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Development of mechanism and machine science in Belarus by an example of gears and gear transmissions

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Abstract. In a paper, the important original results on various topics of gears and gear transmissions are generalized and enhanced, which are described at large in the monograph ‘Gears and Transmissions in Belarus: Design, Technology, Estimation of Properties’, Minsk, 2017 (in Russian). Achievements of Byelorussian scientific schools in field of mechanical gear transmissions and polymer composite gears are presented. Technological aspects, models and methods for calculation and design of drives and their components as well as estimation of lifetime, noise and vibration characteristics are described. The complex of key issues for development, manufacturing, diagnostics and testing gears, which largely determines the competitiveness of machines and their transmissions, is considered. The activities of Belarusian scientists in IFToMM are characterised, including their contribution to identification of terminology on gears. The paper is a kind of guide on science-intensive developments of Belarusian specialists in the field under discussion.

1. Introduction

Gear transmissions contain various components (gears, bearings, shafts, friction elements, spline joints, etc.) that have different conditions and types of loading, damage and limiting states. For the correct determination of vehicle transmission loads, it is necessary to consider the dynamic model of a mobile machine with many aggregates interacting with the transmission. The operating conditions of mobile machines and the driver’s actions vary significantly from machine to machine that leads to a variation in loading the transmission and lifetimes of its components. In addition, the transmission units are distinguished by a wide variety of technical solutions. What is why, the gears and gear transmissions are among the most difficult items for calculating and designing. The methods of their calculation and design have a general machine-building significance and application.

Research topics presented in the paper are relative to lifetime mechanics of machines, evaluation of gear drive quality at the design and manufacturing processes, monitoring of transmission technical state and residual life at operation, gear fatigue and wear resistance; relationship between gear vibration, noise and lubrication, features of designing plastic and composite gears, etc.

Data about developed normative documents – standards and guidelines in the topic of prediction of item reliability during designing, dependability of technically complicated items, classification and description of gear failure modes is presented too.
Final part of paper dedicates the Belarussian scientists’ activity in the field of gearing terminology within the frame IFToMM Permanent Commission on standardization of Terminology in Mechanism and Machine Science for creating the Reference dictionary book on gearing and elaboration of normative document on gear failure modes with identification of failure notions in four IFToMM languages – English, French, German and Russian.

2. Calculation and designing gear transmissions for vehicles [1-13]

The founder of the Belarussian scientific school of calculation and designing gear transmissions for the vehicles is the Corresponding Member of Belarussian academy of sciences Igor Tsitovich (1917–1985). The main scientific ideas and results of the initial stage of the school development (1960–1985), when Igor Tsitovich directly participated in researches, and their transformation and reflection in modern stage as scientific direction ‘Lifetime mechanics of machines’ (LMM) can be presented as follows (1—5) [1].

1. Need for formation of the calculated dynamic model till development of the mathematical model of the transmission and vehicle dynamics, and possibility of creating their electronic dynamic models without formatting of differential equations (the initial stage, [2]) are reflected in concept of regular mechanical system that contains the rules for making the correct mechanical systems for modeling of analogue dynamic processes of mechanical systems with variable states by means of the computer as the discrete computational device (LMM, [3]);

2. The bases of the vehicle theory that considers dynamic processes of the transmission and vehicle as multibody dynamics became essentially new approach. This theory including methods of modeling of reactive links of units in dynamics models, for example, under interaction of transmission and vehicle suspension (the initial stage, [4]) are reflected in methods for typification of translational and rotational systems 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, [5]);

3. Statistical regularities of the load mode of vehicles and their transmissions (distributions of specific traction efforts for standard operation conditions, variation of loading modes and the way of its describing through a curve of distribution of running factor) and methods of their use in practical calculations of transmissions (the initial stage, [6]) 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, [3, 5]);

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 (the initial stage, [7]) 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, [5, 8]);

5. The first state standard of the USSR in the field of prognosis of item reliability during designing [9], guidelines by calculation of machine-building components, for example [10], and others, developed under scientific direction of Igor Tsitovich (the initial stage), received a respective response in the modern state standards of Republic of Belarus in a field of dependability of technically complicated items [11, 12] (LMM).

Historically significant data about the scientific school and new directions of LMM are given in [1]. Details, concerning development of the planetary gear transmissions, are presented in a paper for this Symposium [13].
3. Vibration activity, control and testing of gear drives

3.1. Evaluation of gear drive quality on the base of analysis of kinematics deviation [14, 15]

The interrelation between various parameters of the kinematic error and the main operational defects is theoretically established. This is relevant for the solution of the inverse problem, that is, the diagnosis based on kinematic control data. The impact velocity, the magnitude of which can be quantified from the kinematic control data, is proposed as a new criterion for estimating the smoothness of the gear train. Experimental studies have confirmed the relationship of this parameter with the vibrational activity and the effectiveness of its application in assessing the quality of gears.

The kinematic characteristics of gear drives under operational conditions are determined not only by the geometric parameters of transmission components, but also by parametric characteristics and dynamic phenomena. Therefore, the kinematic control serves as another additional effective tool for controlling the gears, which makes it possible to evaluate the torsional oscillations of the transmission.

The ability to isolate from the general information the most important and informative data is of significant practical importance.

Perfection of the design and technology for manufacturing gears with the combined use of kinematic and vibroacoustic parameters allows to take into account the peculiarities of teeth engagement as much as possible and to minimize the dynamic phenomena that arise during operation.

3.2. Gear vibration, noise and lubrication [16,17]

The lubricating film thickness (LFT) in the gearing significantly depends on the dynamic processes of the teeth interaction, as well as the own and forced oscillations of the drive. The LFT is more affected by the noise of the gear transmission, and by vibrations to a lesser extent. The speed and load modes of the gear operation as well as the presence of resonance zones of oscillations are important factors. Variation in the LFT are in many cases more informative than changes of noise and vibration.

This is advisable to take into account when we develop the systems for monitoring the manufacture and assembly quality, as well as the residual lifetime to operation. The most effective way includes a comprehensive assessment of the quality of manufacturing and mechanical drive monitoring systems based on analysis of the parameters of noise, vibrations and LFT.

3.3. Monitoring of technical state and residual life of mobile vehicle transmissions at the manufacturing, assembly and operation [18, 19]

The technique of dynamic analysis of gear units, which based on the evaluation of shock pulses in gearing, is developed. It allows to allocate from the oscillatory process the components corresponding to a certain defect of a particular gear train, and then to evaluate its technical state.

The problem solution is based on the fact that shock pulses generate vibratory processes in the gears in the initial phase of the teeth engagement, due to their deformation, errors in the manufacturing and assembling the gears. With the development of damages in the teeth, a variation of the amplitude and energy as well as shape of the shock pulse change is taken place, that leads to a change in the vibration characteristics of the gears. As a result of experimental studies, correlation dependencies between these parameters were established. On this basis, a methodology has been developed for estimating the residual life of gears for drive mechanisms and transmission systems of mobile machines that is based on the results of their vibration monitoring.

The developed technique allows to conduct vibration monitoring and diagnostics of drive gears during operation and to transfer from a preventive maintenance system to servicing them by their actual state, significantly reducing the time and costs of repairing.

Some details, concerning monitoring and diagnostics by example for planetary reducer of a motor-wheel of a mining dump truck are presented in a paper for this Symposium [13].
4. Provision of gear quality at the design and manufacture processes

4.1. Designing and assessment of loading for gears of the planetary gear sets [20]
The use of classical methods for estimating the loading of gears, assuming that their axes remain unchanged, can give significant errors in estimating the loading of planetary gears. The noted problem becomes especially urgent for large-sized planetary gears with a tooth module of 5-12 mm and a diameter of crown gears up to 1000 mm, and for assignment of technical requirements and accuracy standards for responsible gears.

One of the key factors in ensuring the required lifetimes of planetary gears is to take into account the changes in the positions of the gears of the planetary gears under operating conditions of loading. It is shown that in order to estimate the accuracy of the planetary gear assembly, traditional indicators of contact standards are not enough.

Taking into account the peculiarities of loading planetary gears, the requirements for material selection, heat treatment and designation of the accuracy standards for sun, crown gears and satellites are formulated. Taking into account the design features of these components, the calculated dependences for determining the parameters of the longitudinal and profile modification of the teeth are proposed.

When using gear grinding of gears, a special tooth shape is suggested, which provides the maximum radius of the tooth cavity and, accordingly, an increase of the bending resistance.

4.2. Provision of demands to fatigue resistance of surface-reinforced gears [21, 22]
The regularities of fatigue resistance, depending on contact stresses, micro-hardness and structural components in the subsurface hazardous zone of the strengthened layer are established. In this zone, origination and development of the fatigue processes take place that leads to the limiting state of the gear wheels. Fatigue characteristics and performance criteria of hardened teeth material are revealed.

It is shown that durability for the gears of transmissions of energy-saturated machines is determined by the deep contact dyeing of the active surfaces of the teeth. The deep contact fatigue of the hardened gears depends on micro-hardness of the local volumes of the subsurface layers of the teeth, as well as on the structural components that are not usually detected by conventional metallographic methods. As a result of experimental studies, the dependence of the bounded limit of the deep contact resistance of the tooth material on the micro-hardness and structural characteristics of the hardened layer was obtained. The proposed technique allows, according to the results of surface hardening, to choose the steel grade for gears, depending on their module and the cooling capacity of quenching units of thermal equipment. This significantly reduces the laboriousness of resource tests when choosing the material of the gears.

4.3. Technological gear quality provision [23, 24]
Using statistical methods, a relationship was established between the error rates for the base surfaces of part blanks of cylindrical gears and the accuracy of gears during their cutting and shaving. The proposed methods for the formation of technological processes ensure the required quality of manufacturing gears, taking into account the processing modes in various operations.

5. Plastic and polymer composite gears

5.1. Results of plastic gear investigations.
The main results in theory and engineering applications of plastic gears are as follows.

1) The gear drives with new original unequally divided basic rack tooth profiles of Wildhaber-Novikov gears with sub-pole and trans-sub-pole meshing was elaborated providing more high load bearing (about by factor of 1.5÷1.6) than gear drives with involute meshing [25, 26].

2) Original structural design of plastic gears, reinforced with metallic armature; gears with polymeric intermediate layers between hob and geared ring applied in different branches of industry: tractor, mechanical-rubber, chemical, textile and others ones [27, 28].
3) Original calculation technique for designing plastic gear female dies providing gear high accuracy through the calculation of three mold shrinkage components (gear and gear mold die tip diameters, base diameters and angular thickness on the base circle) [29].

4) Unique technique (with automation version) allowing to manufacture high accuracy injection molded plastic gears on the base of elementary double measurements of base tangent length at the different number of enclosed teeth or double pin measurements at the different pin dimensions [30].

5) Technique of computer analysis, including plastic gear projecting and checking calculation with execution of input and output data: initial data, tolerances, meshing animation, determined pinion and gear wheel geometrical parameters, monitored parameters, meshing quality control, validity testing computation of measuring dimensions, drawing data and shrinkage values for the pinion and gear wheel, geometrical parameters for pinion and gear calculation and manufacturing [31]. Information, concerning peculiarities of automated designing plastic gear drives any can find in the paper at present Symposium [32].

6) The results of evaluation of plastic gears wear resistance and integrating data of plastic gear friction and wear resistance, generalized in the review [33].

7) Derivation of analytical dependence for optimization of coaxial multistage gear unit with plastic gear clusters mounted in doable parallel axles [34].

8) The results of plastic gears application in different branches of industry: magneto and control drives in the starting motor; plastic derailleur pinions of rubber-braiding machine for manufacturing braided tubes; plastic gears in domestic appliance drives; fine-pitch plastic gears in instrument mechanism drives; motor pinions of loom drive and others [35].

5.2. **Study of stress-strain state of dispersion-filled polymer composite gears.**

To important scientific results of world novelty one can be related the effective two-level method [36, 37] for predicting wear resistance and strength of disperse-filled composite gears. The method allows us to calculate stress-strain state, compliance, strength and wear of such gears aimed to optimal choice of material structure according with the requirements for the gearing without geometrical corrections of wheels. Effectiveness of the method is determined of rational combination of analytical micromechanical theory and advanced numerical techniques of machine parts strength analysis based on finite element approximation and corresponding software. It is suitable to describe the important deformational features of essentially physically non-linear and heterogeneous polymer composites and to calculate parameters of stress-strain state of gear wheels of complex geometry.

Benefits of the method are evidenced as possibility to make computer design namely to optimize material composition, elastic properties of polymeric matrix, form and dimensions of reinforcing and other functional filler particles as well as parameters of interfacial layer between matrix and filler according to the deformational, strength and tribological criteria [38-40]. For details refer [41]. Developed two-level (micro- and macromechanical) calculation method for predicting wear resistance and strength of disperse-filled plastic gears corresponds to modern conception of end-to-end design of machine parts made of heterogeneous structural materials.

6. **Contribution of Belarusian scientists in gearing terminology evaluation**

6.1. **Development of gearing terminology in the frame of IFToMM PC A.**

The settled gearing terminology in the primary IFToMM issues [42, 43] contains 22 terms with definitions, distributed on different chapters. In accordance with IFToMM decision to enlarge the TMM notion to it interpretation as MMS one [44] the new divisions (7-13), including as a Chapter 12 “Gearing” separate division, have been turned on IFToMM terminology, originally in English-language -alphabetical-order version [45]. At the 23-rd IFToMM PC A Working Meeting (2010, Minsk/Gomel, Belarus) the Chapter 12 new thematic structure of 6 subdivisions has been confirmed. Hereafter it was included in IFToMM electronic dictionary [46].
6.2. Reference-dictionary book on gearing.
The start for the first issue of Reference-dictionary book on gearing was given by the paper [47]. In the subsequent issues, the volume of terminological information gradually extends: 68 pages (2002), 90 (2004), 112 (2005), 190 (2008), and 220 (2011). In the last issue, the reference-dictionary book contains about 900 terms. The following divisions in the form of tables, pictures and drawings are presented (terms quantity are in brackets): Geometrical and Kinematic Parameters and Elements of Gears and Gear Pairs. Terms and Symbols (115). Principal subscripts and signs (27); Extraction from Electronic dictionary ‘IFToMM Terminology for Mechanism and Machine Science’ Chapter 12. Gearing (226); Spiroid Gears (79); Facial toothed joints and gearings (37); Accuracy and inspection of gearing (172); Calculation of bending strength, pitting resistance, scuffing and service life of gears (130); Calculation of Scuffing Load Capacity of Gears (118); Forms and location of tooth contact pattern (118); Gear failure modes (83); Classification of the Gear Drives, including Gear Pairs with Parallel, Crossing and Skew Axes (about 70 terms with definitions in shape of initial bodies and its relative arrangements, tooth and profile shape etc.) [48, 49].

6.3. Notion identification on gear failure modes. Creation of state standard
Identification of the terms in gear failure modes was provided with exhaustive normative sources [50-54]. Above 200 gear failure modes have been analyzed [55]. A basic contain of the standard was published in [56, 57]. Official issue of the standard [58] was in 2009. The standard includes a list of terms for durability, interchangeability, metal corrosion, friction, wear and lubrication, calculation methods of gear drives on strength and scuffing, classification of metal fracture modes. There is a corresponding table of gear failure mode classification with different levels (classes), general failure modes, sub-modes, degree of failure. All together, the description of 76 gear failure modes are given, and 104 standard photo-examples are shown, as well as possible reasons of their appearance and recommendations for failure prevention. For details refer [59].

7. Conclusion
Developments of the Belarusian school of calculation and design of transmissions are of general engineering importance, they have prospects for development and application in various scientific and technical fields. The developed methods take into account the features of complicated mechanical items of modern mobile machines, such as the variety of design solutions, the variability of operational conditions and operator actions, the probabilistic nature of loading processes, the dependent behavior of components under the action of common loading factors. This allows us to assess the real reliability of machines and their units, combining mechanical models and models of structural dependability within the framework of unified calculation procedures. Dynamic calculations of the transmission using the concept of a regular mechanical system make it possible to correctly take into account features of the transmission as a system with variable structure, variable directions of power flows, and also take into account the features of modeling real analog processes using a computer as a discrete-based computing device. These methods and approaches developed within the framework of lifetime mechanics of machines are methodologically superior to other known approaches and solutions. The main features of the transmission diagnostic method developed are the model 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 transmission system. This provides advanced capabilities, including analysis of unstable regimes, use of an integral state indicator and calculation of damage accumulation in limiting components. Thus, the developed complex of transmission models and methods of transmission calculation is an information model (digital twin), which allows to simulate and predict the behavior of the transmission during its life cycle, including prediction of individual reliability in operation. This fully corresponds to Industry 4.0 concept.

Some presented methods are included in state standards and used for development and exploitation of technically complicated items of enterprises of Belarus.
Presented in the paper postulates cover the key problems of creating gears and gear transmissions, demonstrate effective ways of their solution and designate the perspective directions of mechanical drive science development.

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