance and novelty of research in this area.

It is known that the energy efficiency of ultra-fine grinding processes and the quality of finished products is determined by the type of process equipment. The vast majority of existing equipment is based on the use of the mechanical principle of action (hammer grinders, spherical mills, and disintegrators). The peculiarity of such equipment is their high energy consumption and low energy efficiency. Therefore, the problem of creating new types of energy-efficient equipment for the implementation of nanotechnology remains open. According to experts, one of the promising areas for improving energy efficiency, intensification of processes in ultra-fine grinding technologies is the creation and use of electromechanical mills [1] and electromechanical disintegrators (EMDs) of multifactor action [2].

EMDs belong to a new class of highly efficient technological equipment, in which technological processes of materials processing are carried out by converting electromagnetic energy of inverse magnetic fields into energy of mechanical motion of discrete ferromagnetic particles (DFPs), which is carried out directly in the active zone of the disintegrator. EMDs find practical application in the implementation of a wide range of technologies: fine and ultrafine grinding of materials; production of nanopowders; homogeneous mixing and preparation of composite mixtures; production of multicomponent fuel mixtures; dispersion of liquid-phase and heterogeneous systems; acceleration of chemical reactions (oxidation, regeneration, neutralization, etc.), intensification of microbiological processes, wastewater treatment, etc. [3, 4]. According to the results of multifactorial action on the processing substance in the technologies of ultrafine grinding (especially in the nanometre range), the physical properties of materials can change significantly and acquire qualitatively new, sometimes unique properties.

According to the results of the analysis of industrial operation and the results of experimental studies on the prototypes of EMDs, a number of specific phenomena and effects that accompany the operating modes of EMDs have been detected [5]. Since the trajectory of the working bodies is determined by 6 degrees of freedom, during the operation of EMDs there appears a problem of controlling the uniformity of distribution and intensity of DFPs, which is directly related to the efficiency of processing, ingredient processing, energy-efficient processing modes and quality of the output product. The lack of flexible control of processing modes does not allow to carry out technological processing of materials at the optimal level. The complex functional relationship between geometric and electromagnetic parameters, the complexity of the collective motion of the DFPs and the turbulence of the treated medium in the active volume are virtually unanalysable and significantly complicate the mathematical modelling of physical processes in EMDs. The presence of this set of significant differences requires the development of new systems approaches to the analysis of physical processes and the synthesis of EMD structures with specified operational properties.

The analysis of data of industrial operation and results of experimental researches of EMDs allow to allocate the following directions of increase of their efficiency [6, 7]:

- optimization of EMD operation modes;
- compensation of negative influence of final electromagnetic effects;
- optimization of spatial geometry and electromagnetic parameters of DFPs;
- optimization of geometric relations;
- synthesis of competitive technical solutions of EMDs;
- optimization of input parameters of supply voltage.

In the following paper, based on the generalization of the results of industrial operation, experimental data and analysis of physical processes and phenomena accompanying the operating modes of EMDs, the purpose is to synthesize structural energy-efficient ways to control the operation modes of EMDs and propose ways to implement them.

2. Features of electromagnetic processes

The specific nature of the structure and features of electromagnetic processes that ensure the operation of double winding EMDs [8, 9], cause significant differences in their operating modes from disintegrators and mills of mechanical and electromagnetic types. These differences are caused by:

- the presence of a two-way system of inductors with counter-orientation of travelling or rotating magnetic fields on active surfaces, phase shifted by an angle $\gamma = \pi/3$;
- a relatively large value of the non-magnetic (inter-inductor) gap $\Sigma\delta$, which houses the working chamber (WCH) with DFPs and process environment;
- the limiting ratio of the value of the non-magnetic gap to the length of the pole division ($\Sigma\delta/\tau \approx 0{,}6 \div 0{,}7$);

- discrete structure of ferromagnetic working bodies, the characteristic geometry of which is much smaller than the length of the pole division ($l/d << \tau$);

- complex spatial motion (6 degrees of freedom) of the DFPs, the idealized motion of which consists of the rotational motion of the elementary DFP relative to its centre of mass (n_p = 3000 rpm, provided f = 50 Hz) and the rotational motion of the particle on a circular trajectory ($n_\tau \approx$ 3000 rpm), within the corresponding pole division τ;

- multifactorial complex action of a number of physical factors on the processed technological environment (Fig. 1), which includes intensive mechanical grinding and mixing, the action of high-gradient alternating magnetic field and high-potential electrostatic charge field, the influence of surface acoustic waves, local thermal overheating as well as the influence of accompanying processes of electrolysis and cavitation (subject to the presence of liquid ingredients);

- a wide variety of genetically acceptable Species of the functional class of EMDs, the quantitative composition of which significantly exceeds the species diversity of electric machines [10].

The working process of machining is characterized by high-frequency collisions of DFPs with each other, with particles of the substance and the walls of the working chamber, which causes a sharp change in the trajectory of their movement, the emergence of alternating accelerations and accompanied by processes of dispersion, mechanical activation, intensive mixing and others (Fig. 1).

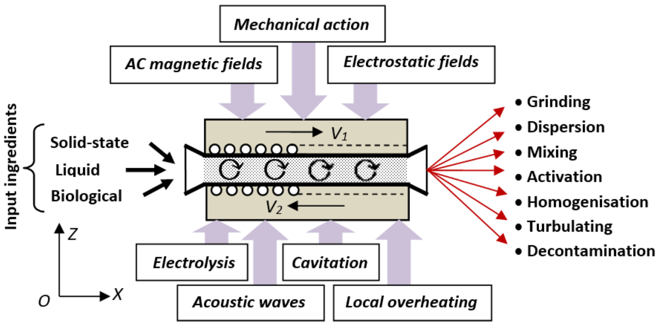

***Fig. 1** Main physical factors and processes that determine the technology of ingredient processing in the active volume of electromechanical disintegrator.*

The presence of the mentioned set of factors (Fig. 1) determines the complex effect on the processed environment, which intensifies the technological process, provides a change of physical properties of the processed substances and significantly expands the range of applied technologies.

3. The genetic model of the structure formation of the resulting magnetic field

The integral function of synthesis F_S must take into account the following set of partial requirements:

1) The presence of a dual-inductor system with equivalent geometry and mass of active parts ($2M_{A1}$);

2) Electromagnetic method of excitation of inductors active surfaces (Φ_{EM});

3) Dual-inductor version of the magnetic system with independent power supply of m-phase distributed windings ($2N_1$);

4) Electromagnetic inversion of the inductors V_1 = ($-V_2$) travelling magnetic fields;

5) The presence of nonmagnetic *WCH* with the discrete ferromagnetic working bodies (nN_2);

6) A number of pole divisions of the windings in the OX coordinate ($N_\tau \geq 2$).

The search space for R^n synthesis is limited by the electromagnetic chromosomes of 2.2y subgroup of the first major period in the periodic structure of genetic classification [11]. Chromosome-isotopes [12] and their hybrid compositions are not taken into account. Given these partial requirements and constraints, the vector of the integral search function in the multidimensional feature space R^n takes the form:

$$F_S = [2M_{A1};\ \Phi_{EM};\ 2N_1;\ V_1 = (-V_2);\ nN_2;\ N_\tau \geq 2]. \quad (1)$$

The structure of an ideal homological series [13] of subgroup 2.2y contains six base-level electromagnetic chromosomes

$$H_{02y} = (C_{CL}, C_{KN}, C_{PL}, C_{TP}, C_{SF}, C_{TC}). \quad (2)$$

The synthesis of the genetic model can be performed on the basis of the parental chromosome C_{PL} with the genetic code of the *PL 2.2y*, which determines the boundaries of the structure of the dominant Species of double-winding EMDs [6, 7]. The given search function (1) corresponds to a multilevel genetic model (Fig. 2). The synthesis of the model is carried out using genetic synthesis operators (replication, intra-Species hybridisation, spatial and electromagnetic inversion and mutation). The sequence of application of genetic operators is determined in accordance with the logic of genetic modelling "from simple to complex", by gradually complicating the parent chromosome [14].

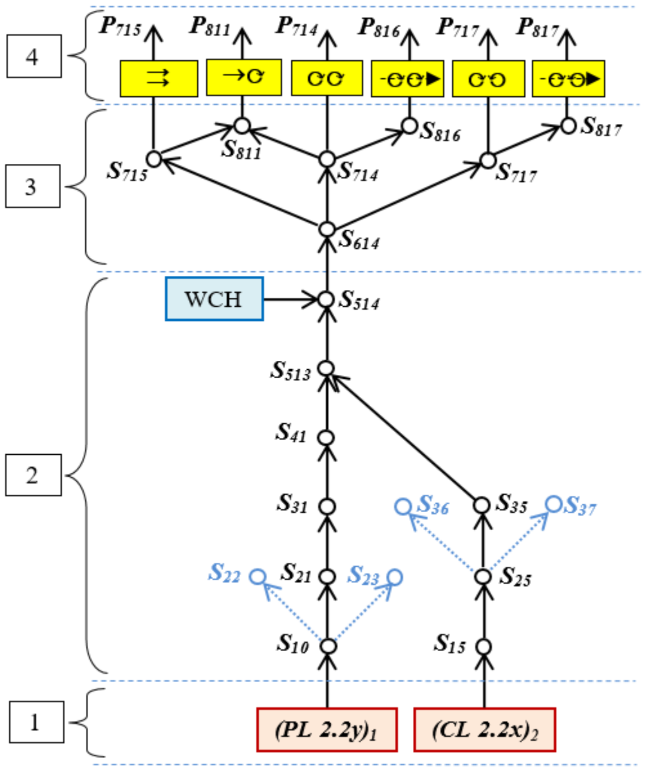

***Fig. 2** Genetic model of synthesis of the resulting magnetic field structures in the EMD active zone: $(PL\ 2.2y)_1$ – parent chromosome; $(CL\ 2.2x)_2$ – secondary chromosome; WCH – working chamber; S_{10}–S_{514} – information chromosomes; S_{614}–S_{817} – generative chromosomes; P_{714}–P_{817} – populations of technical solutions that satisfy the functions of synthesis; 1–4 – levels of genetic organization of structures.*

The synthesized model reproduces the multilevel process of complication of the parental chromosome in accordance with the logic of genetic synthesis for a given function F_S and taking into account the given constraints. The structure of the model (Fig. 2) contains four levels of genetic complexity:

1) chromosomal level, which is represented by the generative (parental) *y*-oriented chromosome $(PL\ 2.2y)_1$ and the secondary chromosome $(CL\ 2.2x)_2$;

2) the level of the genome of the Species, represented by genetically modified information chromosomes S_{10}–S_{514} of increasing level of complexity, modelling the process of structure formation of EMD active parts and its combination with nonmagnetic *WCH*, which has the status of another genetic nature;

3) the level of structural detailing (up to τ) of the generative chromosome S_{614}, which allows to determine possible variants of the structures of the resulting magnetic field in the EMD active zone;

4) population level (P_{714}–P_{817}), which models the deterministic relationship of generative chromosomes with synthesized variants of the resulting magnetic field structure in the active volume (are indicated by graphic primitives in Fig. 2).

4. The results of the genetic modelling

The results of genetic analysis of the structure formation model (Fig. 2) are given in Table 1.

The modelling results show that there is a deterministic relationship between the structure of generative electromagnetic chromosomes (S_{714}–S_{817}), the structure of the resulting magnetic field and the modes of operation of the EMDs (Table 1), which gives the opportunity of pre-selection and technical implementation of control methods for material processing through appropriate adaptation of the structure of the magnetic system and changes in the relative orientation and velocity of DFPs.

Analysis of the results of decoding the microgenetic program (Table 1) shows that each generative chromosome corresponds to a specific structure of the resulting magnetic field and mode of operation:

- mode No. 1 with inverse travelling fields $V_1 = (-V_2)$ and the coordinated orientation of the DFPs vortex zones fixed by the *OX* coordinate (S_{714} chromosome):

$$S_{714} = \{2[(PL2.2y)_1]^{-1}:R_{OZ}:I_{OX}:(R_\tau)_1\}\times \times\{n(CL2.2x)_2:M:R_V\}\times(WCH); \quad (3)$$

- mode No. 2 with the coordinated orientation of the travelling fields $V_1 = V_2$ (S_{715} chromosome):

$$S_{715} = \{2[(PL2.2y)_1]^{-1}:R_{OZ}:I_{OX}:(R_\tau:I_\tau)_2\}\times \times\{n(CL2.2x)_2:M:R_V\}\times(WCH); \quad (4)$$

Table 1: *The results of decoding the genetic program of structure formation of the resulting magnetic field in the nonmagnetic gap of EMDs.*

Chromosome number	Structural formula of a chromosome	Chromosome status	Structure of the resulting field
Level 1. Parental chromosome			
PL 2.2y	$(PL\ 2.2y)_1$	Parental (primary)	–
CL 2.2y	$(CL\ 2.2x)_2$	Secondary	–
Level 2. Genome structure			
S_{10}	$2(PL2.2y)_1:R$	Replicated ($K_R = 2$), information	–
S_{21}	$2(PL2.2y)_1:R_{OZ}$	Oriented isomer (*OZ*), information	–
S_{31}	$2[(PL2.2y)_1]^{-1}:R_{OZ}$	Spatially inverse, information	–
S_{41}	$2[(PL2.2y)_1]^{-1}:R_{OZ}:I_{OX}$	Electromagnetically inverse (*OX*), information	–
S_{15}	$n(CL2.2x)_2:M$	Mutated, secondary, information	–
S_{25}	$n(CL2.2x)_2:M:R$	Replicated secondary, information	–
S_{35}	$n(CL2.2x)_2:M:R_V$	Spatial isomer (V_{XYZ}), information	–
S_{513}	$\{2[(PL2.2y)_1]^{-1}:R_{OZ}:I_{OX}\}\times\{n(CL2.2x)_2:M:R_V\}$	Hybrid (paired), information	–
$\boldsymbol{S_{514}}$	$\{2[(PL2.2y)_1]^{-1}:R_{OZ}:I_{OX}\}\times\ \{n(CL2.2x)_2:M:R_V\}\times(WCH)$	Combined, information	With a coordinated orientation of fixed vortex zones
Level 3. Structural detailing of S_{614} chromosome			
$\boldsymbol{S_{614}}$	$\{2[(PL2.2y)_1]^{-1}:R_{OZ}:I_{OX}:R_\tau\}\times\{n(CL2.2x)_2:M:R_V\}\times(WCH)$	Replicated ($K_{R\tau} \geq 2$), information	With a coordinated orientation of fixed vortex zones
$\boldsymbol{S_{714}}$	$\{2[(PL2.2y)_1]^{-1}:R_{OZ}:I_{OX}:(R_\tau)_1\}\times\{n(CL2.2x)_2:M:R_V\}\times(WCH)$	Isomer 1, generative	With a coordinated orientation of fixed vortex zones (↻↻)
$\boldsymbol{S_{715}}$	$\{2[(PL2.2y)_1]^{-1}:R_{OZ}:I_{OX}:(R_\tau:I_\tau)_2\}\times\{n(CL2.2x)_2:M:R_V\}\times(WCH)$	Isomer 2, generative	With a coordinated orientation of travelling fields (⇉)
$\boldsymbol{S_{717}}$	$\{2[(PL2.2y)_1]^{-1}:R_{OZ}:I_{OX}:(R_\tau:I_{2\tau})_3\}\times\{n(CL2.2x)_2:M:R_V\}\times(WCH)$	Isomer 3, generative	With an alternate orientation of fixed vortex zones (↻↺)
$\boldsymbol{S_{811}}$	$\{2[(PL2.2y)_1]^{-1}:R_{OZ}:I_{OX}:(R_\tau:I_\tau)_4\}\times\{n(CL2.2x)_2:M:R_V\}\times(WCH)$	Isomer 4, generative	With a combined orientation of travelling and vortex zones (→↻)
$\boldsymbol{S_{816}}$	$\{2[(PL2.2y)_1]^{-1}:R_{OZ}:I_{OX}:R_\tau:M_\tau\}\times\{n(CL2.2x)_2:M:R_V\}\times(WCH)$	Mutated, generative	With a coordinated orientation of moving vortex zones (~~↻↻~~→)
$\boldsymbol{S_{817}}$	$\{2[(PL2.2y)_1]^{-1}:R_{OZ}:I_{OX}:R_\tau:I_{2\tau}:M_\tau\}\times\{n(CL2.2x)_2:M:R_V\}\times(WCH)$	Mutated, generative	With an alternate orientation of moving vortex zones (~~↻↺~~→)

- mode No. 3 with the inverse travelling fields $V_1 = (-V_2)$ and alternate orientation of the fixed OX coordinate of the DFPs vortex zones (S_{717}):

$$S_{717} = \{2[(PL2.2y)_1]^{-1}:R_{OZ}:I_{OX}:(R_\tau:I_{2\tau})_3\}\times \times\{n(CL2.2x)_2:M:R_V\}\times(WCH); \quad (5)$$

- mode No. 4 with alternating sequence of zones with travelling and inverse fields by OX coordinate (S_{811}):

$$S_{811} = \{2[(PL2.2y)_1]^{-1}:R_{OZ}:I_{OX}:(R_\tau:I_\tau)_4\}\times \times\{n(CL2.2x)_2:M:R_V\}\times(WCH); \quad (6)$$

- mode No. 5 with the inverse travelling fields $V_1 \neq (-V_2)$ and the coordinated orientation of the travelling fields by the OX coordinate of the DFPs vortex zones (S_{816}):

$$S_{816} = \{2[(PL2.2y)_1]^{-1}:R_{OZ}:I_{OX}:R_\tau:M_\tau\}\times \times\{n(CL2.2x)_2:M:R_V\}\times(WCH); \quad (7)$$

- mode No. 6 with the inverse travelling fields $V_1 \neq (- V_2)$ and the alternate orientation of the travelling fields by the OX coordinate of the DFPs vortex zones (S_{817}):

$$S_{817} = \{2[(PL2.2y)_1]^{-1}:R_{OZ}:I_{OX}:R_\tau:I_{2\tau}:M_\tau\}\times \times\{n(CL2.2x)_2:M:R_V\}\times(WCH). \quad (8)$$

According to the results of structural synthesis, methods of technical realization of energy-efficient modes of materials processing have been optimized and developed. This increases the productivity of electromechanical disintegrators, the efficiency of which is confirmed by experimental studies on flat double-winding EMD samples in technologies of coal-water slurry fuel preparation [15] and the activation of Portland cement [16].

5. Conclusions

1. For the first time a genetic model of structure formation of EMD active parts with three-level structural detailing has been developed, which allows synthesis and analysis of genetically acceptable magnetic field structures in the active zone of the disintegrator at the stages of search design.

2. For the first time a deterministic connection between the genetic information of generating electromagnetic chromosomes and the corresponding structure of the resulting magnetic field in the EMD active zone substance has been established, which significantly simplifies the task of synthesis and analysis of magnetic field structures.

3. According to the results of genetic modelling and synthesis, processing modes, which provide a change in the mutual orientation of the vortex zones and a uniform distribution of working bodies and control of the intensity of their movement in the working volume of EMDs, have been optimized.

4. According to the results of research, methods of technical implementation of material processing modes, which provide the implementation of energy-efficient processing modes and increase the productivity of EMDs of multifactorial action, have been developed.

5. The reliability of the results of theoretical studies is confirmed by experimental studies, the results of which show that the use of the proposed methods of controlling the modes of operation of EMDs in technologies for production of coal-water slurry mixture and activation of cement increases their efficiency.

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