Development of information model of power transmissions in the light of Industry 4.0

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Abstract. *The main features of creating an information model (Digital Twin) for a technically complicated item are formulated. These include: a multitude of systemic representations of the item, individualization of its behavior and state under specific operating conditions, fatal uncertainty in the description of component properties, reconstruction of data based on sensors readings, individual lifetime expense in operation. Above features are illustrated by authors' developments in application to power transmissions. The key issues of synthesis, calculation, design and diagnostics of transmissions based on the created complex of lifetime-and-functional models are solved. Transmission is considered as a multicomponent system with a variable structure and states. Creating a single universal model to reproduce basic properties of the technically complicated item is impossible. Principles of constructing models and methods for calculating, monitoring and predicting functional and lifetime properties are described. The basic representations of the transmission (structure, regular mechanical system, kinematic and dynamic diagrams, diagnostic model, schemes of limiting states, lifetime expense model) and the mathematical models serving them are developed. The approaches considered are methodologically typical for complex mechanical and combined objects based on mechanical systems.*

1 Introduction

The evolution of concepts, which led to the now accepted term "Digital Twin" (DT) and its modern interpretation, is presented in [1, 2].

Many publications analyze various interpretations of this concept and give their own definitions. In some cases, a statistical analysis of formal features from known publications is used. An example of a such work is [3]. It examines three questions: What are the definitions of DT that have been published in literature so far? What are the main characteristics that should be implemented in a DT? What are the domains in which DT applications have been developed?

As the first result, the following definition is formulated: "DTs can be defined as (physical and/or virtual) machines or computer-based models that are simulating, emulating, mirroring, or "twinning" the life of a physical entity, which may be an object, a process, a human, or a human-related feature. Each DT is linked to its physical twin through a unique key, identifying the physical twin, and therefore allowing to establish a bijective relationship between the DT and its twin". The second result (the main characteristics that DTs are supposed to possess): both the physical and the digital twins must be equipped with networking devices to guarantee a seamless connection and a continuous data exchange either through direct physical communications or through indirect cloud-based connections.

Based on such publications, the following conclusion can be made: The term DT has become quite familiar, and specialists at the subconscious level are usually understood it unambiguously, but when defining this concept, they generate a lot of formulations.

As if confirming this conclusion, work [4] states that "the existing DT implementations are fundamentally different from each other, adjusting to the needs of each use case and created with a wide variety of tools. Especially, there seems to be an unfruitful competition between modeling oriented and information management oriented views of the DT concept". The authors of [4] suggest a feature-based digital twin framework (FDTF) to universally define and structure digital twins. The framework consists of three main principles: 1) the idea that all digital twins consist of a definite set of features, 2) the features can be used to compare digital twin instances to each other, and 3) the features can be combined via a data link feature to construct future digital twins more efficiently. Besides, it was found that the features can be identified in existing digital twin implementations and the feature combinations of the implementations are diverse.

In [5], it was noted that most approaches today lack a comprehensive review to examine DT benefits by considering both engineering product lifecycle management and business innovation as a whole. The work conducts a state-of-the art survey of DT in the frame of innovation direction. Aa a result, eight future perspectives for DT are identified: modular DT, modeling consistency and accuracy, incorporation of Big Data analytics in DT models, DT simulation improvements, VR integration into DT, expansion of DT domains, efficient mapping of cyber-physical data and cloud/ edge computing integration. Authors of [5] suppose that this work will become a guide for DT development and application in today's academic and industrial environment.

Moving from the consideration of general issues related to DT to the topic of "gear and transmission", it should be noted the papers, which are directly devoted to DT and related the following questions:

-simulation of the tooth root strength under consideration of material quality, finishing process and size effects [6],

-improved tooth contact analysis by using virtual gear twins [7],

- standardized gear unit model [8],

- Digital Twin of gear measuring center [9],

- combining gear design with manufacturing process [10].

A significant paper for the development of transmissions [8] indicates that nowadays a large number of different CAE tools are available for the design and analysis of a gear unit and its components, each of which has its own strengths. A major milestone for Industry 4.0 is the establishment of industry-wide standards.

FVA e.V. (Research Association for Drive Technology) in close cooperation with industry and research, is developing an industry-wide standard for simple data exchange in transmission development under the name REXS (Reusable Engineering EXchange Standard). The REXS initiative pursues the goal of providing a "digital twin" in transmission development and calculation. REXS defines uniform parametric modeling and nomenclature of gear units and their components across standards and industries, based on detailed terminology from FVA's 25 project committees and 50 years of joint industrial research.

This is meant to reduce the number of interfaces involved in the design process, that covers the following interacting basic procedures (from a REXS point of view): component analysis – first draft design – detailed design-construction (CAD) – FE-analysis – dynamics – customers & external partners – manufacturing simulation.

This is the vision of the REXS initiative: a free, nonproprietary, standardized interface for the exchange of transmission data which reduces the complexity of data exchange in the design process significantly.

REXS has the potential to establish itself on a large scale as a standard model for data exchange in the field of gear unit design and analysis. This would result in a number of advantages for the software manufacturers, for the companies using the tools and for the users: 1) Transmission design and analyses at any level of detail, i.e. from the overall system view via the analysis of individual components to the individual physical phenomena, can always be carried out on the basis of a single data model; 2) A simple data exchange between classic analytical gear design programs and universal dynamic, FE and CAD systems would be possible. Expenses for additional, specific modeling could be greatly reduced, etc.

Summarizing the above, it can be stated that the process of creating the transmission DT is under development and is aimed at unifying the interface during the most common types of gear calculations. At the same time, a complete list of basic issues is not covered, including analysis and synthesis, special types of kinematic and dynamic calculations, dependability assessment of a transmission as a system, diagnostics, etc.

In this paper, using the example of a transmission, the emphasis is placed on considering the following fundamental points of building an information model (Digital Twin) of a complex object.

- *The transmission is considered as a technically complicated item (TCI).* Such items have a hierarchical structure; their workflows take place under varying conditions, there is an operator or an automatic control system for the item, the item structure can change (gear shifting), the item as a system consists of elements of various types (gears, bearings, shafts, clutches), the lifetimes of these elements is calculated according to different, not related techniques, enshrined in various regulatory documents.

- *Systemic representations of a transmission*. The fundamental issue for building a DT of a complex technical object is the development of a system of its interrelated representations. (As it is noted in [11]: "When solving a number of problems, it turns out to be insufficient to use only one system representation and, therefore, to use only one division of the whole into elements. The task is possible to solve only when using different system representations associated with each other. Moreover, the elements into which the whole is divided are fundamentally different in different systemic representations. The object is as if projected onto several screens. Each screen sets its own division into elements, thereby generating a certain structure of the object. The screens are connected with each other so that the researcher has the opportunity to correlate different pictures, bypassing the object itself. We will call such a "device" synthesizing various system representations a "configurator"). This requires the development and application of various models that relate to different representations of the object, and not one universal model.

- *Individualization*. The main feature of the simplest digital twin of a technical object (after its making and assembly) is modeling the individual behavior and state of the object in specific operating conditions. Moreover, the use of sensors is not always required. For example, it is possible, on the basis of a changing description of the external environment, to reflect a change in the behavior and state of the object accordingly. The use of sensors makes it possible to clarify the condition of the object by load and speed factors, but it does not completely remove the problem of uncertainty in assessing the lifetime, since the load-carrying ability of the elements is of a random nature even with the highest quality of their manufacture. (This is confirmed in some respects in a paper [12] on digital twin approach for damage-tolerant mission planning under uncertainty, and where the proposed methodology includes the quantification of the uncertainty in diagnosis, prognosis, and optimization, considering both aleatory and epistemic uncertainty sources).

- *The problem of obtaining and reconstructing operation data*. It is unrealistic to believe that with the development of the sensor base, all the necessary parameters of the processes occurring with the TCI in operation can be obtained directly from the sensors. Of particular difficulty is the data on force factors in mobile parts. Therefore, the problem of data reconstruction arises: how to obtain the necessary information about the object based on the available sensory data? This problem cannot be solved without the correct calculation models. And the task of rational installation and use of sensors is associated with above problem.

- *Lifetime expense of TCI.* To describe the individual state of life of a complex object that consists of components of various types, with different mileages and ages, the term "lifetime expense" and a new indicator are introduced. This can be seen as a response to the paper [13], which considers integrated vehicle health on the DT state.

2 Key points of the approach

At the stage of the transmission life cycle, data describing the transmission as a whole are transformed and developed. The transmission is supplemented with new representations in the following way: structure - kinematic diagram - layout - mechanical model - dynamic diagrams for various dynamic calculations - diagnostic models - schemes of limiting states - lifetime expense model.

These representations are accompanied by a set of component models, including a description of their limiting states / failures.

During operation, the level of the external loading of the transmission stabilizes quite quickly. The main variable individual component in operation is the internal dynamics of the transmission. Data on the internal dynamic loading are determined using the diagnostic system. These data are transmitted to lifetime forecasting systems, and also serve as independent indicators of the technical condition of the transmission. At the same time, the most advanced systems provide data for all significant transmission components.

Data obtained promptly from the operation of the object are used to predict the lifetime of individual components and estimate the transmission lifetime expense in general. The techniques used to solve these problems are of universal importance and are applicable to the machine, which includes the transmission.

3 Basic principles of developing an information model

The authors' vision and understanding of the information model of a machine as technically complicated item (TCI) begins with a paper [14], that developed the idea about the need for an information model of the machine [15]. The paper [14] contains the proposition that the creation and use of science-intensive products should be based on new information technology. The technology involves the development of an information model at all stages of the life cycle of the machine.

The information model should be included in the technical documentation accompanying the machine and allow the use of various sources: semantic, structural (logical), parametric (quantitative, mathematical) models; measurement results; expert evaluations; means of simulating the elements and units of the machine (in slow, accelerated and real time scales in relation to the current, retrospective and predicted state).

Thus, the mentioned methodology anticipated the basic principles of Industry 4.0: the model approach and creation of the digital twin.

The newly developed principles based on [16] cover:

– sharing synthesis, analysis and multi-criteria estimates of the transmission;

– interaction of micromechanical models of materials and reliability theory;

– consideration of drives as multi-component systems with variable states and variable power flows depending on the mode of their operation;

– unity of component loading modes (principle of dependent behavior of components in a loaded system);

– localization of loading in damage models of their simplest components;

– construction of diagnostic models using condition assessment by an integral criterion and predictive calculation based on monitoring the accumulation of transmission damage.

The following basic systemic representations are used for transmissions: regular mechanical system, structural diagram, kinematic and dynamic diagram-schemes, normalized dynamic scheme, scheme of limiting states.

The principles of schematization for the transition from a real mechanical object to its symbolic representation using the concept of a regular mechanical system are developed. The universal mapping of multifarious differentials and gear sets along with the typical displaying of other transmission devices (shafts, controls and a frame) gives the universal representation, formalization and automation of getting equations in the field of transmission kinematics and dynamics. This provides the correct schematization of transmissions of any kind with standard and non-standard components. For the mathematical description of transmissions structures, the developed canonical matrix and structurally-distributive matrix are used.

The presented models and methods are used at all stages of the transmission life cycle to determine loading and qualification of the life state for the limiting components, as well as life expense of the transmission as a whole. Data from the diagnostic system are used to individually synchronize the state of a particular transmission (real object and its digital twin).

4 Typical representations of the power transmission

Considered transmission representations include symbolic mappings and mathematical models serving these mappings. A set of such representations can be considered as typical in a methodical sense for mechanical objects and combined objects, the basis of which are mechanical systems.

4.1 Transmission structure

The initial representation of the transmission is its structure. The stage of structure synthesis is the first in the transmission life cycle. This stage is completed by the development of several promising variants of the transmission (for further developmental work), presented in the form of kinematic diagrams and their parameters (gear ratios and so on).

When describing possible variants of structures, the problem of isomorphism takes place. For unambiguous construction of structures with given parameters (the number of mechanisms and the number of part/links), the canonical matrix method is used.

Fig. 1 shows the canonical matrix and incorrect canonical matrix (selected cells) that correspond to the structure and gear set shown in Fig. 2.

Gear	Parts (links)					
trains	V1	V2	V3	V4	V5	V6
U1	1	1	1			
U2	1	1		1		
U3			1		1	1

Gear	Parts (links)					
trains	V1	V2	V3	V4	V5	V6
U1	1	1		1		
U2	1	1	1			
U3				1	1	1

Fig. 1. *The canonical (top) and incorrect (bottom) canonical matrices (own work)*

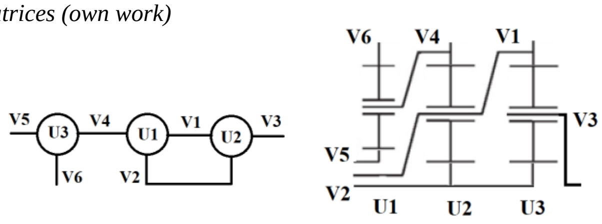


Fig. 2. *An example of the structure (left) and the gear set of World Transmission (right, [17]) corresponding to Fig. 1 (own work).*

The basic rule that ensures the construction of original canonical matrices is as follows: it is necessary to use parts (links) with the lowest numbers for each mechanism.

4.2 Kinematic diagram

The kinematic diagram is used as the basis for designing the layout, calculating speeds and torques, and also for determining the levels of internal loads when predicting the transmission life. Approaches to the construction of kinematic diagrams using software packages are presented in Fig. 3 [18].

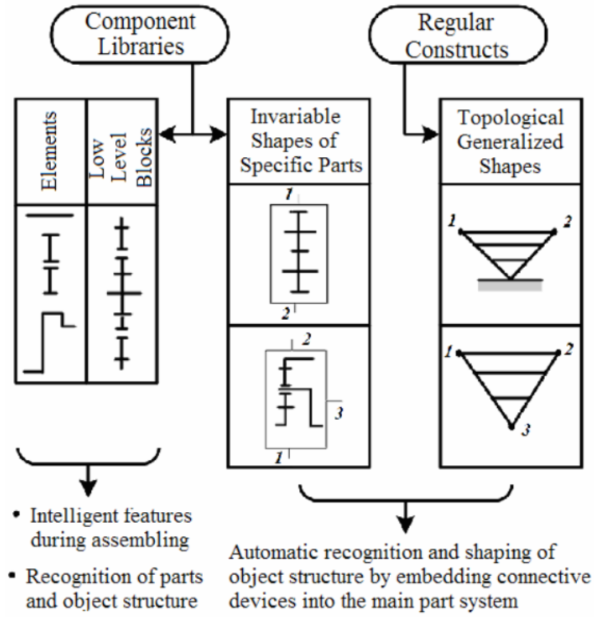


Fig. 3. *Approaches to schematization (own work).*

Most well-known software packages are universal and contain special modules/component libraries for modeling transmission devices (Class "Component Libraries"). These are: ADAMS / Machinery [19]; Simscape Driveline [20]; MapleSim Driveline [21]; Modelica / Power trains and planetary gearboxes // Gears [22]; KissSoft / KISSsys // GRK [23]).

Transmissions are widely used in mechanical engineering; it is advisable to develop specialized software packages for them. As an example, the World Transmission kinematic diagram made in the specialized package “Kinematics” is shown in Fig. 4. The following IDs are used: I = basic parts (links), F = controls (clutches and brakes), z = numbers of gear teeth. This package allows to build kinematic diagrams with planetary and simple gears, controls (clutches and brakes), several embedded shafts, recognize structural relationships, gear ratios of gear mechanisms, perform calculations and optimize transmission parameters when presenting it with the kinematic diagram.

4.2 Regular constructs for forming kinematic and dynamic diagrams-schemes

The complex and manifold systems need two-leveled schematization and representation. The first specific level is based on the commonly used elements for the family of objects under considerations and on their conventional representation (Class “Component Libraries”). The necessity of the second level stems from the fact that any element base of specific elements has limitation. Hence the second level is more abstract and should use the special symbolic representations to multi-purpose description of structural links in concrete kind of objects. Therefore, for the design of the transmission, it was proposed to create a set of mechanical components that are characteristic for the schematization of mechanical objects (class “Regular Constructs”). The level of abstraction increases with a variety of transmission units. In this case, intuitive symbolic icons for transmission parts/devices are offered. Mathematical models are formally generated from the formed design models for the further kinematic and dynamic calculations [18].

Transmission devices, which have the same mathematical structure and differ only in parameters, can be represented in a generalized form by symbolic regular constructs (Fig. 5).

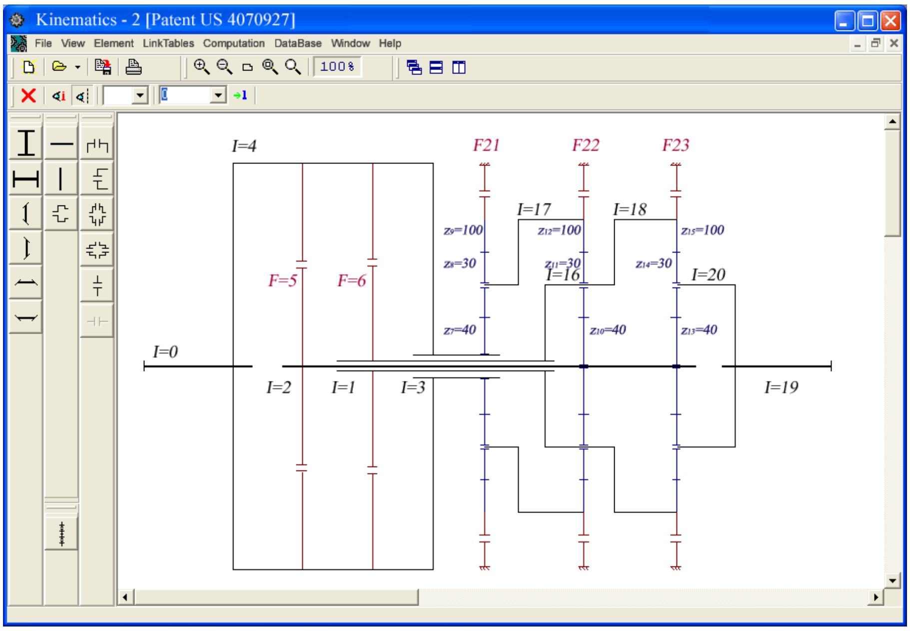


Fig. 4. *Software "Kinematics" by an example of World Transmission representation (own work).*

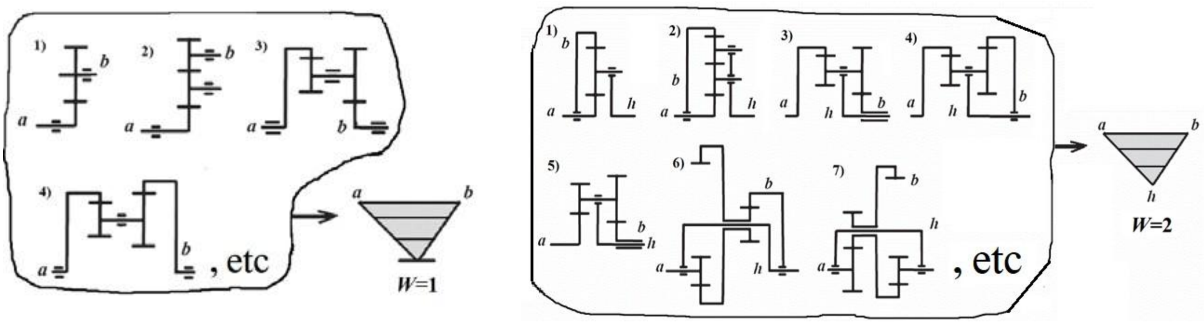
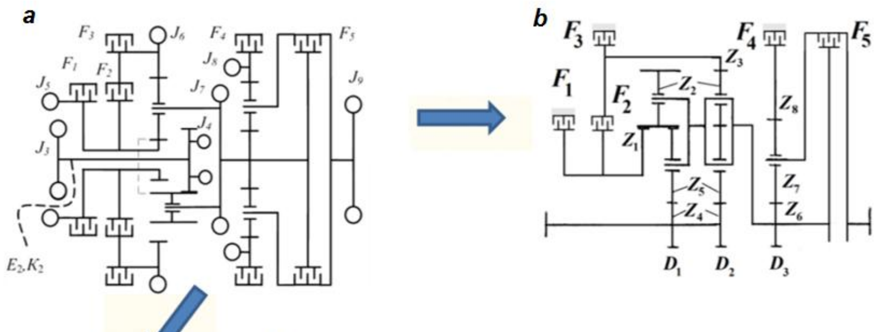
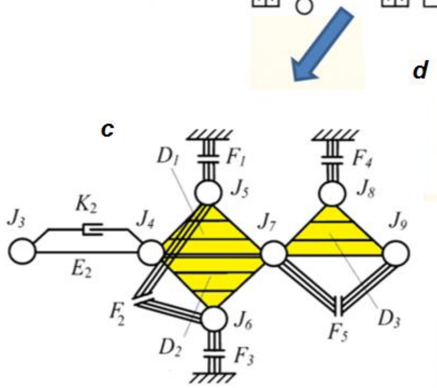


Fig. 5. *Symbolic representation of different types of gears (number of degrees of freedom W=1, left) and differentials (W=2, right) by regular constructs (own work).*

Index for device part	Differential *D*	Train *P*	Shaft *S*	Frame *R*	Clutch *F*	Brake *T*
1 (*i*)	1	1	1	1	1	1
2 (*j*)	$-u$	$-u$	-1 (u=1)	0 (u=0)	-1	0
3 (*k*)	$-(1-u)$	—	—	—	—	—

Fig. 6. *Distribution of internal torques among parts (links) of the typical transmission devices (own work).*





d

Basic parts	Control parts					Transmission mechanisms		
	F_1	F_2	F_3	F_4	F_5	D_1	D_2	D_3
1	0	0	0	0	0	1	1	0
2	1	1	0	0	0	0.8	0	0
3	0	−1	1	0	0	0	−2.6	0
4	0	0	0	0	1	−1.8	1.6	1
5	0	0	0	1	0	0	0	2.461
6	0	0	0	0	−1	0	0	−3.461

Fig. 7. *Schematization of the MZKT-7922 transmission: a = mechanical model; b = equivalent kinematic diagram; c = dynamic scheme; d = structural distribution matrix (own work).*

To describe the structure and distribution of the internal torques in devices, a structurally-distributive matrix (SDM) is introduced. Each mentioned device is presented at such a matrix in the form of a column, as it is shown in Fig. 6.

The meanings of non-zero elements of *k*th column (A_n=A_{jk}) describe the distribution of torques in the kinematic unit (A_n=M_n/M_1).

After describing the structure of the transmission using SDM, the equations for its kinematic and quasi-static calculations are automatically formed. As a result, the speeds of the links, the torques in the devices, and efficiency of the transmission in each of gears are determined [18]. In the latter case, the kinematic gear ratio u is replaced by the power gear ratio $\hat{u} = u\eta^x$ for each device, where η = efficiency; *x* is equal +1 or –1, depending on direction of power in the device.

An example of forming SDM for the transmission with non-standard planetary gear trains is depicted in Fig. 7. **Note**. Here and further: *J* = moment of inertia, *E* = elasticity, *k* (*K*) = damping coefficient.

4.3 Regular mechanical systems and dynamic computing

A mechanical system with elementary mechanical components (the concentrated masses and the massless joining links) is essential idealization which imposes certain restrictions on possible combinations of joints (connections) for mentioned items.

The c**oncept of a regular mechanical system** (RMS) considers that mechanical system consists of the concentrated masses (inertial components) and massless (non-inertial) devices-connectors: shafts, clutches, brakes, gears, motionless links, and other devices imposing kinematic connections for masses (Fig. 8).

Masses can be in contact interaction. For connecting device, the direct contact (not through inertial component) is prohibited. This is a **principle of regularity**, which is used for the representation of a real object. Its violation leads to wrong schematizations and errors in calculations or impossibility of mathematical model realization by the computer.

Clutches/brakes are the typical devices having variables states (Fig. 9). **Note.** Here and further: *M* = external torque or internal in the friction device.

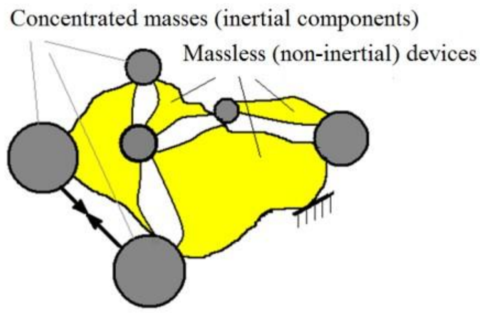


Fig. 8. *General representation of RMS (own work).*

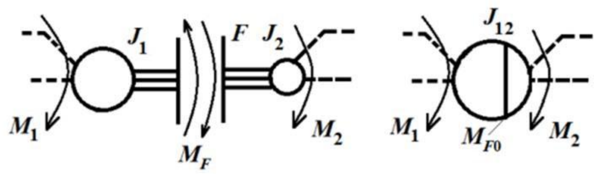


Fig. 9. *States of a clutch: slipping (left) and locking (right) (own work).*

For getting all-purpose mathematical model for their dynamics, a method of internal torques is used. This one is based on logical variables λ_k, named indicators states, which describe states of the clutches/brakes.

The equations corresponding to the clutches are as follows

$$\dot{\omega}_1 = [M_1 - (1-\lambda_m)M_F - \lambda_m M_m]/J_1 \quad (1)$$

$$\dot{\omega}_2 = [(1-\lambda_F)M_F + \lambda_m M_m - M_2]/J_2 \quad (2)$$

where λ_F=0 under locking, and λ_F =1 under slippage (unlocking) of the clutch; M_F is the known function describing a friction torque during slipping friction clutch parts. The equations are the same for all states of the clutch.

In order to use **all-purpose equations** a special procedure should be developed for finding the internal torques (like M_{12}) which acting in rigid devices. In a case presented in Fig. 9, the internal torque of the friction clutch can be calculated by formula

$$M_{12} = (J_2 M_1 + J_1 M_2)/(J_1 + J_2) \quad (3)$$

In addition, the conditions for changing the states of friction clutches should be described when solving differential equations. Generally, it is necessary to consider spasmodic change of a friction torque at transition from slippage to friction clutch locking and inversely.

Generalization of these situations for computing leads to the formulation of **following principle**: if a new condition of contacting inertial parts (for example, slippage or locking of friction clutch/brake) becomes possible then this condition should be necessarily presented at next step of computing process.

In general case, the RMS can be stiff-elastic object that contains rigid and elastic devices. As typical example, RMS with rigid and elastic devices and the corresponding dynamic scheme are shown in Fig. 11.

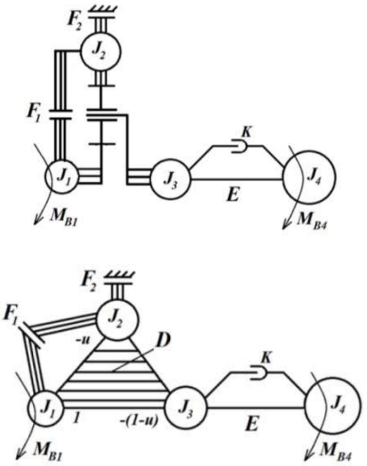


Fig. 10. *Stiff-elastic RMS (top) and its dynamic scheme (bottom) with symbolical representation of the differential D (own work).*

During computing stiff-elastic object, it is necessary to solve a system of differential equations, and this is accompanied by solution of a system of algebraic equations to determine the internal torques in rigid devices.

To avoid forming and solving algebraic equations, the dynamical system can be **normalized** by replacing rigid devices and links with elasticities Ei (Fig. 11). For brakes external links like E_{22} may be rigid. In the normalized system, masses and elastic links alternate. To determine the internal torques of closed clutches/brakes, a simple formula (3) is used instead of solving the system of algebraic equations.

This approach increases the number of differential equations, but simplifies the formation of mathematical models in general, which is very important.

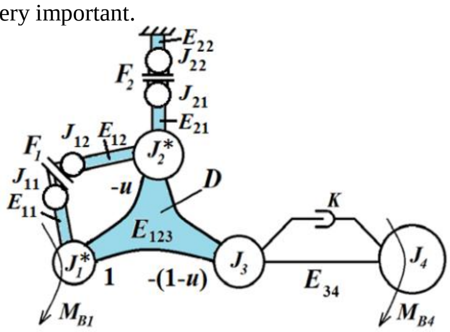


Fig. 11. *Normalized dynamic scheme (own work).*

Fig. 12 shows the normalized dynamic scheme for modeling the dynamic processes of planetary transmission, the kinematic diagram of which is depicted in Fig. 4. Three differentials are shown by curved triangular figures with elasticities E_{B1}, E_{B2}, E_{B3}, which correspond to the planetary gear sets U1, U2, U3 in Fig. 2 of the same transmission.

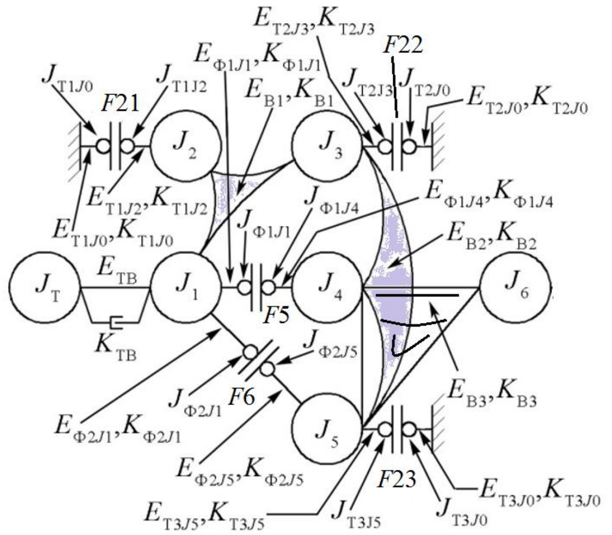


Fig. 12. *A normalized dynamic scheme of the World Transmission; see its kinematic diagram in Fig. 4 (own work).*

5 The factors actualizing the implementation of digital twins for design of gears and transmissions with parts made of composite materials

Forecasting seems to be an important goal of implementing the digital twin, and it becomes an engineering method for estimating the time when machine parts and structural elements will no longer perform their functions.

As distinct from metallic ones, design of gears and transmissions with parts made of thermoplastic composites are hindered by temperature sensitivity, degradation (aging) as well as viscoelasticity of polymers. These time-dependent factors have an essential influence on durability of gears and transmissions with parts made of composite materials.

It is therefore necessary to have more complex digital twins of composite gears and transmissions (refined models of material, extended initial and monitoring time-dependent data) in comparison with metallic analogs. For calculation of stress-strain state, fatigue and wear resistance of such issues hierarchic mechanical models should be implemented [24].

6 Durability (Lifetime)

6.1 General

For transmission as a long-life TCI, the "durability" attribute is of particular importance.

Models for calculating the lifetimes of components are used during all the transmission life cycle, including design and operation stages. The models accompanying the operation reproduce step-by-step damage to the transmission components under the influence of steady-state and transient loading processes. Steady-state loading processes are constantly being adjusted due to data on changes in the coefficients of the internal dynamic loading of transmission units.

In traditional probabilistic calculations, it is assumed that many objects of the same type are taken into account. Durability indicators are defined for a set of these objects. All objects are anonymous (not individualized). When sensors are used, the object is individualized. As a result of tracking data on the load mode(s) of the concrete object in operation, the uncertainty associated with external factors is removed. However, the uncertainty due to load-carrying ability of its components remains. In this case, the lifetime estimate is probabilistic (predictive) in nature too.

6.2 Individualization of the object when evaluating its lifetime

In probabilistic calculations of a technically complicated item, the following provisions are of particular importance: 1) the principle of the dependent behavior of elements in a loaded mechanical system and 2) the complex logic of the limiting states of an object as a multicomponent system.

The first provision means that loads acting on various components of the assembly (gears, bearings, etc.) must be coordinated. This should be taken into account when calculating damage measures for various components using load data using load data from real operation sources or operational models.

The second provision assumes that the limiting state of a complex item is usually determined by a complicated way, based on combination of limiting states of its components.

To describe and calculate such states, the scheme of limiting states (SLS) is introduced. This is one more systemic representation for the transmission and any TCI. It describes the limiting states of a complex item much easier than the known tools (Failure tree and Reliability block diagram). In addition, SLS is convenient for use in statistical modelling procedures, where it is presented in the form of simple records.

The SLS consists of a hierarchical structural scheme and records describing limiting states for objects except for ones that don't have component parts (descendants). All objects other than the highest-level object are assigned a specific type: the first type, the second type, and so on. Objects whose limiting states have the same significance for a higher-level object are classed as the same type. The object type corresponds to its position (first, second, etc.) in the schematic record, which describes the criterion of the limiting state.

The schematic record (X1, X2, etc.) means that the limiting state of the object occurs if the limiting states are reached with its X1 parts of the first type (here X1 is the number standing in the first position), its X2 parts of the second type (here X2 is the number standing in the second position), etc. The object (unit, assembly, machine) can have some the SLS. For example, a mechanical gearbox (Fig. 13) has the following SLS: (1,0,0,0) (0,3,0,0) (0,0,1,2).

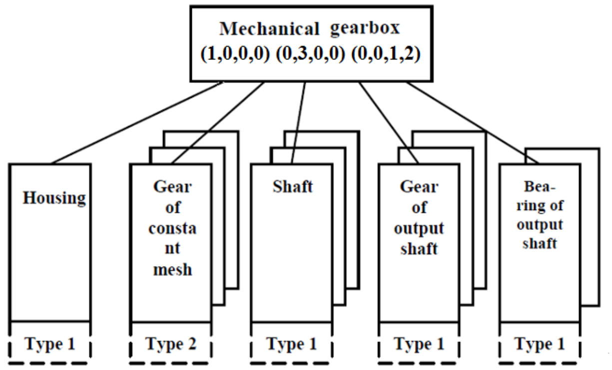


Fig. 13. *SLS for the mechanical gearbox (own work).*

In the general case, there is a multilevel SLS that reproduces the following levels: 1 = the machine (e.g. a car); 2 = aggregates and systems (e.g. transmission, carrier system); 3 = units and subsystems (e.g. gearbox, drive axle); 4 = parts (e.g. gear), typical component parts (e.g. ball bearing), joints (e.g. splined connection); 5 = constructional elements (e.g. gear teeth); 6 = the simplest components (e.g. local area of the surface layer of the gear teeth). Methods of mechanics are used for calculations of limiting states at levels 6, 5, and 4 (in some cases), and structural ones are used at levels from 4 or 5 to 1.

The complex object life cycle forecasting is based on the Monte Carlo method that has the following features. Every simulation cycle after determining components lifetimes is supplemented by the SLS analysis and lifetime determination for objects of intermediate and highest levels bottom-up. When reproducing processes and states related to mechanical levels, factors and effects leading to dependent behaviors of the mechanical components are realized, for example, the general loading levels of components in the particular transmission unit.

Above provisions and methods are included in the State Standard of the Republic of Belarus [25].

7 Monitoring lifetime and diagnostics of transmission in operation

Individualization of TCI and its information model (Digital twin) from stage "making and assemblage" is presented in Fig. 14**.** These are the supplied components; used equipment and personnel (the stage of making and assemblage); the operation conditions, the operator(s) of TCI, the maintenance (the stage of operation).

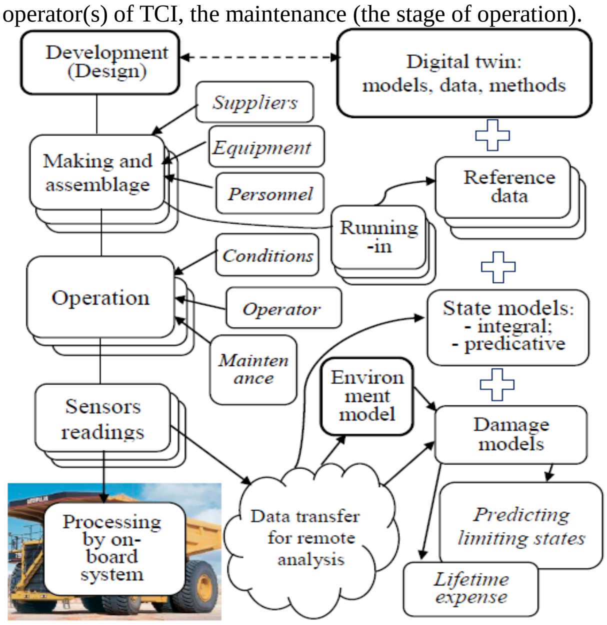


Fig. 14. *Individualization of TCI and its information model (Digital twin) from stage "making and assemblage" (own work).*

The current level of development of sensors and computer facilities also allows recognizing the state of the environment and transferring data for management systems and forecasting models that use data from the environment [26]. In this case, the environment model also refers to the TCI digital twin.

7.1 Peculiarities of TCI monitoring formation

When installing the sensors, the **principle of minimum multiplicity** should be adhering. Sensors, even in the minimum number, should reflect the force and speed constituents of the unit operation modes. In the ideal case, a one sensor can be used to obtain a load (force) spectrum, by which the load processes of all the limiting components are reconstructed.

Since it is not always possible to install a sensor to generate a signal about the loading the limiting element, the task of **reconstructing local loads** of limiting elements arises. To solve it, models that allow to re-construct the stresses (or other loads) of the limiting elements from the signals of existing sensors, should be developed and used.

It is rational to use the data on the loading in the form of general power flows, and individualize the loads for the limiting components to conduct when considering their limiting states

The feature of the developed diagnostic method is using conceptual modeling the oscillating process for the gear drive and the propagation of vibrations in the transmission. It is advisable to applicate together **integral diagnostic** models and **predictive** ones based **on damage accumulation** (Fig. 14, block "State models"). Such a "two-coordinate" approach (from two points of view) ensures a higher veracity of the individual lifetime forecast.

The main **variable individual component** of the transmission unit is the level of its internal dynamic loading. Changes in this level are due to the peculiarities of the manufacture of the unit and the operating conditions of the machine, which includes the transmission unit. The most sensitive components to changes in the internal dynamic load of the assembly are gears and bearings. The greatest damage to the clutches is associated with short-term transient processes, which requires individual monitoring of the modes of these processes.

7.2 Development of technique and means for transmission diagnostics by example of the gear units of mining dump truck

Transmission systems of vehicles and tractors operate under conditions of varying speeds and loads. In addition to internal factors, external ones (the road surface, vehicle loading, driver skills) influence on the vibration characteristics of transmission units.

Under such conditions, the nature of vibrations is constantly changing. The well-known equipment and techniques are not suitable for vibration monitoring of the technical state of the transmission components.

Wear and pitting change the parameters of the gearing and the areas of the contact pads; fatigue cracks reduce the rigidity of the engagement. This leads to the appearance of a shock pulse during the teeth contacts. As a result of theoretical and experimental studies [27], the vibroimpulse, which is the response of the system to the shock pulse produced by the interaction of the teeth of the gears, was selected as the main diagnostic feature. The chosen approach uses a dynamic model containing all the main components of a real object. This model serves to establish the features of the dynamic process under study and the links between the sources of vibration and the parameters being diagnosed.

Developed approach based on the consideration of a meaningful model of the oscillating process for the tooth gear drive and the propagation of vibrations in the reducer system. This provides advanced capabilities, including analysis of unstable regimes, use of an integral state indicator and calculation of damage accumulation in limiting components.

The main processes for the emergence, transformation and processing of signals in the reducer of a motor-wheel (RMW) and its monitoring system are shown in Fig. 15.

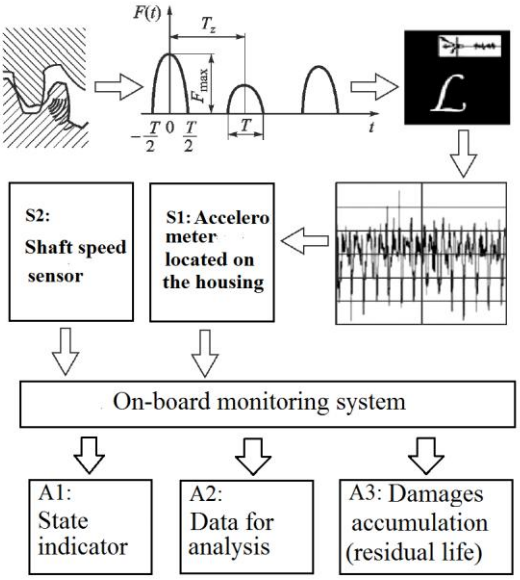


Fig. 15. Processes in the RMW and its monitoring system (own work).

The problem of rational choice of sensors and the task of **reconstructing data** for processes occurring in gears is solved as follows.

Two different types of sensors are used to diagnose RMW. The first sensor S1 is an accelerometer that senses the vibration of the housing. The second sensor S2 transmits data on the speed of the RMW shaft.

The signal S1 is the result of the propagation of a shock pulse along the mechanical transmission paths. It manifests itself in the vibration spectrum of the motor-wheel housing.

Vibrodiagnostics problems associated with the non-uniformity of rotation of the gears, solved by using the developed algorithms for processing the vibration signal and the signal of the rev counter recorded in real time. As a result, the temporal realization of the vibration signal is converted into a realization by the angle of the shaft rotation for the diagnosed gear. Analysis of this implementation using the method of synchronous accumulation and ordinal analysis, adapted to the solution of a particular task, allows us to estimate the vibration parameters for each gear wheel (Fig. 16).

The spectra clearly show peaks at frequencies of 21, 42, 63, 84 Hz, multiples of the tooth frequency of the sun gear, which has 21 teeth.

The technical state of gears is monitored as follows.

The mean square value and the mean amplitude of the first seven harmonics for the tooth frequency are adopted as indicators of the technical state of the gears. They characterize the aggregate energy of the vibrations of the drive elements at the tooth frequencies.

The operation of the system (Fig. 15, block A1) includes:

- analysis of the parameters for vibroimpulses synchronized with the angle of rotation of the diagnosed tooth gear;

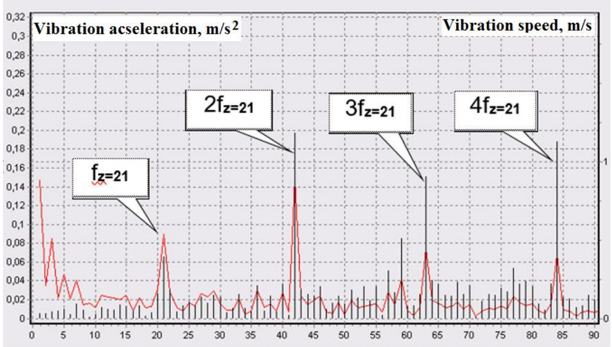


Fig. 16. Harmonic spectra of vibrations generated by the sun gear of the RMW planetary row (own work).

- identification of vibroimpulse harmonic components, which multiple of the tooth frequency and locate in the region of resonance frequencies of the mechanism as well as excite the most intense oscillations in the system;
- analyzing the changing the parameters of vibroimpulses.

The system periodically interrogates the sensors, processes the diagnostic information, evaluates the technical state of the reducer, comparing the received root mean square (RMS) values of vibration acceleration with the maximum permissible values for each of the states of the reducer. The system constantly informs the driver by means of an appropriate light signal on the instrument panel in the cab of the truck.

Actions, marked in Fig. 15 as blocks A2 and A3, are carried out by the service department with the help of special software. They include the following operations:

- transfer of stored data files from the on-board system memory to a stationary computer;
- obtaining harmonic spectra of vibrations of each gear of the reducer by means of synchronous accumulation algorithms and ordinal analysis;
- analysis of spectra and identification of gears generating high levels of vibration;
- for the teeth of gears with high vibration levels, the operating load and contact stresses are determined using the parameters of the vibroimpulses.

Then, taking into account the loading cycles, the residual life is calculated according to the developed technique. After that, a decision is made to continue the operation of the reducer or opening it to eliminate the causes of increased vibration (adjustment, tightening of connections, topping up oil, etc.). Based on the results of the opening, a decision is made to repair or further operating the truck.

At the same time, lifetime forecasting is performed based on a **predicative model.**

The method of forecasting the lifetime is based on the determination of the shock pulse in a meshing according to the results of vibration monitoring. From these data, the actual circumferential force and contact stresses in the meshing are calculated [27].

The measure of fatigue damage to the gear is determined for each fixed *i*th interval of the running time by the formula

$$\Delta Q_{Hi} = \sigma_{Hi}^{q_H} N_i \qquad (4)$$

where σ_{Hi} = contact stress; q_H = the exponent of the fatigue curve under calculating the gear for the contact endurance; N_i = the number of loading cycles of the gear tooth.

An example of the application of the technique for estimating the state of the gearing “sun gear / satellite” of the second planetary row of RMW is presented below. When the technical state is evaluated via integral assessment, the change in root mean square values of the vibration acceleration is monitored. The change in this indicator is shown in Fig. 17. When the dump truck mileage is less 200,000 km, this value remains practically constant. Further it increases, at the same time the peak value of vibration acceleration begins to increase.

When lifetime is calculated using the diagnostics current data, it is taken into account that a linear relationship exists between the amplitude of the shock pulse and the peak value of the vibration acceleration. The growth of peak values means an increase in the dynamic factor K_{Hv}, which is used in the calculation of contact stresses σ_H.

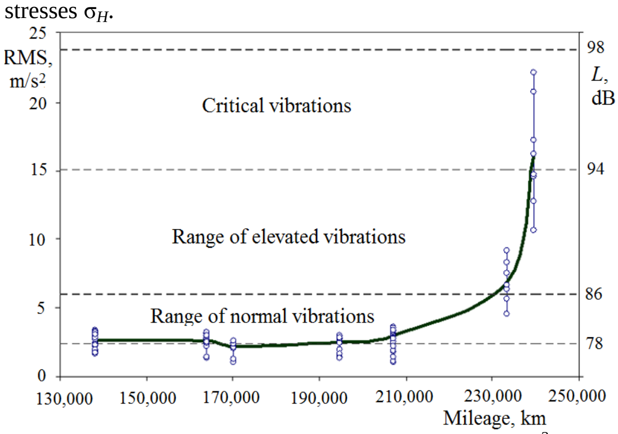


Fig. 17. *Dependence of root mean square (RMS, m/s²) values of vibration acceleration in RMW on the mileage of a dump truck (own work).*

The calculation performed for the most probable value of the load-carrying ability of the considered gears gave a result similar to the integral assessment. Residual life is equal to zero under the general dump truck mileage equal to 235,000 km (taking into account the descent movement in the opencast mine and the transportation mode).

The developed technique of dynamic analysis of gear units which based on the evaluation of vibroimpulses in gearing is universal. Unlike other known approaches, it can be used in steady-state and transient modes of transmission operation.

8 Lifetime expense

The concept of the term “consumption of lifetime” for the component is obvious, as well as the understanding of its additional term “residual life”. The assessment of the state of life for a complex object, consisting of several components and having several different SLS, is ambiguous. And besides, some components can be replaced or repaired.

To eliminate this uncertainty and evaluate this property, the term “lifetime expense” of a complex object and a new indicator are introduced. This indicator has the value of the life potential of the object and is determined as follows

$$K_A = \sum_{i=1}^{n} \xi_i K_{Pi} \qquad (5)$$

where K_{Pi} = lifetime expense of the *i*th main part of the TCI (presented as relative value); ξ_i = the weight factor that determines the contribution of the main part to the total lifetime expense of the TCI. It is proposed to consider ξ_i as the relative mass of the main part (the fraction of this part mass in the total mass of n parts that determine the TCI lifetime).

The next fundamental point is lifetime expense of the main part:

$$K_P = 1-(1-K_L)\,(1-K_T) \qquad (6)$$

where K_L = lifetime expense by lifelength (mileage, operating time); K_T = lifetime expense by time (age); K_L relates to damage processes under loads during working; K_T relates to damage processes under time (ageing processes).

The values of K_L and K_T are determined at the time of monitoring / evaluating the technical condition of the object. Usually, the processes responsible for K_L and K_T can be considered as independent. Then, K_L can be interpreted as the probability of failure in the running hours (under the influence of loads in the duty cycle), and K_T as the probability of failure in age; and K_P is the probability of failure of the main part of the object under the combined action of loads and age at the considered time.

Fig. 23 shows the graphs of KL=K_L, KT=K_T, and KP=K_P. It is estimated that 100% lifetime expense by age occurs over 30 years. The same period corresponds to 100% lifetime expense by lifelength (mileage). This case is illustrative, because in real practice, the full expenditure of the lifetime in mileage and age, as a rule, is not achieved simultaneously.

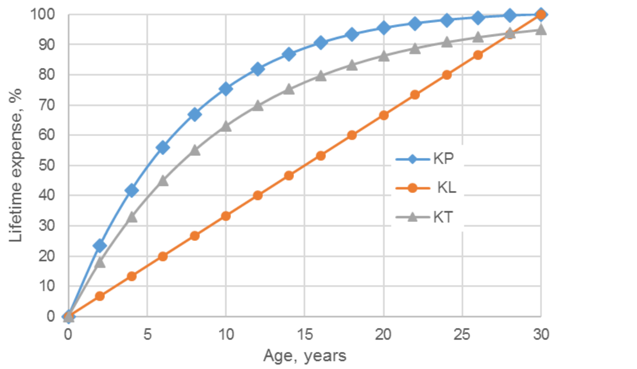


Fig. 23. *Lifetime expense KP for linear law KL and exponential KT (own work).*

9 Conclusions

The features of creating an information model of technically complicated items (as an analog and the predecessor of Digital Twin) by the example of the power transmission is presented. This model covers and coordinates a set of systemic representations, as well as models and methods for calculation and diagnostics of gear transmissions.

System representations of transmission in the area of mechanics include regular mechanical system as well as kinematic and dynamic schemes. The latter contain symbolic representations of various components with the same mathematical descriptions. This makes it possible to create universal methods and software for solving kinematic and dynamic problems based on a structural-distribution matrix that reflects the structural relationships of transmission components.

In the field of dependability, the scheme of limiting states is entered that provides a simple way to calculate reliability indicators for objects with complex logic of their limiting states.

Individualization of the transmission condition during operation provides for using a system of diagnostics based on monitoring of vibroimpulses generated by gears. This provides information for a comprehensive assessment of the transmission state, as well as internal dynamic load data for predicting the lifetime calculations of limiting components.

Individualization of the transmission condition is also based on a new concept of lifetime expense which provides a comprehensive assessment of a specific object, taking into account the lifetime expenses of its main parts from mileage and age. The weighting of each part contribution is also taken into account.

The presented models and methods are assumed as the basis for information support and calculation of the life cycle of transmissions that includes using data from diagnostic system for individual synchronization of the state of a particular transmission.

A set of representations and methods developed for transmissions can be considered as typical in a methodical sense for mechanical objects and combined objects, the basis of which are mechanical systems. Many of them are universal and can be applied to a wide range of technical items. They are implemented in practice.

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