Structural analysis of Braking Energy-Conservative Systems of Transport Technological System

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Abstract. The possibilities of application of the ways and means allowing beneficial use of kinetic energy of moving masses of various transport and transport-technological machines in the course of braking are considered. The concepts of development of inertial and energy-storage braking means for different types of actuating units are presented. The generalized block schematic diagram of a multimass object with the inertial energy-storage braking system and morphological matrix of possible technical solutions are offered. Various offers on realization of inertial and energy-storage braking systems in the designs of technological machines are shown and the results of the researches of energy-storage braking are presented.

1. Introduction
The modern mechanical engineering assigns tasks to engineers to create the multipurpose machines and the equipment, universal technical objects, adaptive and indifferent devices capable to change the functions, structures or parameters in the automatic mode depending on external and (or) internal factors. The considerable group of such machines is made of transport and technological ones, providing all variety of construction, materials-handling, roadway, underground mining processes and works[1].

The basis for such combination is the unity of structures, uniformity of working and executive bodies, transmissions, blocks unification, control devices and other modules. However, not all the blocks and modules are adequately researched and covered in literature. Among them a specific place is held by the brake and traction and brake modules capable to provide efficient use of the braked objects kinetic energy through the creation of braking power or brake energy recuperation and its use in further work.

Unfortunately, the majority of transport-technological machines is equipped with the brake means transforming kinetic or potential energy of the moving objects to thermal energy with its dispersion into the environment. Energy is spent for creation of brake power (torque) in such means in addition.

2. Energy-Storage Braking Conceptual Baseline
The first mentions in literature on efficient use when braking kinetic energy of the moving vehicle belong to the crew of "horse car" and the railway train. In the first case wheels kinetic energy when
braking was transferred in to the vehicle body hoisting mechanism, i.e. it was transformed into potential energy. At start-off the crew fell and via the same transmission gear it rotated wheels, helping horses to pull away. In the second case, the American scientist Gibbs [6] offered the inertial brake using the efforts arising in train hitches when braking the engine.

The modern inertial brake energy-storage and energy-saving means allowing to carry out recovery of energy of the braked object in one guise or another are used on the motor transport (coasting brakes and the combined drive gears) [1,3], on the trains of underground locomotive haulage [8], on mine rise [9], on rotary platforms of excavators [9], bridge cranes [4], etc.

Actually, by recuperation [2] is meant the return of kinetic or potential energy which is saved up by an object to its source or the consumer. Predominantly, this refers to the transformation of kinetic energy of the moving vehicle to electric one with its return to contact system or to the accumulator unit. Such systems are rather widely used on locomotive transport and motor transport with the hybrid drive, on the lifting equipment (at load-lowering).

The energy transformation into other kind can be absent. In this case kinetic energy of an object is transferred to the special storage device – a flywheel, and if necessary it is restored to an object without transformation either [3,4]. The scheme of such drive is shown in Figure 1.

![Figure 1. Actuator configuration with inertia braking energy-storage system. SS – Supervision System; E – Engine; V – Variator; FW – Fly Wheel; TG – Transmission Gear; CD – Controller Device.](image)

The engine (E) through the variator (V) and the transmission gear (TG) transfers torque to the controller device (CD) in the mode of working motion. At the same time the variator allows the supervision system to slow down the flywheel shaft. Thus, in the mode of working motion the flywheel remains motionless.

In the mode of braking SS unblocks FW, switches (blocks) the engine. As a result kinetic energy of CD and TG through V is transferred to FW. At the maximum acceleration of FW or in case the speed of FW exceeds the speed of the output shaft of V, the supervision system disconnects the flywheel and blocks the output shaft of V. The fly wheel continues to rotate by inertia.

In the mode of starting of SS connects FW through V and TG to the controller device. E can be disconnected. In case the torque value of FW becomes less necessary, SS switches E.FW and E work simultaneously. At the stop of FW the supervision system blocks its output shaft. The drive works as in the mode of working motion.

Generally, the stores can be mechanical (flywheel-type, springing, gravity, etc.), chemical, thermal, electric, hydraulic (hydraulic-pneumatic). Each type of the energy store has the advantages and shortcomings which need to be considered at designing of energy-storage drives of certain motor-cars.
The general requirements to the stores should be considered the saved-up energy conservation with the time minimum losses, the smoothness of transition of their traction mode into braking one and back, a possibility of energy return regulation to the system at start-off, the steady motion and other purposes.

As it is seen from the description of the modes, the energy potential of CD and TG in the mode of braking is to change from the maximum value to zero. At the same time the kinetic energy of FW is to change from zero to the maximum value.

If we take the ratio of the \( \omega_{\text{actuator}} \) and the \( \omega_{\text{flywheel}} \) for transfer ratio of the \( i_{\text{transmission}} \) between the flywheel and the actuator, then it is seen from the diagram that the transmission gear should have variable gear ratio from \( \infty \) at the beginning of the braking process up to 0 at a motor-car stop. At the same time the transfer ratio should be changed smoothly. To a greater extent, the application of a planetary differential reduction device as the transmission gear meets the case that is proved in [4,5].

The authors have conducted theoretical and experimental researches of the energy-storage braking process which showed operating capacity and efficiency of the braking system in which the fly wheel store is attached by means of the differential planetary reduction device to the actuator drive.

![Figure 2. Energy-Storage Drive Gear Elements Speeds Change Diagrams.](image)

In figure 2 the diagrams of the fly wheel braked object and the traction engine speeds change in the course of energy-storage braking on the test stand (Figure 2a), and as a result of the mathematical model equations solution are presented (Figure 2b). The researches have shown the possibility of the adjustable braking of the object to a full stop and the fly wheel acceleration during the entire period of braking. The volume of the kinetic energy which is saved up in the fly wheel store can reach more than 60% of initial energy of the braked object.

The differential reduction devices usage proposals in the energy-storage drive gears of the wheeled vehicles are shown the works [5,6].

3. Multimass Objects Inertia Braking Systems Synthesis Methodology Validation

As it is proved in the works [1,9] kinematic structure of any technical object, equipped with the inertial energy-storage braking system and storage, includes the closed kinematic circuit with the constant or variable value of voltage. For example, for the vehicles connected consistently the value of voltage is defined by a number of parameters:

\[
H = f(m_1; m_2; ...; m_n; \dot{x}_1; \dot{x}_2; ...; \dot{x}_n; \ddot{x}_1; \ddot{x}_2; ...; \ddot{x}_n; T_1; T_2; ...; T_n; \psi); \\
\text{at } -|H_{\text{max}}| \leq H \leq +|H_{\text{max}}| \tag{1}
\]

where \( \dot{x}_1; \dot{x}_2; ...; \dot{x}_n; \ddot{x}_1; \ddot{x}_2; ...; \ddot{x}_n \) are corresponding speeds and acceleration;
\( m_1; m_2; ...; m_n \) are connected in series technical objects masses;
\( T_1; T_2; ...; T_n \) are corresponding masses braking strains value and character;
\( \psi \) is tire-to-surface or rail friction coefficient.

The voltage value defines the drive capacity for energy-storage in collaboration with the variator constructional features.

Thus, varying the braking devices parameters, transformation and storage of energy, we can improve and synthesize new traction braking systems.

The general approaches to variable search of new technical solutions on the basis of functional and structural morphological tables are stated in works by V.V. Dloukh, S. Nurakov, V.P. Bykov, A.V. Andreychikov, A.G. Voytov, etc. K. Rot [1] developed the system of catalogs and tables which allowed to systematize separate knots and devices, providing completeness of engineering development of products. D.P. Volkov, V.Ya. Krikun, K.K. Shestopalov, V.I. Balovnev, L.A. Chmara [1] and some other scientists were engaged in the development of the generalized structural-morphological schemes and systematization of functional modules in the field of construction and materials-handling machines.

In the works of G.Sh. Hazanovich, Yu.M. Lyashenko, A.S. Nosenko and other authors [1,7,9] the questions of synthesis of new technical solutions of mine loading and transport modules of heading machines on the basis of constructive and functional structure are considered. The creation of structural-morphological classifications is constructed by V.I. Solod and G.I. Solod in relation to a number of mining machines taking into account their specifics and structural systematization.

The principle of consecutive synthesis of models of admissible options of creation of separate elements, blocks and system in general with the subsequent choice on synthesizable model of structure of a system of the best option of its realization and development is exploited by A.D. Tsvirkun, V.M. Odrin and others. A.N. Drovnikov, V.S. Isakov [1] offered the generalized model and the technique allowing to develop the functional mechanisms of materials-handling, construction and mining machines using the intense closed circuits.

Such approaches allow to systematize and unify systems, modules, blocks, and to choose the most rational and perspective constructive decisions, to systematize the general principles and to unify calculation procedures. Thus, in the works by L.A. Chmara, A.P. Holodov, V.F. Scherbakov, A.N. Drovnikov, G.M. Vodyanik, V.S. Isakov [1,9] the researches in the field of creation of recuperative systems of drives for construction mining machines with use of hydro-pneumatic accumulators and thermal accumulators are presented.

In the work [1] the attempt to create the classification of the tandem-coupled machines and their modules based on possible types of the connected masses movements is stated. The scheme depicted in Figure 1 does not consider the nature of the masses movement, the possibility of their mutual movement and change of the mechanism structure including "singular points".

Systematization of any technical systems having the intense closed kinematic circuits in the structure and a search technique on its basis of new technical means is sufficiently detailed in the works [1,9]. However, the technique does not consider the system of energy-storage, mobility the coupled elements mobility, etc.

In this regard, we can propose the generalized structural diagram (Figure 3) of a multimass object with the inertial energy-storage braking system and a morphological matrix of possible technical solutions based on the scheme depicted in Figure 1.
Figure 3. Multimass object structural scheme with inertial energy-storage braking system.

- $m_1, m_2, \ldots, m_n$ are masses of the series-connected objects;
- $\Delta x_1, \Delta x_2, \ldots, \Delta x_i, \ldots \Delta x_{n-1}$ are moving variable couplings permitting masses relative movement;
- $BC1, BC2, \ldots, BCi, \ldots BCn$ are brake-conventors making kinetic energy transfer of the moving object into another type and transmission to its accumulator;
- $LA1, LA2, \ldots, LAn$ are local accumulators;
- $CA$ is central accumulator.

SS is supervision system.

The inertial traction-braking system provides the set mode of the movement of the objects group $m_1, m_2, \ldots, m_n$ due to braking at least one of the masses. Other objects accomplish braking, using the efforts arising in the conjunctions $\Delta x_1, \Delta x_2, \ldots, \Delta x_i, \ldots \Delta x_{n-1}$ allowing relative motion of the masses.

Transformation of energy to another type can be absent. The wastage when braking, transforming and storage of energy are inevitable and natural. Depending on design and functional features of the brake converter $BC1, BC2, \ldots, BCi, \ldots BCn$ wastage value will be various.

Thus, the possible solutions matrix will include:

$$M = \{\sum_{n-1}^{0} m_i \times \sum_{n-1}^{0} \Delta x_i \times \sum_{n}^{i} BC_i \times \sum_{n}^{0} LA_i \times \sum_{n}^{0} CA\}$$ (2)

Moving variable couplings can accept zero value, i.e. they are not interconnected. For example, movement and braking of the trolley with simultaneous load-lowering. Local accumulators in the presence of central can be absent, i.e. they possess value “0”. Transmission of energy is carried out to central accumulator directly. $CA$ can possess values “0” or “1”. The matrix can include the additional couplings providing transmission of energy to the consumer i.e. coupling $L_n \rightarrow m_i$.

A variety of masses and the nature of their movement, and consequently the storage, it is possible to show on derived schemes from the matrix (Figure 4):
In Figure 4a the scheme of the tandem-coupled objects $m_1$; $m_2$; $m_3$ is shown, having moving constraints $\Delta x_1$; $\Delta x_2$. Such scheme corresponds, for example, to the underground locomotive haulage train. In Figure 4b the scheme of the single-mass object, having rotary motion about motionless (referred to the reference) masses, is depicted. The work of the excavator rotary platform can be an example: braking in motion for digging bucket unloading and return of the platform and a digging bucket to a drift. The scheme 4c presents the dual-mass system having the mass $m_1$ moving linearly and which is movably connected to the mass $m_2$ and also the mass $m_2$ moving rotationally and having rather motionless reference $m_1$. For example, tractor-hauled roller having overrunning brake and at the same time a brake converter of the roll rotary motion relating to the tow-bar attached to the tractive vehicle. Figure 4d displays movement of three masses simultaneously connected in tandem and one mass rotating concerning the mass 2 which is rather motionless reference for mass 4. As an example we can present the movement of the jib type crane crab with the boom swing, simultaneous load-lowering and movement of the very crane (theoretical case).

The researches [9] conducted by the authors showed that at traction-brake systems operation the maximum effect is reached by the first four-five consistently connected objects. In Figure 5 the braking process parameters of the train equipped with inertial brakes are presented.
Figure 5. a,b – The interdependencies of braking strain (a) and braking path (b) on number of in sequence connected wagonettes in operation.

The working capacity and efficiency of energy-storage braking application is also confirmed while investigating the dynamics of the hydraulic excavator rotary platform with the hydraulic impulse storage unit which is built in hydraulic system. In considering the studied system functioning dynamics the interrelation of all links (lift arms, arms, digging bucket) is taken into account.

In Figure 6 the changes of pressure in drain lines of hydraulic actuators in the course of the rotary platform braking are presented.

\[ P, \text{ MPa} \]

Figure 6. – Pressure change in drain lines of the hydraulic actuator \( Z_{n,13} \), actuation cylinder of the lift arm \( Z_{n,14} \), arm \( Z_{n,15} \), digging bucket \( Z_{n,16} \), accumulator \( Z_{n,19} \).

The results of the conducted researches showed a possibility of accumulation in the hydraulic impulse storage unit to 90% of the kinetic energy of the rotary platform.

4. Conclusion

The conducted analysis of the existing energy-storage and energy-conserving brake devices (including developed and tested by the authors of the article) allowed to establish their operability and efficiency of functioning in various operating modes for the tandem-coupled multimass objects with the common
support platform, to reveal the general structural regularities of such devices for construction, materials-handling, roadway and mining machines.

The multimass object principal structural model developed on this basis with the inertial energy-storage brake system can be used in the structural-morphological analysis and synthesis of new energy-storage systems and generic modules, development of consistent methodological approaches to justification and calculation of their rational parameters.

The developed methodology of the structural-morphological analysis allows to mark out standard structures taking into account hierarchical levels of specification: from the general functional and structural diagrams at the high hierarchical levels to the general basic and constructive – on the lowest, taking into account concrete characteristics of the designed technical object.

Theoretical and experimental studies confirmed a possibility of use of the central accumulator of multimass objects energy for reasonable redistribution of energy resources among potential consumers.

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