50 years in the theory and practice of gearing

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Abstract. The author's life line has been traced from the investigation of various exotic gears to design and manufacture of gear-boxes for the main drive of rolling mills.

The end of the 50-ies of the last century was marked by two outstanding events in the formation of the Russian school of the theory of gearing. First, in 1959, for the development of gears with a new system of meshing, M.L. Novikov was posthumously awarded the Lenin Prize, which led to an explosion of public interest in the gears in the country. Secondly, in 1960 prof. F.L. Litvin published his monograph "Theory of Gearing", which marked the release of this theory in a separate scientific discipline.

At this time, the author of the proposed notes had already experience of two years of work as a fitter and planer, and studied at the Faculty of Mechanics at the Novocherkassk Polytechnic Institute. In the oldest high school in the south of Russia he was lucky to communicate with many talented teachers and students. Actively visiting the scientific library, he got acquainted with the books of the above authors. And this acquaintance determined his entire further scientific destiny. In third year of study he developed a system of trochoidal gearing. Like all the numerous attempts of those years to combine the merits of involute and Novikov gears, this study was of no special interest, but it allowed the author for mastering the mathematical apparatus necessary in the future.

Since 1964, fixing the knowledge gained in the Institute, the author worked as a teacher and mastered gear cutting machines in the metal cutting laboratory of the Electrostatl technical college. At the same time, studying the literature, he chose a close-minded scientific supervisor. He had a rich choice. During these years of Sturm und Drang a whole galaxy of brilliant researchers built an analytic theory of gearing, collaborating and competing with each other. Along with F.L. Litvin the patriarchs of our science N.I. Kolchin and V.A. Gavrilenko actively worked. N.N. Krylov and L.V. Korostelev recently defended their doctoral theses. Ya.S. Davydov, K.M. Pismanik, G.I. Sheveleva, M.L. Yerikhov, I.I. Dusev, E.B. Vulgakov, and M.G. Segal already began to create their own scientific schools.

In 1967, the author entered postgraduate studies at the Moscow Machine Tool Institute of the young Professor of the ToMM LV Korostelev. Professor belonged to that rare, Kepler, type of scientists who had a lucky ability to comprehend in some inspiration the scientific truth in the last instance as if at once. For a new post-graduate student, he proposed such a paradoxical idea.

As is known, in the higher kinematic pair the active surfaces can geometrically contact only at a point or along a line. The surface contact, to which one should strive to increase the carrying capacity of the transmission, is in principle unattainable. However, nobody prohibits the instantaneous contact line from being a closed curve and, moreover, to contract during the meshing. Playing the role of the
third body, the lubricant jammed inside the closed contour must distribute the pressure throughout the entire area of the oil pocket and, being squeezed out of it, provide fluid friction between the active surfaces [1].

The post-graduate student appreciated the idea and was intensively involved in its development for three years. Using Dupin’s indicatrices, he identified those general conditions under which the characteristic of the envelope surface becomes a closed, smooth or broken curve [2]. He showed that these conditions can most easily be realized in the extra-centrode worm gears with an oval or close to it convex axial profile of a cylindrical worm [3]. He formulated very specific criteria for the bearing capacity of a new type of gear, such as the closed pocket area or consumption of extruded lubricant, and selected the profile parameters that satisfy them. He designed, manufactured and tested the first gear of this kind. Starting from the equations of classical hydrodynamics, he studied the conditions for the appearance of a lubricating layer between active surfaces and found out that its thickness is an order larger magnitude than in conventional gears [4, 5].

![Figure 1. Worm gears with closed contact lines. Meshing area in section by wheel mean plane and projections of instantaneous contact lines on the plane perpendicular to worm axis.](image)

In 1970, as a result of this work, the author defended his PhD thesis. Then he continued theoretical and experimental studies of such gears together with A.V. Verhovsky. These studies showed that in order to achieve the effect of fluid friction in a real worm gear, it had either to be made to the 4th degree of accuracy or to undergo a prolonged (about 150 hours) run-in under a gradually increasing load [6]. Therefore, when in 1980 the author went to work on the heavy machinery plant and saw that he could not realize such conditions on this plant, he stopped working in this direction. But in itself this idea remains attractive, and at a new technological level it can be realized by someone. So in order not to get it lost in old journals, the authors summarized the results of their research in the paper [7].

From 1971 to 1979, the author worked as a senior researcher at the department that he graduated. During these years, in collaboration with S.A. Baltadzi, G.A. Ivanov, P.D. Balakin and others, accepting and developing ideas of L.V. Korostelev, he performed a number of interesting works in theory. For the geometric analysis of orthogonal gears with cylindrical worms of an arbitrary profile he proposed the method of the analogy with a plane rack gearing, which made it possible to simplify this study and in particular to solve the problem to prevent undercutting of the teeth [8], defined the specific slip, pressure angles and efficiency on the meshing axis of cylindrical worm gears [9, 10] and found analogs of the axes of meshing in worm gears of general type [11]. He put his hand to the synthesis of worm gears with two meshing zones [12], eccentric and wave "screw-and-nut" drives [13] and gears insensitive to the mutual position of the wheel axes [14, 15]. Applying the methods of screw calculus to the synthesis of gears with screw motion of the wheels, showed that in this case the
screw of the absolute motion of the generating wheel should belong to a linear combination of screws of the gear wheel motions, and extended the concept of the screw generating wheel to cases of non-rigid and incongruent generating pairs [16, 17].

The results of these studies were generalized and deepened in the paper [18], where the author had introduced into scientific circulation the concept of a meshing space as a physical space constructed on the wheel axes of the synthesized gears. In this space each point has its own complex of rays of the relative motion screw. Considering each of these rays as a potential contact-normal and connecting them by vector equations with wheel speeds, he distinguished in this space different iso-surfaces - the geometric places of points at which the gears will possess certain properties: a given pressure angle, a specific slip, etc. Such surfaces may be used as well as the boundaries of the area of gears existence and the potential surfaces of action. Later, using the concept of the meshing space, the author performed a synthesis of worm gears of a general type [19, 20] and found equivalent settings-up for cutting of spiral bevel gears [21].

In Stankin period the author was also involved into applied researches. Among them the most effective was the work to improve the production of globoid gears made with L.I. Sagin and B.F. Fedotov (TSNIITMASH) at the Donetsk and Odessa machinery plants. In particular, the proposed method for calculating the setting up of machine tools in production of globoid hobs allowed, instead of combating with the organic errors of sharpening and relieving, to use them for the purposeful localization of the contact [22]. The same approach was used together with A.I. Sandler in the development of technology for multi-thread worm gears for the Moscow plants of gear-grinding and coordinate-boring machines [23] and in the further work of the authors.

Since March 1980, the author moved to work at the Electrostal Heavy Machinery Works (EZTM). The plant in those years was specializing in the individual production of pipe mills and metallurgical machines, for the drive of which special reducers and gear stands were needed [24, 25]. Annually the reducer shop manufactured up to 2000 such reducers of 150-200 different sizes from 9 kg to 80 tons in weight and cut about 6000 helical, spiral bevel and worm gears. The design of these gears, as well as the supervision of their manufacture, became the main responsibility of the senior researcher of the Reducer Engineering Bureau.
In this bureau unique combined gearboxes of the main drive for many large objects were designed. Among them, aggregates for the production of seamless pipes in Slatin (Romania), Pervouralsk and Chelyabinsk, the section mill of the plant “Electrostal”, the bar-type mill 700 for Nigeria, the ball rolling mills for Gurievsk and Bekabad, Mexico and India, the ring rolling mill for Timken (USA).

In the post-Soviet period, the demands of domestic metallurgists and, together with them, the volume of products manufactured by EZTM fell significantly. However, in recent years we continue to produce quite interesting gearboxes for rolling equipment. Among them, a reducer type C2-715 with an output torque of 450 kNm for the main drive of cold rolling mills for pipes with the diameter 350 mm, delivered to the USA, China and Iran. For the piercing mill 450 of Seversky Pipe Plant, a two-stage herring-bone reducer CD-1600 was designed with 77 tons weight, 6 MW power and 1300 kNm torque, provided that it should be operating reliably for 7 years [26].

The gearboxes created at EZTM are also working in the drives of crushers for titanium sponge and rocking machines for oil wells in many countries around the world. The constant production is apron feeders for the mining industry, and the third generation of bevel-cylindrical reducers for their drive had been put into production by 2012 [27]. In recent years, many efforts have been made to the replacement of reducers and open gears for cement kilns and mills [28]. Increase in the power of the drives required increasing the load capacity of the gear couplings and spindles by improving the tooth geometry [29].

Over the years of work, the author has calculated and launched over 6,000 gears of various types, including a multitude of spur, helical and herring-bone, several hundreds spiral bevel gears, dozens of worm and globoid, as well as 5-10 hypoid, spiroid and crossed-axis helical ones. In order to optimize the parameters of gears and a gearbox as a whole, taking into account the technological and economic

![Figure 3. Combined gear box for drive of vertical stand of the section rolling mill.](image-url)
factors, each of the pairs, as a rule, was calculated in several variants. When designing complex gearboxes, with branched power flow, the seventh option was usually twice as light as the first one.

Geometric optimization was an effective means of reducing the specific material consumption of reducers. So, with the modernization of the range of 216 standard sizes of two- and three-stage reducers, the methodical alignment of the output torques allowed by the contact and bending endurance of each stage has made it possible to increase their load capacity by 20-40% [30].

Naturally, all this amount of work could not be done manually. And the first priority was the development of computer-aided design programs. To solve it, the author actively used his scientific connections. At his request and with his participation TSNITMASH developed programs of geometric and strength calculation of the main types of gears first for large and then for personal computers. In 1998 these programs were combined into a package of calculation of helical, bevel and planetary gearboxes REDUK4.3, which is still used daily in the work of the Design Bureau.

The software package EXPERT, developed in Stankin by A.E. Volkov and V.I. Medvedev, has very effectively proved itself for the technological synthesis of spiral bevel gears. For EZTM it was brought to the issuance of maps for setting up each of our gear-cutting and grinding machines [31]. In this package, setting-ups were made for the cutting of more than 300 bevel pairs without the use of trial pinions.

Professor of IzhSTU V.I. Goldfarb was involved into the design of spiroid reducers with the software package SPDIAL developed under his guidance.

With the advent of personal computers, the author began to write independently the necessary programs of nonstandard calculations. In the software package MathCAD, he wrote programs for calculating the geometry and strength of W-N gears, the geometry of the modified couplings, the kinematics and geometry of helical gears with a variable center distance and helical-worm gears with screw motion of the links, as well as for the profiling of disk and finger cutters for cutting coarse wheels and screws of extruders for plastic processing.

In the 90s, an integrated system of technological preparation of gear-cutting production was developed in the SuperCalc spreadsheets [32]. The system included checking the possibility of manufacturing three types of gears on the existing equipment, choosing a route for mechanical and thermal processing, machine tools, tools and cutting modes, printing out operating charts and calculating labor intensity. Unfortunately, together with SuperCalc, this system became outdated hopelessly.

In 2005, two young engineers came to the Reducer Bureau and successfully continued the work in this direction. V.V. Akimov did a great job of improving the spiral bevel gears [33, 34] but after defending his Ph.D. thesis, to our regret, he left the plant. E.A. Gudov became the leading designer and without interrupting the execution of working projects of different gearboxes he developed two programs of geometric, strength and technological design - DUPLEX for cylindrical worm gears, including duplex gears, and GLOBE for modified globoid gears.

For all the diversity of interests, the worm gears of the general type remain the favorite subject of the author's research [35-43]. This concept combines orthogonal and non-orthogonal gears with cylindrical worms of various types, classic and modified globoid gears, spiroid gears with conical and cylindrical worms. As the main elements in the synthesis of such gears, in addition to the working worm and wheel, the generating worm is considered, as well as those tools with which the working and generating worms are profiled. Putting the five listed elements into the meshing space, we compose a system of four vector equations connecting the position of the common normal at the calculated point with the vectors of relative velocities. In a brief and clear form, that is invariant to a coordinate system, this mathematical model describes the necessary and sufficient conditions for conjugation of active surfaces. And these conditions turned out to be less stringent than the usual requirement of tangency for the screw lines of the active and generating surfaces, so the possibilities of synthesis of gears expand.
Directly from this model the formulas are obtained, in particular, for the settings of gear-hobbing and worm-grinding machines for localizing contact in a given area of the tooth surface of the wheel by using hobs having the increased diameter in relation to the worm. In itself, this idea is well known and was developed in detail by F.L. Litvin and other authors. But in all previous works it was silently assumed that the worm and the hob must have equal normal and, consequently, unequal axial pitches. It makes to adjust the worm-grinding machine to a non-standard, irrational value of the axial module and is not accepted by practice. In work [37] it was shown how, by varying the profile angles of the worm thread and the hob teeth, their axial modules can be selected from the standard series as equal or adjacent to each other. Therefore, this method is easily implemented on existing equipment using standard worm hobs and is actively used in the plant practice.

From the same model, the conditions were obtained for the conjugacy between Archimedes worm and an involute helical wheel cut by a standard hob. Such transmissions are used in mechanisms for adjusting the size of rolled products to convert the screw motion of the pressure screw into rotation of the sensor shaft. For a gapless Duplex gears with a worm having a variable thickness of the turn, the conditions for cutting the wheel with a standard worm hob are found. The transmissions of the listed types allow for minimizing the amount of gaps in the kinematic chain of the mechanism and, thereby, increasing the accuracy of rolled products [39].

![Figure 4. Duplex worm gears and setting-up for cutting of the wheel with standard worm hob.](image)

![Figure 5. Globoid worm gears and setting-up for modification of the worm by a-u method.](image)

The functional influence of the direction of tooth modification on the work of various gears is considered. In gears with ruled cylindrical worms, the contact lines are extended along the wheel tooth, so the profile modification smoothes the edge impacts that occur when the teeth are reconnected due to pitch errors, and the longitudinal modification preserving the instantaneous gear ratio, prevents the bearing contact from emerging on the lateral edges of the tooth, i.e. reduces the gear sensitivity to assembly errors. In the globoid gears, on the contrary, the contact lines make up an angle close to the straight one with the tooth line, so the profile modification mainly compensates the negative effect of the assembly errors, and the longitudinal one compensates the pitch errors. The author took into account these considerations when he participated in the development of State standard GOST 16502-83 on the accuracy of globoid gears.
The results of the synthesis of gears with the localized contact turned out to be especially in demand in the new economic environment. Firstly, in the conditions of aging of gear cutting machines, tool wear and the inevitable decrease in their accuracy, only the deliberate localization of the contact reduces the sensitivity of gears to manufacturing errors and allows keeping the quality of the produced gears at a sufficiently high level. Secondly, in search of new customers the plant was forced to master new types of products and to undertake the production of spare parts for extraneous equipment. These circumstances made it necessary to expand sharply the nomenclature of worm gears that are accepted for manufacturing. The proposed methods of synthesis made it possible to find, practically for each of them, the possibility of cutting the wheel with a worm hob from the available series, and thus solve the problem of expanding the range of products without expanding the range of tools.

The results of the theoretical investigation of worm gears of general type and the experience of their practical application are summarized in two monographs [38, 43] published in co-authorship with A.I. Sandler.

A separate line in the biography of the author is the work by the invitation of Professor F.L. Litvin at the Laboratory of Gears of the University of Chicago in the 1996-97 school year. For most of this year, the guest was engaged in the synthesis of helical gears, which would combine the high contact strength of Wildhaber-Novikov gears, with reduced sensitivity to errors and low vibration activity. It has been shown that such gears can be generated by a pair of incongruent racks with a parabolic profile at a longitudinal modification of the tooth surfaces. Computer modeling of the form and behavior of the bearing contact in the proposed gears and the comparison with the results of the study of involute and W-N gears confirmed the success of achieving the goal [44]. The proposed solution was protected by US patent [45].

In the course of this research, in particular, the question arose about preventing the teeth undercutting by a generating rack of an arbitrary profile. The author solved it quite simply, proceeding from the fact that the limiting point on the line of action is the one in which the velocity vector of the cut wheel touches this line. F.L. Litvin approved such an alternative to his own approach to finding singular points, put in the strict math form and extended to a wide class of plane and spatial gearing [46].

New impressions and communion with the ageless founder of the theory of gearing contributed to an increase in the creative tone of the hero of this essay. After his return from Chicago, he published a series of papers in which he tried to combine the early results of scientific research with the experience of his work in industry and show how quite specific formulas for the engineering design of gears, tools and machine settings follow from systems of highly abstract vector equations. When speaking at international conferences and publishing papers in foreign journals, he tried to convey the methods and results of his research to a foreign-language audience [47-51].

In recent years the author, paying tribute to his teachers and contemporaries, has prepared together with D.T. Babichev and N.A. Barmina essays on the history of the creation of the Russian school of the theory of gearing [52-54].

**Question** from the resume form: "Were you abroad, and if "yes", then why did you come back?"

**Answer:** "If we want Russia to remain a civilized country capable of providing citizens with basic living conditions, then someone must design and cut those gears, without which those rolling mills cannot be turned, on which the pipes are made, in which our apartments are supplied with gas and water."
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