Development of mechanism and machine mechanics in Belarus and interaction with Bulgarian scientific and engineering centers and associations
Part 1. Gear drives and power transmissions

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Abstract*: Main directions and trends of mechanism and machine mechanics developing in Belarus are considered. Results of investigations fulfilled in the Joint Institute of Mechanical Engineering and V.A. Bely Metal Polymer Research Institute of NASB, Belarusian National Technical and Belarusian-Russian Universities, as well as in Belarusian State Transport University and other Belarusian research centers are presented. Generally, these investigations are forwarded for modernization of drives of various machines and mechanisms, including mobile machines, instrument mechanisms and estimation of their operation characteristics in the frame of "Industry 4.0" conception. The paper is divided into two parts. The first part focuses on gears and powertrains. Parts of the paper contain sources of information and main publications of Belarusian scientists. Thus, the paper as a whole bears informational and bibliographic character.*

KEYWORDS*: GEAR DRIVES, TRANSMISSIONS, DYNAMICS, RELIABILITY, VIBRATION*

1. Introduction

Power transmissions contain various components (gears, bearings, shafts, friction elements, spline joints, etc.) with different conditions and types of loading, damage and limiting states. For determination of vehicle transmission loads, it is necessary to consider the dynamic model of a mobile machine including many aggregates that interact with the transmission.

Gear shifting, clutch and propulsion slips, engine disconnection and other modes and actions change the state of the dynamic system of the transmission and the machine, the composition of the working components and their loading conditions. During transient processes (starting, gear shifting, braking with the participation of the transmission), changes in the direction of the power flows passing through the transmission mechanisms, the occurrence of dynamic loads, which significantly exceed the quasi-static level, are possible.

The operating conditions of mobile machines and the driver's actions vary significantly from machine to machine, which leads to a dispersion of the load indicators of the transmission and the lifetimes of its components. In addition, there is a wide variety of structural, schematic and design solutions of the transmission, its gearboxes and other units. Because of this, the transmission of a mobile machine is one of the most methodically complex objects of technology for calculation and design. The methods of its calculation and design are of general machine-building significance and application, especially in terms of dependability calculations and dynamic calculations of multi-element loaded systems.

This Part 1 contains main scientific ideas of the Belarusian school of calculation and design of transmissions of mobile machines, the founder of which is the corresponding member of the Belarusian Academy of Sciences Igor Tsitovich (1917–1985), as well as the results of other Belarusian specialists on certain issues related to gearboxes and transmissions.

Modern results are also presented, which obtained within the framework of "Lifetime Mechanics of Machines", including the development of information models (digital twins) of transmissions.

2. Belarusian scientific school on gears and transmissions

2.1. Construction of the theory of transport and traction machines based on dynamic models of their interacting units

For the correct design of the transmission and other units of a mobile machine, it was proposed to build a new theory of transport and traction machines based on the dynamic models of their interacting units [1].

An important position of the theory is the need to form a computational dynamic model before developing a mathematical model of transmission and vehicle dynamics, as well as the possibility of creating their electronic dynamic models without constructing differential equations.

Within the framework of this theory, the interaction of the engine, transmission, suspension, brake system and other systems should be described [2, 3].

One of the theoretically significant and practically important issues is the determination of the maximum dynamic loads of the transmission.

The monographs [2], [4] provide unique information, including the parameters of the dynamic schemes of the main cars and trucks produced in the USSR, as well as methods and results of calculating the maximum dynamic loads and natural vibration frequencies of transmissions on gears (monograph [4] is dedicated to the memory of Igor Tsitovich).

The bases of the vehicle theory became essentially new approach that considers dynamic processes of the transmission and vehicle as multibody dynamics. This theory including methods of modeling of reactive links of units in dynamics models, for example, under interaction of transmission and vehicle suspension [4]. Figure 1 shows mechanical models for determining the dynamic load of the transmission. In this case, E = elastic links of the transmission, e = elastic links of the suspension, J = rotating masses of the engine, transmission, driving wheels and vehicle equivalent (J_5), m_1 = sprung mass are designated.

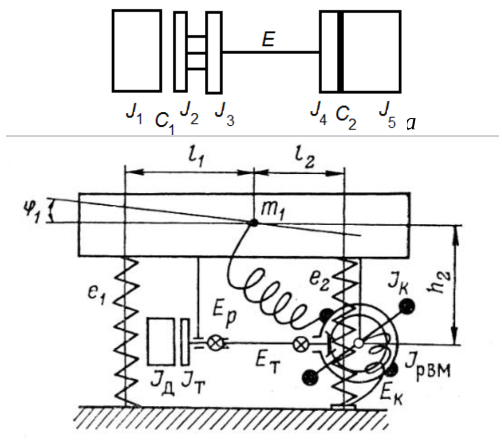

Fig. 1. *Mechanical models for determining dynamical load of transmission during vehicle starting: a = single shaft model, b = multilink model that reproduces the transmission-suspension interaction*

2.2. Statistical regularities of the load mode of vehicle transmissions

Numerous experiments have been carried out, experimental data on loading conditions have been generalized, and characteristic distributions of loads on the semi-axles of mobile machines have been obtained. Specific tractive forces (STF) were used to describe loading. Entering and analyzing STF as dimensionless parameter made it possible to establish patterns in the load modes of various types of mobile machines. Typical curves of STF for mobile machines of various classes were constructed [5].

It was shown that within the selected classes of cars, it is possible to use universal curves of STF, and in calculations for durability, one can pass from them to quasi-static loads on different parts of the vehicle (gear wheels, bearings). The dynamic components of the loads are taken into account in the calculations of parts by the coefficients of internal and external dynamic loads. As a result, a set of parameters was identified, according to which it is recommended to calculate the load mode for a general transport vehicle and its transmission [6].

2.3. Development of probabilistic calculations of machine parts

There are known proposals to use for probabilistic calculations the generalized data, obtained by "mixing" the load distribution curves for individual conditions (taking into account their shares) into a common (generalized) curve. It is shown that such proposals are wrong. The approach of the scientific school of Igor Tsitovich is that to construct a correct probabilistic calculation, it is necessary to take into account the variation of loads from machine to machine [1].

In dissertation [7] executed under the direction of Igor Tsitivich it is offered to use **average value of specific traction effort** for describing a severity (heaviness) of operation conditions. Thus the variety of operation conditions can be described by distribution of the given parameter, and every operation condition gives its load distribution curve.

In practice calculations the load distribution curve can be replaced by the calculated load and the **run factor** (mileage coefficient). This factor described the damaging effect of the load curve at a certain limit state relative to the design load. The run factors were determined for typical load curves in advance by the ratio of the average and calculated loads (P_p/P_{cp}) (Fig. 2). In this case, the variation of the load curves is reproduced in the form of the distribution of the run factor.

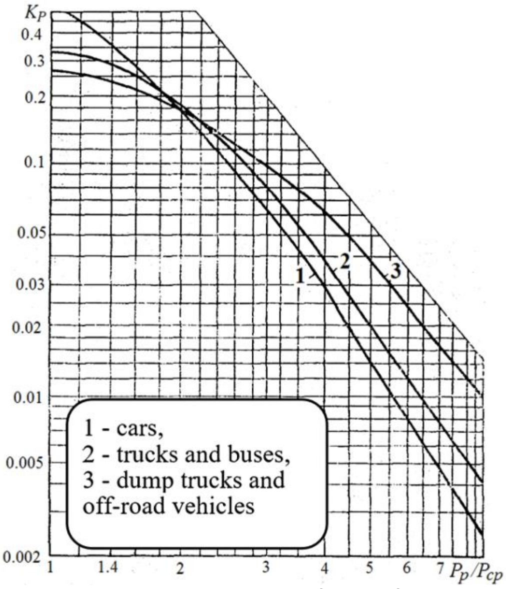

Fig. 2. *Graphs to determine the run factors for contact stresses (exponent for the fatigue curve m = 3) [8]*

This approach made it possible to bring probabilistic calculations to real computational practice. In the beginning, the deterministic calculation with use of the run factor is carried out. Then calculated measures of load-carrying ability R and extent of damage for one km q serve as reference points for construction of distributions of these parameters. Random character q is determined by a random value of the run factor, and random character of the $R = f(\sigma_r)$ is determined by a random value σ_r. This parameter is a characteristic of the load carry ability, for example, the endurance limit of a part.

The lifetime (mileage) is also a random value and is determined as

$$L = R/q \tag{1}$$

The probabilistic calculation has been brought to practical use under the assumption that the distributions of R and q are logarithmic normal distributions. This assumption is confirmed by experimental studies. Then L is also distributed according to this law. The distribution parameters L are determined by the corresponding parameters of the distributions R and q. The distribution L is used to find the reliability indicators of a machine part on the considered limiting state.

For the main parts of the transmission (gears, bearings, spline joints and others), methods of calculation for variable loads and computer calculation programs were developed [6, 8, 9].

2.4. Using probabilistic calculations in practice

The results were recognized in the USSR and abroad, were included into state standard documents of the USSR [10], [11]. In motor industry of the USSR the supervising document has been accepted for a choosing and calculating the rolling bearings [12], where loading factors are applied instead of run factors.

Until now, these approaches, described in the educational and reference literature [13], [14], [15], [16], published in the USSR, are used in the educational process and in the practice of design.

2.5 Direction "Vibration monitoring of mobile machine transmissions"

At present, improving the reliability and significantly increasing the lifetime of machines, mechanisms and equipment is not possible without the wide use of methods and tools for technical diagnostics. Solving this problem contributes to the development of a method of vibration-pulse diagnosis of gears. This method is based on the analysis of parameters of vibration impulse, synchronized with the rotation diagnosed gears, with the identification of the harmonic components of vibration impulse multiple of the tooth meshing frequency and are in the region of the resonant frequencies of the mechanism. These components stimulate the most intense vibrations, by changing the parameters which determine the technical condition of gears under variable loading-speed modes of their work. This makes it possible to create systems for on-board diagnostics and forecasting the remaining life of elements of transmission units of mobile machines in operation [17]–[19].

The results obtained are used in the creation of methodological and instrumental tools for diagnostics of drive mechanisms and transmission systems operating in various operating conditions (i.e., both in quasi-stationary modes of operation, and in conditions of variable speeds and loads), in relation to heavy-duty and specialized equipment produced by BELAZ, MZKT, etc.

3. Modern stage: Lifetime mechanics of machine

3.1. The features of the Lifetime mechanics of machines

Development of the Igor Tsitovich school (ITS) results in modern stage can be presented as a scientific direction "Lifetime mechanics of machines" (LMM). The features of the LMM and its integrating role in assessing the lifetime and functional properties of technical items are in Fig. 3 [23].

LMM integrates the approaches of strength mechanics (force, stress, damage), multibody dynamics, reliability theory, system theory, and computer technologies. The use of a computer involves more than just the use of technologies based on digitalization. It is essential to take into account the peculiarities of using a computer as a discrete computing device for simulating real analog processes of mobile machines, for example, fast-flowing processes when shifting transmission gears.

The traditional reliability theory deals with systems consisting of the depersonalized components, which are described by the set of reliability indexes. Engineering operates with stresses of machine parts, and sometimes with their lifetimes. Dependences of components which take place at mechanical level are not reproduced in the traditional theory of reliability. That leads to erroneous results in evaluating machine reliability.

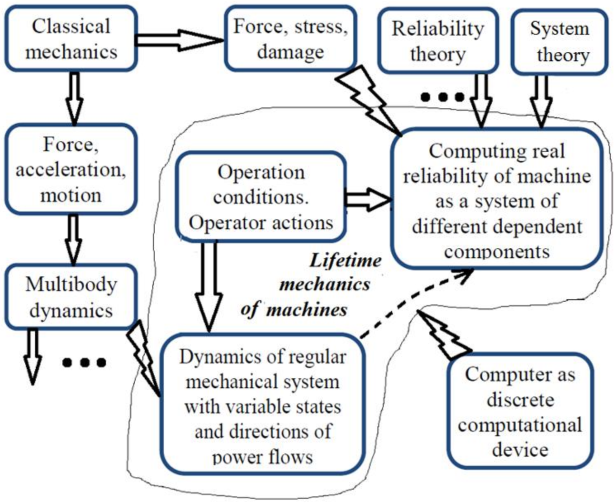

Fig. 3. *LMM and its integrating role*

LMM gives novel approaches and techniques for calculation of machine reliability, since mechanical levels and finishing by structural levels, with consideration of complicated logic of limiting states for machine components (parts, units, assemblies, and so on) and for the machine as a whole (Fig. 4) [22], [24]. The dependent behavior of elements is taken into account when calculating the real reliability of machines and other complex systems.

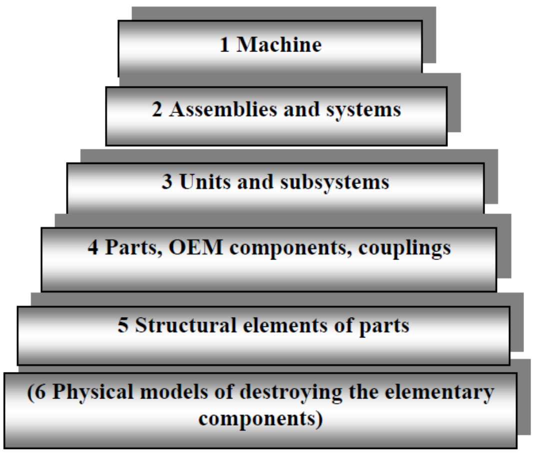

Fig. 4. *Levels of machine presentation as hierarchical system [24]*

Modern mechanical objects can change their configurations or states, for example, under the action of friction forces or external and internal factors. As result the direction of power flows in the object varies. Typical representatives of such systems are vehicle transmissions.

The important practical problem for such objects is determination of the loads acting on their elements. The object behavior (dynamics, functional properties) and its loading (damage/destruction, lifetime) are interconnected. Therefore, it makes sense to investigate problems of determination of functional and lifetime properties in a single direction "Lifetime mechanics of machines".

The ideas of ITS are reflected in a number of provisions of the LMM. Five highlights (1–5) are presented below [20], [21].

1. The need to form a computational dynamic model before the development of mathematical models of the transmission and vehicle (ITS, subsection 2.1) is reflected in the concept of a regular mechanical system, which contains the rules for constructing correct mechanical systems for simulating analog dynamic processes of a mechanical system with variable states using a computer as a discrete computing device (LMM, [22], [23]);

2. The bases of the vehicle theory including methods of modeling of reactive links of units in dynamics models, for example, under interaction of transmission and vehicle suspension (ITS, subsection 2.1, Fig. 1) are reflected in methods for *typification of translational and rotational subsystems* of vehicle, as well as in the universal mathematical models of vehicle and their components, containing the indicators of state, for clutches, brakes and other devices with variable structure (LMM, [23], [25], [26], [27]);

3. Statistical regularities of the load mode of vehicles and their transmissions (ITS, subsection 2.2) and methods of their use in practical calculations of transmissions (ITS, subsection 2.3, Fig. 2) were transformed in more general representation of operation conditions in the form of a probabilistic spectrum of relative durations of standard conditions, and were added with classification and the use of various driving styles in calculations of lifetime for mechanical components (LMM, [23, 24]);

4. Probabilistic calculations of the main transmission parts (tooth gears, bearings) on the basis of the universal loading modes and representation of lifetime calculations with use of typical laws of distribution for relative lifetime (ITS, subsection 2.3) have served as prerequisites to creation of essentially new types of calculations of real reliability of parts, assembly, units, and the vehicle as a whole on the basis of the principle of dependent behavior of elements in the loaded mechanical system (LMM, [23], [24], [28]);

5. The first State Standard of the USSR in the field of prognosis of item reliability during designing [10], guidelines by calculation of machine-building components [11], [12] and others (ITS, subsection 2.4) received a respective response in the modern State Standards of Republic of Belarus in a field of dependability of technically complicated items (TCI) (LMM [29] – [32]).

Details of historically significant data on IST and the new LMM direction are given in [20].

3.2. LMM and digitalization

Digitalization provides new opportunities for individualizing the technical condition of the product in operation. The evolution of concepts, which led to the now accepted term "Digital Twin" (DT) and its modern interpretation, is presented in the works of M. Grievez [33], [34].

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. The analysis of such publications, taking into account the topic of gears and transmissions, is given in [35], [36]. 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.

Within the framework of the RMM, the vision and understanding of the information model as a DT of a technically complex object (TSI) begins with the paper [37], that developed the idea of academic A. Ershov about the need for an information model of the machine [38]. The paper [15] 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).

The following aspects are essential:

– each part of the machine is represented as a source of information signals;

- the machine units in which it is possible and appropriate to implement the principles of reflexive control are allocated (the control object and the controlling part change functions at some point);
- procedures for identifying information sources, control objects and reflex-ive nodes are provided, their interrelationships are determined nodes are provided, then their interdependences are determined.

The information model should be designed in such a way as to 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.

Basic features. With regard to a mobile machine and its transmission, the features associated with the construction of the information model can be summarized as follows:

1) a plurality of system representations (a complex of symbolic types and models covering kinematics, dynamics, reliability, resource consumption),

2) a description and consideration in the development of the transmission of the operating environment of the machine and the operator's actions (a model of operating conditions taking into account its variability - a probabilistic representation),

3) individualization (including on the basis of diagnosing and assessing the resource consumption of a specific product).

The **new developed principles** cover [23], [35], [36]:

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

– interaction of mechanical models of materials and reliability theory;

– consideration of a transmission as a multicomponent system 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 diagram, dynamic diagram, normalized dynamic diagram, scheme of limiting states and scheme of faults.

The principles of schematization are developed for the transition from a real mechanical object to its symbolic representation using a regular mechanical system. For the universal representation, formalization and automation of equations in the field of kinematics and dynamics, a universal mapping of differentials and gears is used, which, along with the display of shafts, controls and a frame, allows the correct schematization of transmissions and gears of any kind with standard and non-standard elements. For the mathematical description of objects structures, the developed canonical matrix and structurally-distributive matrix are used.

3.3. Peculiarities of TCI state monitoring in operation

Individualization of TCI and its information model (Digital Twin) from stage "making and assemblage" is presented in Fig. 5 [39]. 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).

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. In this case, the environment model also refers to the TCI digital twin.

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 reconstruct 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 [35], [36], [39]. It is advisable to applicate together integral diagnostic models and predictive ones based on damage accumulation (Fig. 5, block "State models"). Such a "two-coordinate" approach (from two points of view) ensures a higher veracity of the individual lifetime forecast.

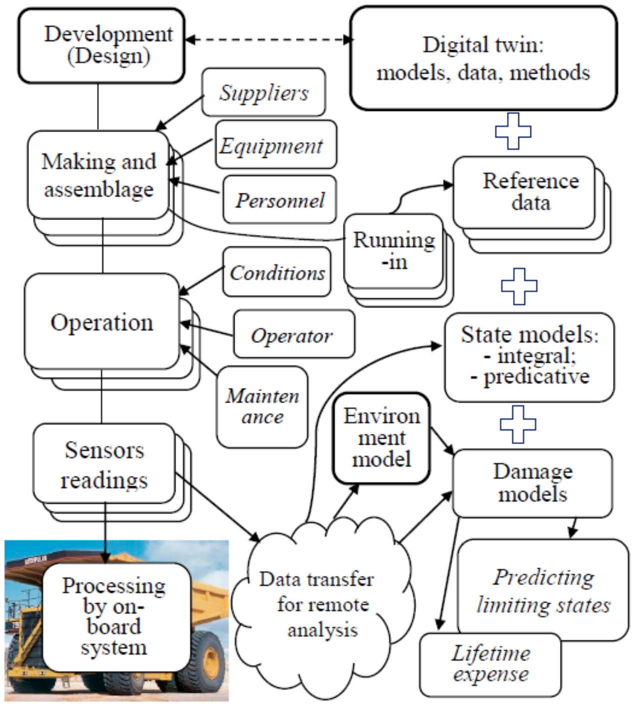

***Fig. 5.** Individualization of an item and its information model (Digital twin) from stage "making and assemblage".*

The main variable individual component of any 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 unit 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.

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 [35], [36].

An example of the implementation of the described approach is presented below. The reducer of a motor-wheel (RMW) of a mining dump truck with installed sensors is shown in Fig. 6. The main processes for the emergence, transformation and processing of signals in the RMC and its monitoring system are shown in Fig. 7. Details, concerning this approach, are in [39].

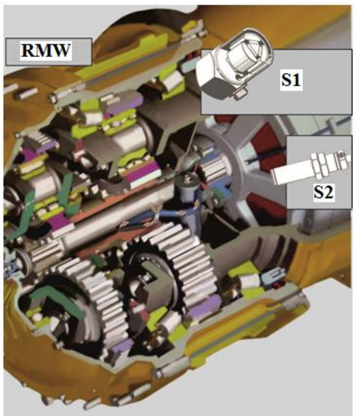

Fig. 6. *RMW with sensors*

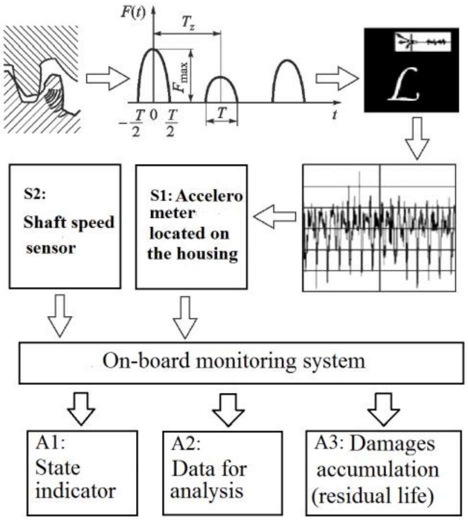

Fig. 7. *Processes in the RMW and its monitoring system*

Some of the above provisions on vibration monitoring the state of spur gears of drives of the TCI for assessment of their residual lives have been included to State Standard of Republic of Belarus [32].

3.4. New concept and method for assessment of lifetime expense of TCI

A new approach based on the concept of "lifetime expense" is proposed to personalize the state of TCI.

The concept of the term “consumption of lifetime” for the single 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, is ambiguous. And besides, some components can be replaced or repaired.

To eliminate this uncertainty and evaluate this property, the term “lifetime expense” for TCI is introduced, as well as a new indicator. This indicator has a sense of the life potential of the TCI and is determined as follows

$$K_A = \xi_1 K_{P1} + \xi_2 K_{P2} + \ldots + \xi_n K_{Pn} \qquad (2)$$

where K_{Pi} = lifetime expense of the ith 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) [36, 40].

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

$$K_P = 1 - (1 - K_L)(1 - K_T) \qquad (3)$$

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 TCI. 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 (time). Then K_P is the probability of failure of the main part of the TCI under the combined action of loads and age at the considered time.

The developed methodology is realized in the State standard of the Republic of Belarus [31].

Formulas for typical calculations of the lifetime expense of transmission and other units of mobile technics as well as examples of calculations are given in [31, 40].

Fig. 8 shows the graphs K_L, K_T, and 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; in real practice, the full expenditure of the lifetime in mileage and age, as a rule, is not simultaneously achieved.

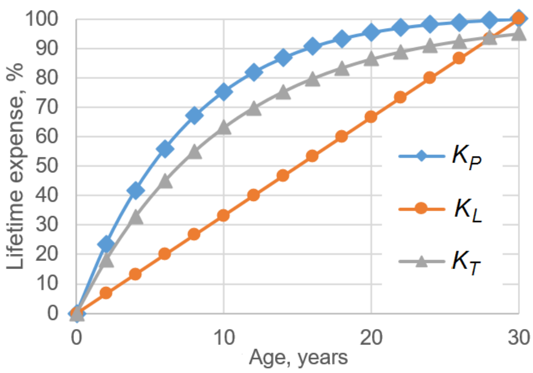

Fig. 8. *Lifetime expense K_P for linear law K_L and exponential K_T [36]*

4. Conclusions

In the development of the Belarusian scientific school, created by Corresponding Member of the Academy of Sciences of the BSSR Igor Tsitovich (1917–1985), the following periods can be distinguished: the first, initial (1960–1985), when Igor Tsitovich was directly involved in R&D; the second one (with 1985) when the LMM has been formed, and the third (informational) period connected with development of information model of the transmission as a technically complicated item.

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 have been implemented in practice. in educational, industrial and research activities.

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