Chapter 1
Russian School of the Theory and Geometry of Gearing. Part 2. Development of the Classical Theory of Gearing and Establishment of the Theory of Real Gearing in 1976–2000

Dmitry T. Babichev, Sergey A. Lagutin and Natalya A. Barmina

Abstract Authors of this paper initiated the work on Review of the Russian school in the theory and geometry of gearing in the second half of the 20th century. The Review comprise the analysis of the carried out works with an application of tables that allow to obviously see who of the experts published their papers with the date and the theme of these publications. Essays are provided for the experts who contributed most into the development of the theory of gearing. Part 1 of the Review under name "Origin of the theory of gearing and its golden period 1935–1975" has been published in 2016. The presented part 2 considers about 230 publications in Russian and 30 publications in English made by the Russian gear experts in the period 1976–2000. The important feature of this period is that gear design and production techniques started to be regarded as the united complex issue which requires the agreed solution of many interrelated tasks. Note here, that, publication reviews usually indicate which problems have been solved in the cited references, but they do not comprise the methods for their solution; the original source should be addressed for this purpose. In order to facilitate this point for the readers, especially beginners in the theory of gearing (students, engineers, post-graduates), we supplemented the review with the statement of methods for the solution of the most important issues.

D. T. Babichev
Tyumen Industrial University, Volodarskogo Str. 38, 62500, Tyumen, Russia
e-mail: babichevdt@rambler.ru

S. A. Lagutin
Electrostal Heavy Engineering Works, JSC, 144000, Krasnaya Str. 19, Electrostal city, Russia
e-mail: lagutin@eztm.ru

N. A. Barmina (✉)
Institute of Mechanics, Kalashnikov Izhevsk State Technical University, Studencheskaya Str. 7, 426069, Izhevsk, Russia
e-mail: barmina-nat@mail.ru

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1.1 Introduction

During the second half of the 20th century, Soviet scientists were among the world leaders in the gear geometry and applied theory, that are the theoretical fundamentals of designing gears and gear-cutting tools.

The authors of the current paper have considered works related to the development of the theory of gearing (TG) published in Russia from the mid-1930s to the present. Overall, the review covers more than 400 publications of nearly 200 authors (among more than 1000 studied works).

The first part of this review was published under name "Russian school of the theory and geometry of gearing: Its origin and golden period (1935–1975)" in J. Front. Mech. Eng. Higher Education Press and Springer-Verlag Berlin Heidelberg, 2016, 11(1), pp. 44–59. Having examined 165 publications of more than 70 researchers, the authors talked about the authoritative scientific schools that emerged and worked actively during this period in Leningrad, Moscow, Saratov, Novocherkassk, Gorky, Kurgan, Izhevsk. The main scientific and practical achievements of these schools were considered. Among them:

- the kinematic, matrix and other methods of analysis and synthesis of gearing,
- the technological synthesis of spiral bevel and hypoid gears.
- the mastering of new types of gears, including the W-N gears, globoid and spiroid gears etc.

The present, second part relates on development of Russian school of the theory of gearing in 1976–2000 years. This period has a number of features provided by historical reasons. First, the USSR industry revealed the first obvious symptoms of stagnation at the late 1970s. Second, the number of post-graduates decreased, since universities generally solved the problem of teaching stuff that was urgent in the early 1960s because of the abrupt increase of the number of engineer students.

However, within these hard 15–20 years preceding the USSR breakup, certain old scientific schools continued functioning in the Soviet Union and new centers developing the theory and practice of gearing arose.

The list of publication involves the most profound works of the leading scientists and the most original works of less famous experts with the advanced ideas and results. To make this review interesting for a wide audience, it involves a certain number of works on designing tools, on gear strength and accuracy.

1.2 Review of Works Published in Russian in 1976–2000

By the mid 1970s the theory of gearing as an individual science has reached its completeness: basic and priority problems of gearing analysis and synthesis have been solved. The number of novel theoretical works has declined. The structure of scientific theses has been mainly unified: construction of design formulas for a specific gearing → algorithmization → computer-aided analysis → production → experiment → implementation certificates. Investigations came closer to the production; and the theory of gearing became, first of all, the tooling for solving specific engineering problems.

The main results of the review of works dated the last quarter of the 20th century [1–227] are introduced in two tables. The table in Fig. 1.1 represents 5 groups including 26 scientific problems that comprised the main results of theoretical investigations. The table in Fig. 1.2 enumerates 30 types of gears, mechanisms and their parts, and also 3 areas of activity that implement the practical results of works in 1976–2000.

Each of the tables contains: (a) names of the solved problems (investigated objects, spheres of their application), (b) family names of main authors who solved these problems (with indication of the work number in the reference list and publication date), (c) connection lines that relate the authors and their solved problems. Family names of the authors who contributed most to the theory of gearing (to our opinion) and the most essential works are highlighted in bold in the tables. The tables allow for tracking:

- themes that are considered to be the most popular and important at that time;
- researchers working on the theme of your interest;
- issues considered by the researchers and the scope of the subject matter for each of them.

The tables cover both directions of development of the theory of gearing: "*world-wide*"—IGD, and "*Russian*"—theory of real gearing. Features of the "*Russian*" direction is mainly considered. As far as the "*world-wide*" direction is concerned, it comprises the following technique for solving the problems of analysis and synthesis for in Russia and abroad:

- methods of the classical theory of gearing (at computer-aided design of geometry of any type of gears);
- non-differential methods of analysis of gear generating processes when implementing both versatile and special applied software,
- numerical methods of optimization (at synthesis of geometry of tooth operating flanks and transient surfaces);
- the expanded list of quality features of gearing which includes the criteria for assessing the terms of oil wedge generation and other;
- methods of boundary and finite elements at analysis of contact interaction of work surfaces and of the tooth deformation mode;

Let us consider the features of the "*Russian*" approach in four paragraphs:

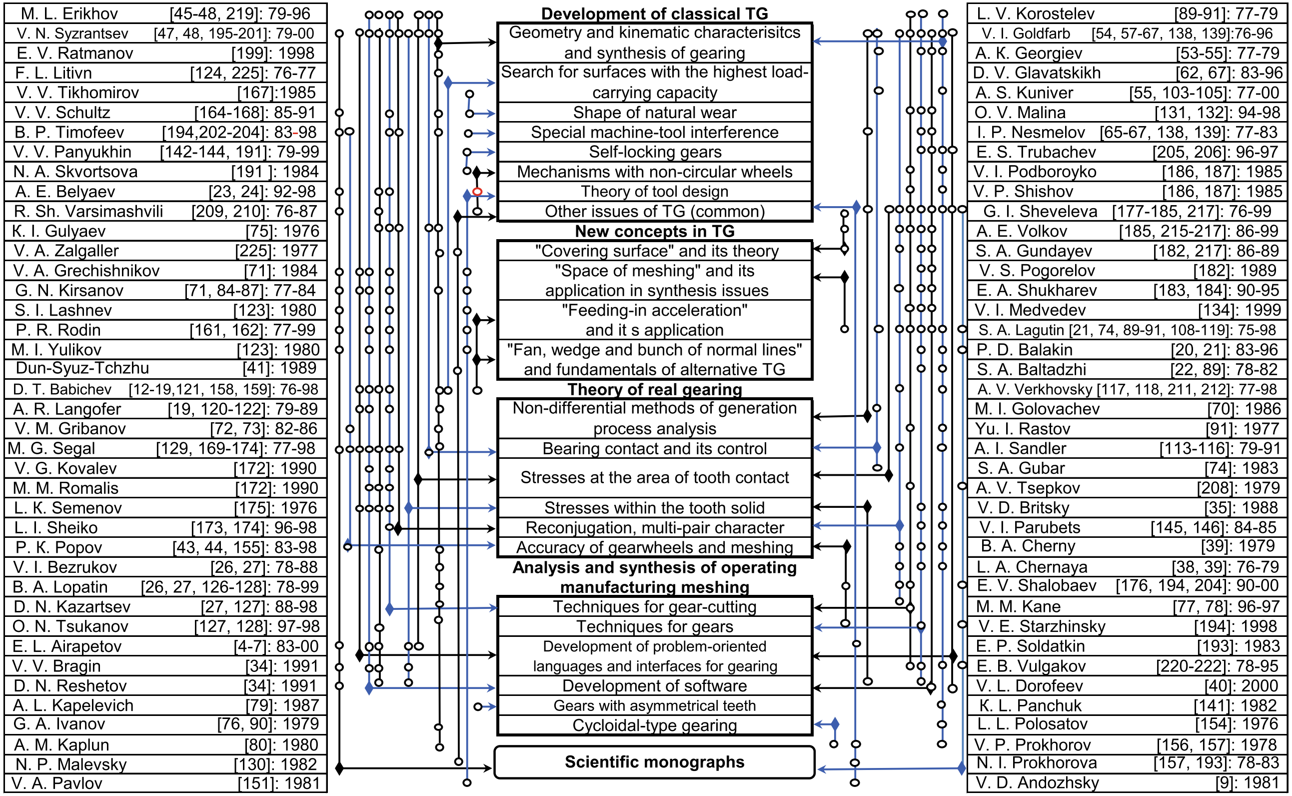

Fig. 1.1 Theoretical developments in the period 1976–2000

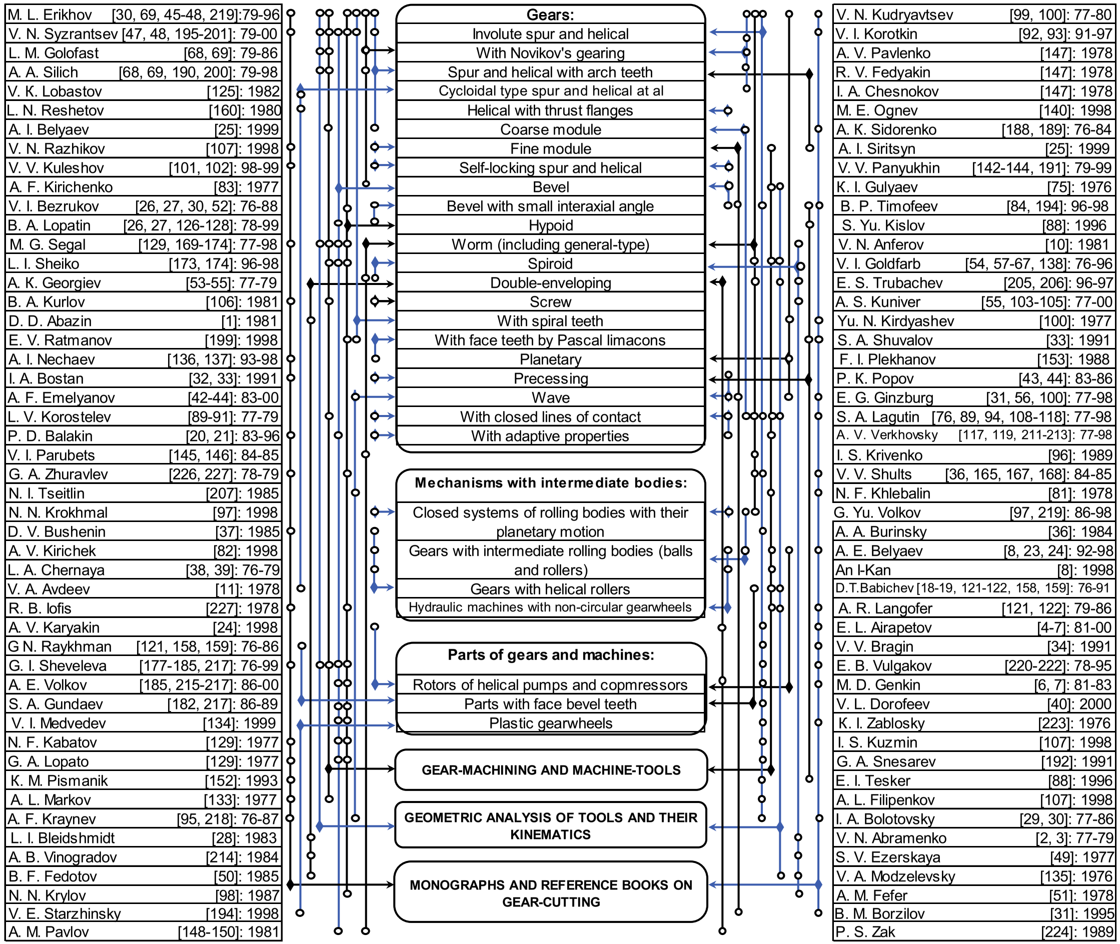

Fig. 1.2 Practical results in the period 1976–2000

2.1. new geometric concepts in the theory of gearing;
2.2. development of methods of optimization synthesis;
2.3. development of methods of generating process analysis;
2.4. software: features of development and implementation.

1.2.1 New Geometric and Geometry and Kinematic Concepts

The crucial contribution to the development of the theory of gearing after 1970s was the introduction and application of new concepts:
(1) *covering surface* (Sheveleva [180]); (2) *fan, wedge, bunch of normal lines* (Babichev [14]); (3) *feeding-in acceleration* [121]; (4) *space of meshing* (Lagutin [108]); Let us consider these innovations.

1.2.1.1 Enveloping and Covering Surfaces

In the theory of surface generation by moving solids two following types of the *obtained surfaces* should be distinguished: undulated covering line Σ_1 and smooth enveloping line Σ_2—see Fig. 1.3.

The covering surface Σ_1 is the set of a discrete family of fragments of basic tool surfaces (BTS); the enveloping surface Σ_2 is the surface contacting all elements of this discrete set. The enveloping surface Σ_2 is usually a smooth surface, while the covering surface Σ_1 is always the faceted surface. The concept "covering" was proposed by G. I. Sheveleva and effectively applied at study of bevel and hypoid gears [180]. Note, that the term "*covering*" is not perfect when translated into English. In practice it means a real, wavy or rough surface.

The surface Σ_2 is usually determined as the enveloping for one- or two-parametric family of generating surfaces. The covering surface Σ_1 is determined by direct tracking of the position of points of the generating surface Σ_0 with respect to the blank; it is the method of *direct digital modeling* (DDM) sometimes called the "*method of direct enveloping*". Methods of DDM are more reliable than kinematic ones, so it is preferable to determine the covering surface Σ_1 rather than the enveloping surface

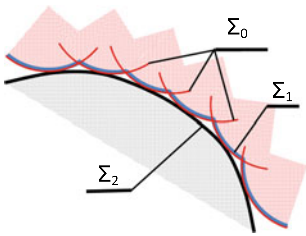

Fig. 1.3 Covering Σ_1 and enveloping surface Σ_2 of the generating surface Σ_0

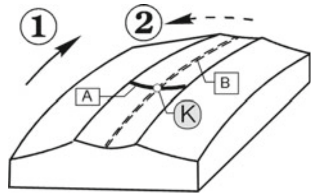

Fig. 1.4 The band type of roughnesses

Σ_2 in many CAD and CAE systems. Although, in order to determine Σ_1 it is required to perform hundreds of calculations more than for Σ_2.

Note, that covering surfaces $\Sigma_1$can consist of stripes (bands), for instance, at line grinding of teeth—see Fig. 1.4, each of the "bands" is the surface obtained by enveloping process (line A is the contact line at one-parametric enveloping). Each stripe is contacting the two-parametric Σ_2 enveloping surface along the line (this line passes along the stripe). When the feed is reduced, the "bands" become narrower. When the feed value tends to zero, the generated surface will be approaching the enveloping surface of a family of "bands". It will be exactly the surface Σ_2 generated by *two-parametric enveloping by the surface* Σ_0.

The covering Σ_1 can consist of individual "flakes", for example, when cutting the gearwheels by module hobs or diagonal gear grinding. Figure 1.5 shows the deviations of the flake covering surface Σ_1 from the enveloping Σ_2. "Flakes" are contacting with Σ_2 at the centre of the flake. The shape of "flakes" is in general case hexagonal that can degenerate into parallelogram.

The curvature of band and flake covering surfaces Σ_1 crucially and essentially differs from the curvature of the enveloping surface Σ_2. Thus, the radius of curvature for the involute is smoothly increasing from its base circle. And the radius of curvature for the covering surface generated by the rectilinear rack is $\rho = \infty$ at all points (and at jogs it is $\rho = 0$), since the covering profile is the broken line contacting the involute by each of its rectilinear segments.

Using of the concept of the covering surface instead of the enveloping one creates a number of difficulties when solving the contact problem by numerical methods: errors of strains and contact stress analysis increase, boundaries of instant contact areas lose their smoothness. The common means of "approaching" the covering surface with the enveloping one is the issue of small feeds at computer-aided modeling of the generating process. It reduces the roughness of the surface obtained at modeling and

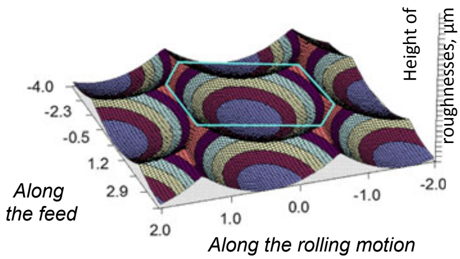

Fig. 1.5 The shape of roughness is hexagonal "flakes"

decreases the errors at solving the contact problem. But it does not solve the problem of analysis of the enveloping curvature, since the curvature of the covering surface does not depend on the feed value.

1.2.1.2 Jogs on Tooth Profiles and Flanks

Jogs (lines of surface intersection or points of profile intersection) are present practically on all gear parts and tools. The concept of jogs as of specific features of generating surfaces comes from Rodin [161]. He wrote: «the surface of a part consisting of a number of adjacent areas can be *considered as a single surface*. The point of jog of the profile located at the boundary of adjacent areas can be considered as an arc of a circumference with the radius tending to zero». Figure 1.6 (left) shows three possible types of jogs which give rise to three types of normal lines families: a fan (at intersection of two profiles), a wedge (at intersection of two surfaces) and a bunch (at intersection of three surfaces). Figure 1.6 (right) specifies, why the point B at the jog of the rack is the contacting one, that is, it lies on the generated transient curve of the tooth fillet; and the point C does not belong to the transient curve. The reason is that one of the normals of the fan at the point B passes through the pitch point, while there is no such a normal line at the fan of the jog C. Note, that the classic theory of gearing does not answer the question why the point B is the contact one and the point C is not. Terms "fan, wedge, bunch" have been later replaced by terms "sector, prism, pyramid" – see chap. 6 by Babichev and Barmina in this book.

Figure 1.7 shows that the jog and its adjacent segments of surfaces are the *single surface with the continuous curvilinear coordinate v*. In this figure: **1** is **v**-line; **2** are brushes of normal lines; **3** is fan of normal lines; $\mathbf{n_A}$, $\mathbf{n_B}$ are main unit vectors.

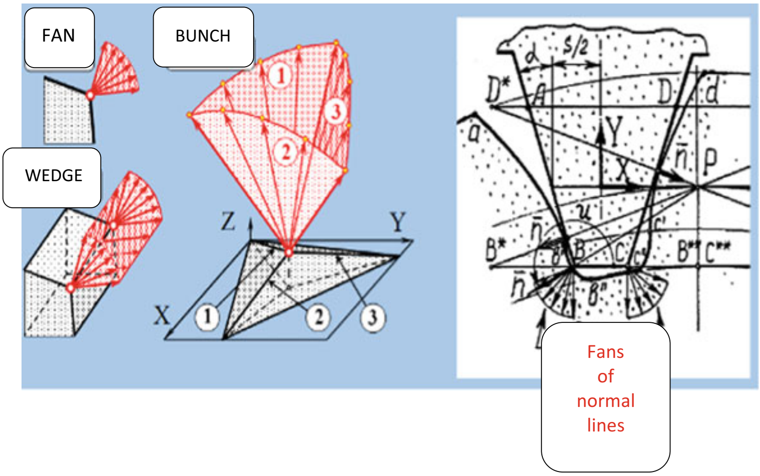

Fig. 1.6 Types of jogs and contact at the point B

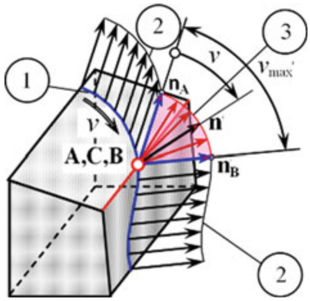

Fig. 1.7 Parameters of the edge jog: 1—v-line; 2—brushes of normal lines; 3—fan of normal lines; $\mathbf{n_A}$, $\mathbf{n_B}$—main unit vectors of the fan of normal lines

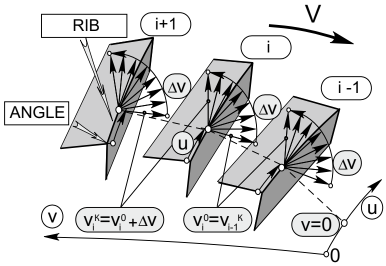

Fig. 1.8 Curvilinear coordinates on the real BTS for hobs and broaches

Publications [12–19] are devoted to the development of the kinematic method for investigation of generating processes with higher reliability as compared to the classic method. It applies both jogs and curvilinear coordinates that are single for the whole tooth or the gear rim (and even along the whole BTS for all edge tools: hobs, mills, broaches, shavers [13]—see Fig. 1.8).

Figure 1.8 shows several neighboring teeth of the edge tool with pointing the curvilinear coordinates *u* (along the cutting edge) and *v* (across it). The coordinate *v* is related here with the tooth number *i*.

From physical point of view, the real BTS is the set of cutting edges with adjoining front and back planes (surfaces). From mathematical point of view, the real BTS is the smooth surface with two continuous curvilinear coordinates on it.

For the real BTS we should know all information related to the geometry that influences the generating and cutting processes. Computational models for such tools are to be found in [17].

Summary: jogs are the useful means when analyzing the generation processes.

1.2.1.3 Feeding-in Parameters of the Generating Surface to the Solid of the Generated Part: Velocities and Acceleration of Feeding-in, etc.

One of the main issues of the theory of gearing is to determine the tooth surface Σ_2 of the second element when knowing the tooth surface Σ_1 of the first element.

When solving this problem one should consider the motion of the **surface** of the *first element* solid in the coordinate system of the second one, that is, in the three-dimensional space of the *second element* (Cartesian). It is logical to assume that the motion parameters of **the solid 1 surface** in the **space of the solid 2** should be used. However, in classical theory of gearing there is no common system of concepts and characteristics specifying the interaction of the **solid surface with the space**. And in order to describe this interaction the parameters are used that specify the spatial motion of only the *solid as the set of points* rather than the *solid limited by the surface*. In order to eliminate the misunderstanding of the essence of the said above, let us explain the difference of any point A of the solid from the point K lying on surface Σ_1 of this solid. At the point K there is the normal line to the solid surface Σ_1 (and the tangent surface and curvature parameters), while at the point A (inside the solid) there is nothing similar to it. For the generation process of the solid surface Σ_2 of the second element it is important to know the motion in space of the second element of points of the surface Σ_1 projected on its normal **N** at these points. V. A. Shishkov paid attention on it at the end of 1940s, proposed the *local parameter of interaction of the solid surface with the space* and called it the "velocity of feeding-in". It is obtained as the scalar product:

$$V_{\mathrm{N}} = \mathbf{V}_{12} \cdot \mathbf{n} = V_{12x} \cdot n_x + V_{12y} \cdot n_y + V_{12z} \cdot n_z \tag{1.1}$$

where **n** is the unit vector of the normal **N** directed outwards from the solid 1, $\mathbf{V}_{12}$ is the vector of the relative velocity at this point: $\mathbf{V}_{12} = \mathbf{V}_1 - \mathbf{V}_2$.

Velocity V_N is also called the velocity of mutual approach (for $V_N > 0$) and removal (for $V_N < 0$). If $V_N = 0$, surfaces Σ_1 and Σ_2 are contacting at this time instant and at this point. V_N is the important but not the only parameter of feeding-in motion. Other parameters should be considered: acceleration of feeding-in a_N, as the first time derivative of the velocity V_N; and its higher time derivatives.

Applying V_N and a_N, it became possible to develop the generalized method of study of load for cutting edges of a wide range of enveloping gear cutting tools (hobs and grinding wheels) for rough and final machining. It also became possible to implement this method by the software that allowed for investigating the operation of a large group of different types of tools [120–122].

Let us show examples of investigations carried out by means of this software.

Figure 1.9 shows the example of investigating the cutting process for arch teeth of cylindrical gears by spiral disk mills proposed by M. L. Erikhov. On the left in this figure the cutting scheme is shown; on the right the boundaries of the cutting zone and thickness of the layers to be cut (in mm when the mill is fed along its axis S = 1 mm/rev) are shown. Parameters of the machine-tool meshing are: z = 20, $m = 5$, mill radius $r_m = 100$ mm, the number of racks (chaser) k = 8, the ratio of angular velocities of the mill ω_1 and the blank ω_2 is equal to $i_{12} = \omega_1/\omega_2 = z$.

Results of computer-aided modeling of spiral disk mills operation show that:

(1) two teeth of each three-teeth chaser are constantly participating in cutting;
(2) the most loaded teeth are the middle teeth of all chasers;

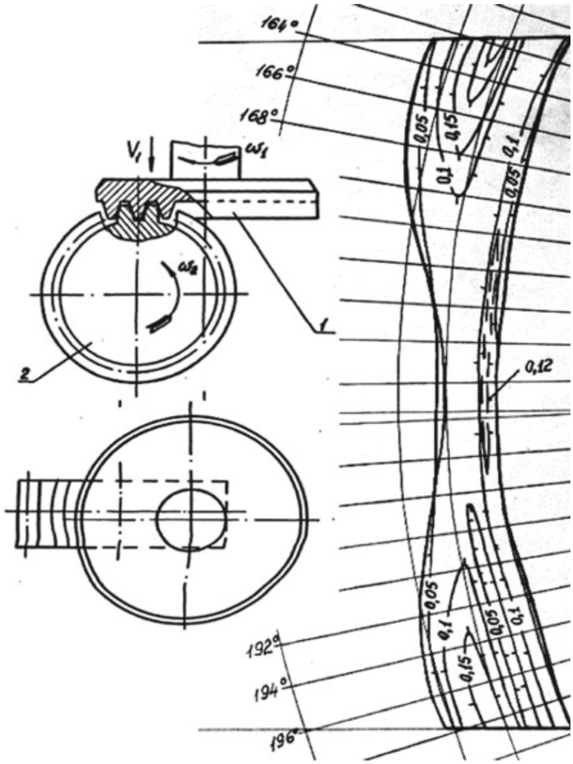

Fig. 1.9 Scheme for cutting arch teeth and boundaries of the cut layer on the developed view of the cutting edge trace

(3) outer cutting edges of all chasers practically do not participate in operation;
(4) the maximum thickness of the cut is at the top edge of the fifth rack, it is $S_{max} = 0.35$ mm since the cutting start;
(5) the maximum thickness S_{max} of the cut layers in the course of the tool cutting-in is transmitted from the top and the transient segments to the lateral ones;
(6) the double increase in the radius r_m of the tool widens the cutting layer by 8%, but it practically does not influence the value of S_{max};
(7) the decrease in the number of chasers doubles the value of S_{max};
(8) the double decrease in the radial feed decreases the value of S_{max} in two times with simultaneous narrowing the cut by 30%.

Figure 1.10 shows the cutting scheme and cutting zone for face bevel teeth which applied as half-couplings in systems of control and as gearwheels in wave gears.

Flanks of face bevel teeth are the enveloping lines of a two-parametric family of lines (cutting edges of the disk hob in Fig. 1.10). These surfaces were investigated by Ya. S. Davydov, V. I. Bezrukov, L. Ya. Liburkin; their works are described in the first part of our review. But only in [158, 159] the problem was solved for determining the curvature radii of surfaces generated by two-parametric motion of the generating line. The difficulty of this problem solution is that the surface circumscribed by the

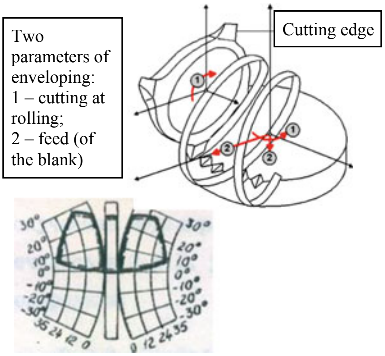

Fig. 1.10 Scheme for cutting the face bevel teeth and boundaries of cutting zones: dotted line—computer-aided analysis; solid lines—wax model experiment

cutting edge when running-in 1 (Fig. 1.10) is the "spiral surface on the bagel". And the spiral pitch is decreased when the tool is approaching the axis of the blank rotation due to the feed motion. That is, the tooth surface on the item is the envelope of the single-parametric family of a "spiral surface on the bagel" *deformed* at motion (due to feed 2).

Further in Figs. 1.11, 1.12, and 1.13 the investigation results for cutting the spur involute gears by shaping cutters are shown. Note, that Figs. 1.11 and 1.12 are

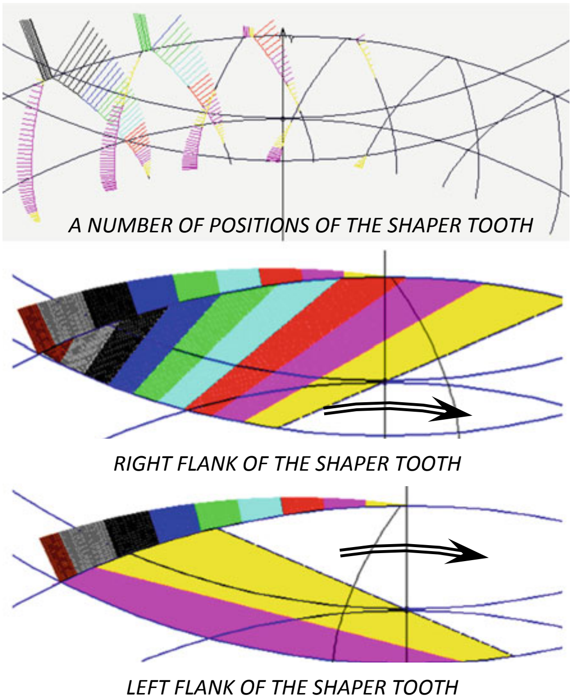

Fig. 1.11 Thicknesses of layers cut by the involute shaper with $z_0 = 20, x_0 = 0.5$ when cutting the gearwheels with $z_1 = 20$ and $x_1 = 0$

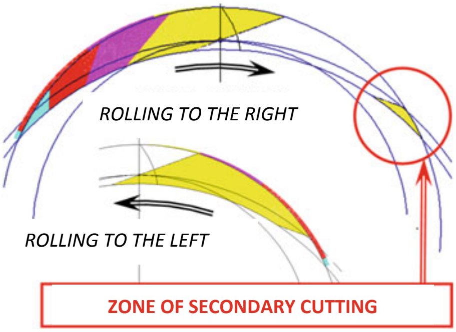

Fig. 1.12 Cutting zones at machining of the gearwheel with internal teeth with $z_1 = 30$ and $x_1 = 0.5$ by the shaper with $z_0 = 20$ and $x_0 = 0.5$

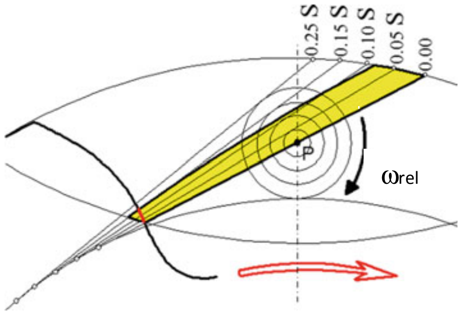

Fig. 1.13 Cutting zone and lines of equal thicknesses of cut layers for the finishing pass of the involute shaper

based on the concept of the feeding-in velocity (as by V. A. Shishkov). The role of the feeding-in acceleration a_N is lower: to increase the computational accuracy for thicknesses of cuts and the boundaries of cutting zones (including the zones of secondary cutting) when analyzing the finishing passes of the tool.

In planar meshing the following theorem allows for assessing the load of the tool:

Theorem If the point of the tool profile is in the machining allowance, then the tool load is proportional to the moment developed by the normal line to the profile with respect to the pitch point (Fig. 1.13).

Figure 1.13 shows the example of the finishing gear shaping of the involute gearwheel. The cutting zone with the variable width is stretched along the meshing line (as the "oasis" along one river bank). When the direction of running-in is changed, the cutting zone ("oasis") is transmitted to the other side of the meshing line ("river") scarcely changing its width.

The velocity V of the material removal by abrasives and the thickness S of the cut layer are:

$$V = (\omega_0 - \omega_1) \cdot R_\Sigma$$

$$S = S_0 \cdot R_\Sigma \cdot \left| \frac{\omega_0 - \omega_1}{V_P} \right|$$

where ω_0 and ω_1 are angular velocities of running-in motion for the tool and blank ($\omega > 0$ when rotating counterclockwise); R is the arm of the normal line to the tool profile with respect to the pitch point P; V_P is the circumferential velocity at centroids; S_0 is the circumferential feed per lead.

Note: The point at the tool is work loaded if the profile normal line *coming out of the tool solid* creates the moment directed along the relative angular velocity $\omega_0 - \omega_1$ with respect to pitch point P.

In accordance with the theorem, it is seen in Fig. 1.13 that the maximum thickness of the cut is $S = 0.15 \cdot S_0$ (at the beginning of the tool operation).

When determining the thickness of the cut layers, it is rather difficult to find the boundaries of cutting zones, especially at finish gear machining. Acceleration of the cutting-in allowed for solving this problem (though approximately) even for such a complex process as gear hobbing by generating method. These issues are studied in details in the thesis by Langofer [120].

The issues considered above in p. 2.1.3 and shown in Figs. 1.9, 1.10, 1.11, 1.12, and 1.13 reveal only one of possible direction of applying the concepts of cutting-in parameters (velocity, acceleration and higher derivatives) for analysis of tool loading. But application of the concept "acceleration of cutting-in" simplifies the solution of other important problems of gear geometry. For instance, when $a_N > 0$, the envelope is formed inside the solid of the generating element which is physically impossible. When determining Σ_2, the value a_N allows for simultaneously determining the radii of curvature and micro-roughness height along the whole surface formed by generating for the band-type and flaky shapes of roughnesses—see Fig. 1.4 above.

By means of the concept of the feeding-in acceleration the new formula has been obtained to analyze the reduced curvature at any normal section at the point of contact of two moving solids that are contacting along the line:

$$\frac{1}{R_\Sigma} = -\frac{\omega_W^2}{a_N}$$

where ω_W is the angular velocity of solids rolling on the plane of the section where the curvature is analyzed; The fundamental nature of this formula means that according to its generality it is commensurate with the known in geometry Rodrigues and Frenet formulas, but it is intended for surfaces developed in the process of their forming by generating methods.

1.2.1.4 Space of Meshing

This concept was introduced to the scientific circulation by Lagutin [108]. The term implies the physical space obtained at axes of gearwheels of the synthesized gear, each point of the space possessing its set of beams of the screw of relative motion (Fig. 1.14). By considering each of these beams as the probable contact normal and relating it to velocities of elements by vector equations, different isosurfaces can

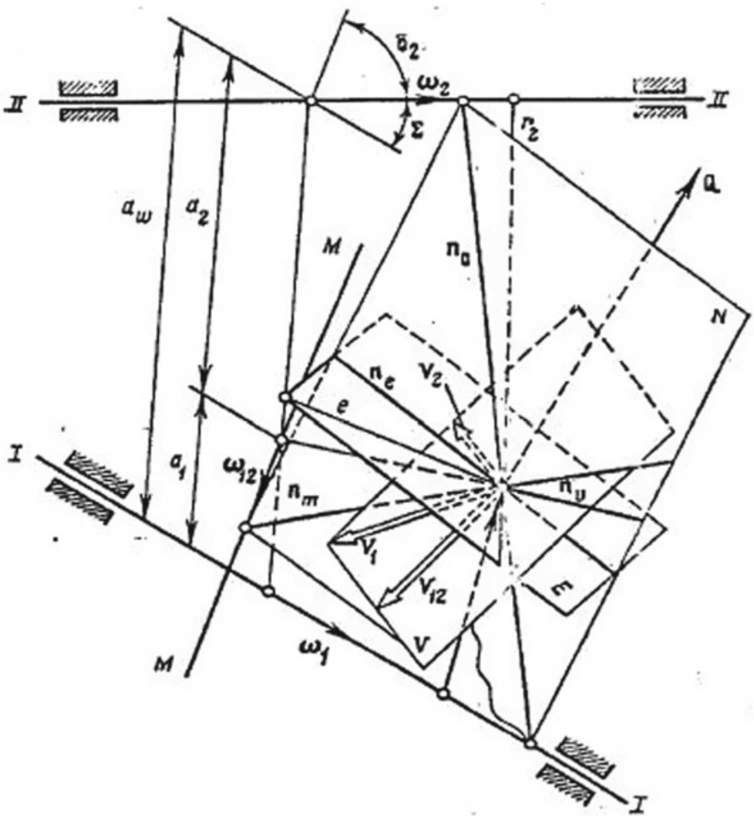

Fig. 1.14 Point and plane of contact normal lines in the space of meshing

be singled out of this space, that is, the geometric loci for points at which the gear will possess specific properties: the assigned pressure angle, specific sliding etc. S. A. Lagutin proposed to apply such isosurfaces as boundaries of the area of gear existence and as potential surfaces of meshing.

Publication [108] enriches and makes more profound the investigation results on synthesis of gears with helical motion of elements [91], on determining analogs of meshing axes in general-type worm gears [89], on gear synthesis by method of loci [90] that were obtained together with L. V. Korostelev and his followers.

Later, the author performed the synthesis of general-type worm gears by means of the meshing space [110, 119] and was looking for equivalent settings for cutting bevel gears with circular teeth. We suppose that the significance of the analysis of meshing space at gear synthesis will be increased in time.

1.2.2 Development of Methods for Synthesis and Optimization of Gearing

The priority practical problem of gear design is to determine tooth profiles or surfaces that provide the maximum load carrying capacity of a gear. Figure 1.15 presents the basic methods for increasing the load carrying capacity of gearing (by example of spur and helical gears). This figure systemizes the methods based on advancement of tooth geometry. The left column (blocks 1–4) represents the ways of increasing the tooth bending strength, that is, procedures of changing the tooth shape aimed at decreasing the stresses inside teeth and, first of all, at the tooth dedendum.

The central column in Fig. 1.15 (blocks 5–8) presents the methods for synthesis of tooth flanks that provide the least contact stresses and thereby the increased lifetime of teeth.

The right column (blocks 9–12) includes the ways of correction and modification of profiles (both for the synthesized and the existing gears, first of all, for the involute ones). Here the word "correction" means the agreed variation of conjugate segments on the pinion and gearwheel at once (block 9), for example, in order to decrease the contact stresses by increasing the reduced radii of curvature in the danger zone.

"Modification" is the deviation of one of the conjugate segments of profiles (usually on the addendum) from mutual enveloping in order to redistribute the forces at multi-pair contact or within the areas of reconjugation (with account of tooth deformation under load). Modification also decreases the forces of tooth impact at the initial moment of tooth contact, thus decreasing the vibration activity of the meshing which is vital for heavy-loaded high-speed gears. The following procedures are distinguished at modification: simple flanking (block 10), when the curve is assigned (segment of the straight line, circumference arc, etc.) on the profile of the generating rack or on the tooth; and complex flanking (block 11), when the profile is synthesized on the modified segment. Such flanking simultaneously eliminates the edge tooth contact at the initial (final) stage of their contact; and it gives the smooth load increase on teeth coming into contact (and the smooth load decrease for teeth coming out of the contact) etc.

The complexity of the problem in blocks 7–9 is that tooth deformations depend on the value of the torque T, that is why, optimal values and the shape of modification lines and flanking are various for different T. The gear should be designed so that it could operate properly at all its loading modes. The situation is worsened by the tendency of heavy-loaded gears to trochoidal interference, that is, untimely coming of teeth into the edge contact at tooth deformation.

Based on Figs. 1.1, 1.2, and 1.15, let us enumerate the works on analysis and optimization of geometry for tooth profiles and flanks for plane and spatial gearings in order to increase the load-carrying capacity of gears:

Block 1 (Fig. 1.15): optimization of the shape of the transient curve in order to decrease the stress at tooth root: works by Vulgakov [220, 221] specifying bending strength of heavy-loaded aviation gears. Investigations of tooth mode of deformation are also presented in works by Airapetov and Genkin [4–7], Reshetov and Bragin

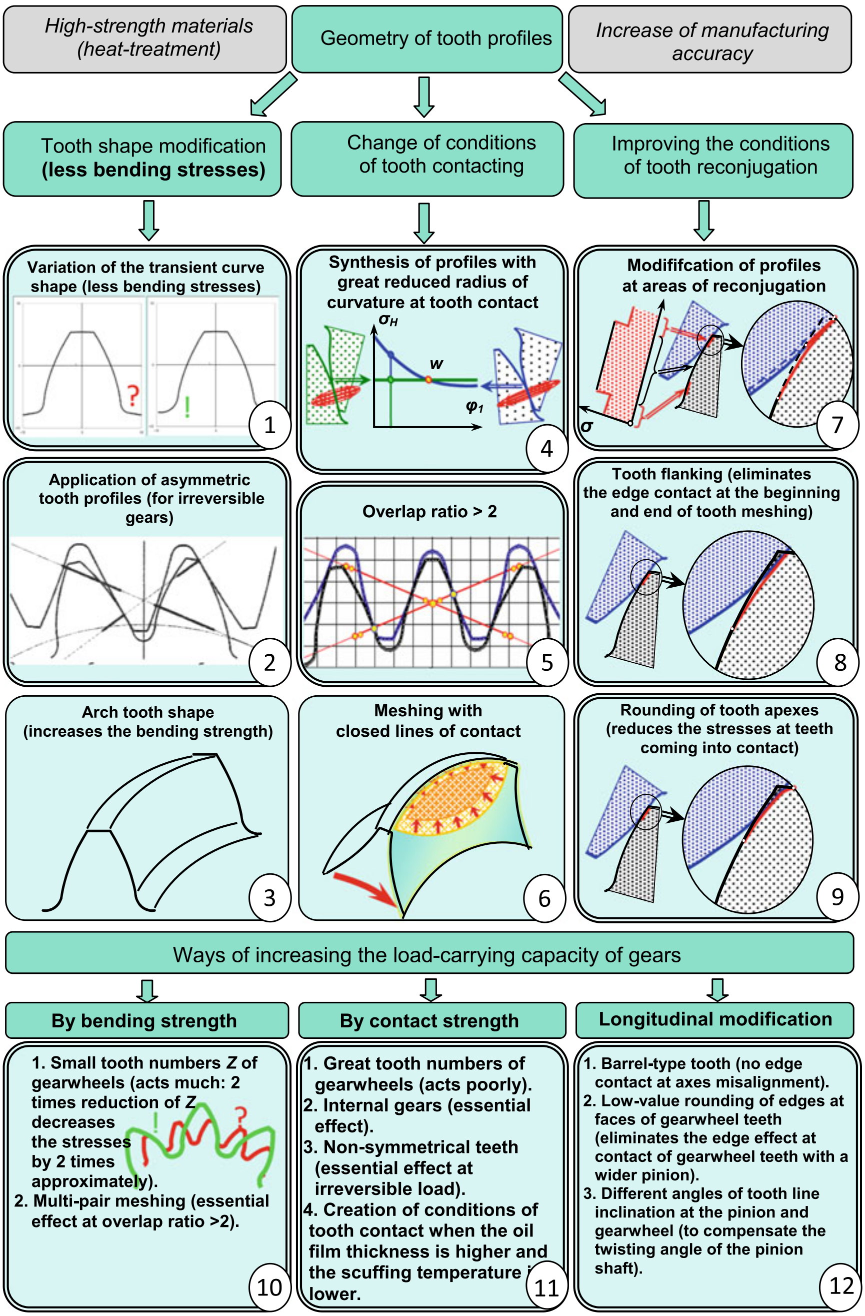

Fig. 1.15 Ways of increasing the gear load-carrying capacity

[34], Syzrantsev [196], Goldfarb with his followers [61, 64], Dorofeyev [40]—see Fig. 1.1.

Block 2 (Fig. 1.15): application of asymmetric tooth profiles: Kapelevich [79] and Vulgakov [221]. They are efficient in many gear drives, in which the tooth load on one flank is significantly higher and is applied for longer periods of time than for the opposite one.

Block 3 (Fig. 1.15): arch tooth shape that increases the tooth bending strength. In spur and helical gears there are works by Erikhov [46, 48] and Syzrantsev [48, 196]; Belyaev and Siritsyn [25]; Reshetov [122]. In bevel and hypoid gears there are up to 20 authors and dozens of publications—see "gears"–>"bevel" and "hypoid" in Fig. 1.2.

Block 4 (Fig. 1.15): synthesis of tooth profiles and flanks for the big reduced radius of curvature R_Σ at tooth contact thus reducing the Hertz contact stresses. There are different methods for such a synthesis:

Method 1. For the assigned type of conjugated profiles (or flanks) it is necessary to determine the segments where $R_\Sigma \to \max$. It is the method for designing involute gears by determining the optimal shift coefficient x_1 and x_2 (for instance, applying the blocking contours): Bolotovsky et al. [29, 30].

Method 2. It is necessary to search for new types of gearing and (or) optimize the geometry of new and existing types of gears. Such gears involve the following types (see Fig. 1.2):

- W-N gears: Kudryavtsev [99], Fedyakin, Chesnokov, Pavlenko [147], Korotkin [92, 93], Kirichenko [83] et al.
- Worm gears: Lagutin, Verkhovsky and Sandler [89, 108–110, 112–119, 211–213], Krivenko [96], Parubets [145, 146], Shultz [164, 165, 167, 168], Pavlov [148–150], Volkov [97, 219].
- Spiroid: Georgiev [53–55], Goldfarb [54, 58, 60–66], Kuniver [55, 103–105], Anferov [10], Trubachev [205], Abramenko [2, 3], Ezerskaya [49], Modzelevsky [135], Fefer [81].
- Gears with face teeth by Pascal limacons: Nechayev [136, 137].

Method 3. It is necessary to apply numerical methods at optimization synthesis of gearing. It can be used both at local synthesis and global one. The global approach is more complex but it gives more reliable results. The versatile method of the global synthesis by criterion of location and dimensions of the bearing pattern is developed and implemented for bevel and hypoid gears by M. G. Segal in the early 1970s. The certain contribution to the development of the global method of synthesis at the same period was made by B. A. Cherny and K. I. Gulyaev. These works were considered in our previously published first part of the review. Note, that from mathematical point of view the optimization synthesis is reduced in general case either to the problem of non-linear programming or to the variation problem. In the first case the *values* of the set of parameters (vector $\mathbf{x}$) are determined for which the target function $F(\mathbf{x})$ reaches its extreme point (under the set of limitations). In the second case the control function $f(u,v)$ (the profile or flank of a tooth with curvilinear coordinates u and v) is determined for which the target function $F(f(u,v))$ reaches its extreme point.

Such approaches started producing the results only after 2000, that is why, we do not consider them in this second part of the review.

Block 5 (Fig. 1.15): application of gears with multi-pair engagement. They are:

(1) *Spur gears with the overlap ratio more than 2* ($\varepsilon > 2$); teeth of such gears are shown in Block 5 in Fig. 1.15. The minimum pinion tooth number in these gears is about 30. At any instant of meshing at least two pairs of teeth are interacting; and the force transmitted by the tooth is reduced almost in two times, thus decreasing contact and bending stresses. Gears require high production accuracy: the error of pitch and profile should be an order less than tooth deformations under load.

These gears were first applied in aviation in 1980 abroad and only in the 21st century in Russia. It became common to replace classical gears with $1 < \varepsilon < 2$ by gears with $\varepsilon > 2$ (for instance, in gearboxes of lorries "Belarus": the casing geometry, shafts and bearings, mounting surfaces are left the same; gearwheel tooth number are increased in 1.5 times with decreasing the module by 1.5 times (with correcting the shift coefficients if necessary); parameters of the basic rack profile are taken to be as follows: $\alpha = 20°$, $h_a^* = 1.25$, $h_l^* = 2.5$, $c_0^* = (0.2–0.25)$. It provides the increase in the transmitted power up to 30…50%.

(2) *Wave gears* (Fig. 1.16) are also related to gears with multi-pair meshing: up to 30…40% of the whole tooth number are in the simultaneous contact, thus providing high load carrying capacity, kinematic accuracy and smoothness of operation. In these gears one of the meshing gearwheels is flexible (3 in Fig. 1.16). It is used to transmit the deformation wave from the element 1 which is called the generator. Gearwheels are always spur and helical, but sometimes there are gears with face bevel teeth. The gear ratio of *all* wave gears is usually i= 40…300 and it is determined by the expression:

$$i = \frac{z_{driven}}{z_{driven} - z_{stationary}}$$

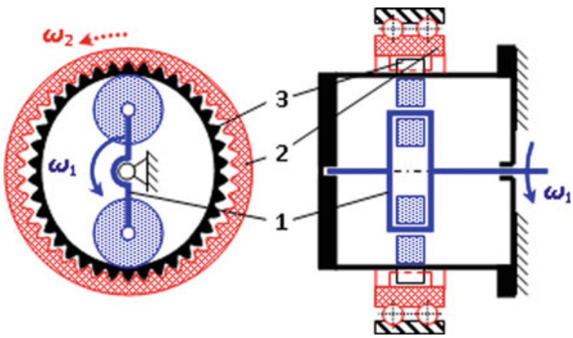

Fig. 1.16 Example of wave gear: 1—driving element (generator); 2—driven element (rigid gearwheel); 3—column (thin-wall elastic barrel with teeth of the *flexible* gearwheel cut on the outside)

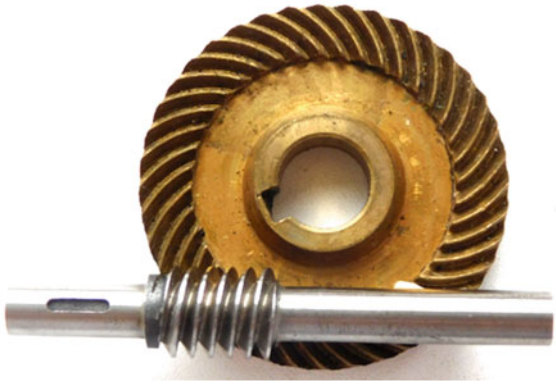

Fig. 1.17 Example of spiroid gear

The tangible contribution to the design and implementation of wave gears was made by Ginzburg [56]; Emelyanov and Popov [44], Kraynev [218] et al.

(3) *Spiroid gears* (Fig. 1.17) can also have multi-pair contact (up to 10 tooth pairs in simultaneous contact). By the end of the 20th century the leader in investigation, design and implementation of spiroid gears in Russia (and in fact in the world) was acknowledged to be Izhevsk Mechanical Institute (now Kalashnikov Izhevsk State Technical University). It was presented by two active groups of scientists headed by A. K. Georgiev and V. I. Goldfarb. Great contribution to development of theoretical investigations and implementation of spiroid gears was made by their followers: D. V. Glavatskikh, A. S. Kuniver, O. V. Malina, I. P. Nesmelov, V. N. Anferov, E. S. Trubachev, V. N. Abramenko, S. V. Ezerskaya, A. M. Fefer, V. A. Modzelevsky et al. The most important works published in 1976–2000 by these experts are presented in tables in Figs. 1.1 and 1.2.

(4) *Planetary type precession gears with small tooth number difference*. It is common that internal spur and helical gears can have small difference of gearwheel tooth numbers (up to z_2-z_1 = 1). The advantage of such gears is low contact stresses because of a high reduced radius of curvature and big number of teeth that are in simultaneous contact. The drawback is the gear ratio $i = z_2/z_1$ close to 1. Similar properties are also specific for bevel gears at the shaft angle Σ close to 180°. The main drawback (closeness of i to 1) can be overcome by making precession planetary gears. Definite layout features are also revealed by bevel gears with the shaft angle Σ close to 0° (Fig. 1.18a). Figure 1.18b–d presents the schemes of precession gears studied thoroughly in Zlatoust by Bezrukov, Lopatin and their followers [26, 27, 52, 126–128]); in Kishinev by Bostan [32, 33]), in Volgograd and Saint-Petersburg by Kislov, Tesker, Timofeev [88]); in Snezhinsk by Nechaev [136, 137]), and lately in Tyumen by Syzrantsev.

Block 6 (Fig. 1.15): gearing with closed lines of contact (CLC). Investigations of *worm* gears with CLC were carried out in the late 1960s in the USSR. Later similar investigations were made in Germany, Czech Republic and Japan. In gears with CLC the closed space is developed between contacting teeth, where the lubrication

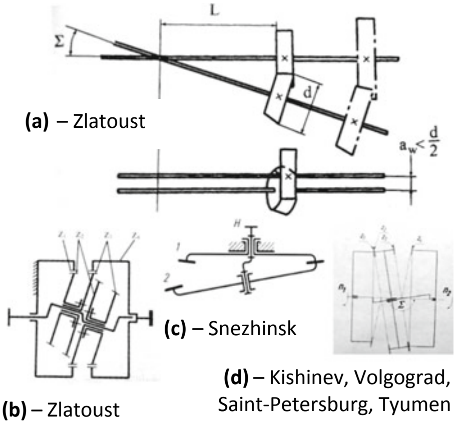

Fig. 1.18 Bevel and precession gears: **a** bevel gear for the boat; **b**–**d** precession gears with bevel gearwheels

is blocked—see Fig. 1.19. The force from the driving tooth to the driven one is transmitted here not only by their CLC, but through the blocked oil. The volume of the space with oil is decreased at rotation of the gear elements and the pressed out oil provides good lubrication conditions for teeth. It reduces the wear and power losses in gearing and increases the transmitted force. In the late 1980s the issue of organizing a serial production of worm gearboxes with CLC was discussed, though it required high accuracy of meshing (5th–6th degrees of accuracy), the increased rigidity of the whole layout and precise bearings. Investigation results for worm gears with CLC in 1976–2000 are presented in works by Lagutin and Verkhovsky [117–119, 211–213].

Blocks 7–9 (Fig. 1.15): these issues are not considered in this part of the review, since works on these methods of increasing the load carrying capacity were only at the primary stage before 2000 both in Russia and CIS countries. Works according to blocks 10–12 are also not described here since the approaches considered there are of auxiliary importance.

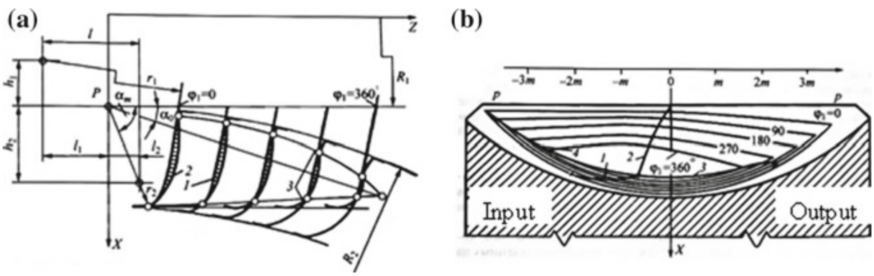

Fig. 1.19 Worm gear with closed lines of contact: **a** section by the mid plane of the gearwheel; **b** projections of contact lines on the plane perpendicular to the worm axis

Finishing the p. 2.2 "Development of synthesis methods…", we refer the reader to the Table in Fig. 1.2. It can be used in order to:

Step (1) choose the interesting gear, mechanism, gear part or theme of investigations;

Step (2) follow the lines coming from the right and left to your chosen theme, family name of authors and number of publications;

Step (3) look through the title of publications in the list of reference and decide the priority of their studying.

1.2.3 Development of Methods for Analysis of Generating Processes and Theory of Gearing

In order to obtain information on this theoretical theme, refer to the Table in Fig. 1.1. By performing all steps described above, get the necessary information.

1.2.4 Software: Development and Application

Software applied at gear design and performance of other engineering analysis can be divided into 4 categories:

Category 1. Commercial software focused on solving the wide range of typical problems. They are CAD/CAM/CAE—systems with English interface, for instance, **Pro/ENGINEER**, **ANSYS**, **CATIA**, **Solid Works** and oth. The special software is intended for gear design: **KISSsoft** (Switzerland); **LTCA** (Gleason, USA); **Kimos** (Klingelnberg, Germany); **PCM** (USA); **PCD** (Japan) and oth.

Category 2. Russian software that tends to be commercial but usually solves a less number of problems. It involves the following systems for design of gears and their elements: (1) **WinMachine** by NTC, Korolev; (2) **CAD KOMPAS** by "Askon" supplemented by software "**Compas#Gears**" on gear analysis.

Category 3. Russian software developed in the leading scientific schools on gears and tools for "internal use". They are:

(1) Software **Reduk 43** for analysis of geometry and strength of involute spur and helical gears with internal and external meshing, planetary gears, bevel gears with straight and circular teeth. The software was developed in 1990s by Department of gear technology of TsNIITMASH (D. E. Goller, A. A. Birbrayer and S. L. Berlin). It implements the techniques of analysis stated in the corresponding standards (GOSTs 16532-70, 1643-81, 21354-87, 19326-74, 1758-81 and other) that were developed at the same Department. This software allows for analyzing the load carrying capacity and durability of both individual gears and multi-stage gearboxes with account of tooth heat treatment, loading cyclogram,

efficiency, power flow, etc. The software is actively applied at heavy engineering plants.

(2) CAM/CAE "**Volga 5**" for geometric and manufacturing analysis of bevel gears with circular teeth developed in 1980s at Saratov SKBZS headed by M. G. Segal.

(3) Software "**SPDIAL+**" for design, optimization and preproduction of spiroid and worm gears (Izhevsk, ISTU, Institute of Mechanics, headed by V. I. Goldfarb, leading developers are E. S. Trubachev, O. V. Malina et al.).

(4) Software "**Expert**" for analysis and synthesis of bevel gearwheels with circular teeth (Moscow, "Mosstankin", headed by G. I. Sheveleva, leading developers are A. E. Volkov and V. I. Medvedev).

Category 4. "Personal" software for solving the problems of analysis and synthesis of gears and tools developed for and gear design at enterprises. Majority of high-skilled experts have such programs. Basics of these programs are standard calculations plus own developments. Let us name only several such software:

(1) Analysis and optimization design of aviation gears (V. L. Dorofeev, Moscow).
(2) Synthesis and optimization of bevel gears (V. N. Syzrantsev, Tyumen).
(3) Design and optimization of parameters of spur and helical, worm and double-enveloping gears (S. A. Lagutin, Electrostal).

Note that during the last third part of the 20th century there were works in the USSR on development of convenient and rational interfaces of programs on analysis and synthesis of gears (Saratov, Izhevsk, Khabarovsk, Leningrad, Tyumen, Minsk and oth.). In particular, an intensive work on development of task-oriented programming language was done in Tyumen [18, 19]. The dialog support system for IBM compatible computer was also worked out. The language involved the means for description of: (1) systems of coordinates and motions; (2) geometrical objects; (3) deviations and deformations; (4) the problem to be solved; (5) types of output data; (6) processing and cataloguing of results; (7) operation with regulating information (tables and formulas). Operations with interval arithmetic were thought out, that is, information (and results) could be represented not only by number, but also by range of numbers (for example, of allowable stresses). Syntax of the developed language was described by Backus-Naur method, since the formal grammar was made to be context-free. Moreover, it was LL(1) grammar which assumed, as known, the efficient methods of syntax analysis and translation by push-down automatons (PDA). When applying PDAs, semantics of the language was implemented by semantic sub-programs. Unfortunately, events of 1990s and rapid development of computer technologies along with the lack of experience and means put an end to that work that seemed to be future-oriented.

1.3 Achievements and Problems of Development of the Theory of Gearing in 1975–2000

1.3.1 Development of the Theory of Gearing

- New concepts were introduced and applied: (**a**) the space of meshing (S. A. Lagutin); (**b**) the covering surface (G. I. Sheveleva); (**c**) the fan, wedge and bunch of normal lines, acceleration of feeding-in (D. T. Babichev).
- Non-differential and kinematic methods for analysis of working and manufacturing meshing gained their development.
- Having applied "the acceleration of feeding-in", new techniques for solving a number of problems were developed: analysis of radii of curvature in meshing, determination of cutting zones and thicknesses of layers removed by cutting edges of tools; analysis of faceting values and other.

1.3.2 Main Theoretical Results on Development of the Theory of Real Gearing

- Methods of gear synthesis were developed with account of many quality characteristics and factors of gear operation: terms of reconjugation, accuracy of production, deformations, vibration activity and other.
- Techniques for investigation of tooth contact interaction and deformation mode of the whole tooth (including multi-pair tooth contact) were developed and implemented. It became possible to control the contact pattern.
- The system of assigning the real ITS (initial tool surfaces) was developed and mathematical models for ITS were created.

1.3.3 The Important Practical Results—A Great Number of Very Adverse Types of Gearing Was Investigated (and Often Implemented: In Gears, in Hydraulic and Pneumatic Machines, in Machine-Tool Gearing)

- Traditional gears and gearing: (**a**) spur and helical: involute (small module, big module, high-speed heavy loaded), with Novikov gearing and other; (**b**) bevel and hypoid; (**c**) spiroid, worm, double-enveloping, screw; (**d**) face gears; and other (Fig. 1.2).
- Non-traditional gears and gearing: (**a**) gears with intermediate rolling bodies; (**b**) devices with closed systems of rolling bodies; (**c**) precessing bevel gears with

shaft angles close to 0° and 180°; (**d**) hydraulic and pneumatic machines: helical (two- and three-rotor) common and planetary type; (**e**) hydraulic and pneumatic machines with non-circular gearwheels; and other.

Appendix 1: Review of Publications of Russian Authors in Foreign Editions in 1976–2000 (Published in English)

During considered period the Soviet science was held in respect in the world; and the leading scientific technical journals ("Vestnik mashinostroyeniya", "Stanki i instrument", "Mashinovedeniye"—since 1980) were fully or partially republished in English. They were published with different titles, in particular, "Machine & Tooling", "Journal of Soviet Machine Science". Later, the journal "Soviet Engineering Research" was issued in the USA in which the featured manuscripts from all three mentioned above journals were published.

Unfortunately, there was "The Iron Curtain" in that period between the USSR and Western countries. It prevented much the cooperation between Russian authors with their foreign colleagues. As a rule, translations of the manuscripts were not authorized by the authors. The authors did not get the proofs of their published papers and even did not know the exact bibliographic data of those publications. That was why, though the majority of papers from the mentioned above journals were translated and published in English, we decided to list the Russian originals in the Reference to the review.

Chronologically the first manuscripts directly published in English in the leading USA editions were the papers by Professor F. L. Litvin and his co-authors. These papers provided the foreign reader with the latest at that time fundamental achievements of the Russian school of the theory of gearing. But the value of those publications was not only in their specific content. The advanced user of the Internet now can not perceive their psychological effect papers on contemporaries due to the breakthrough of the Iron Curtain to the international society.

In 1990s after the breakdown of the Iron Curtain the Russian investigators began actively participating in international conferences, including IX (Milano, 1995) and X (Oulu, 2000) World Congresses on Theory of Machines and Mechanisms, IV World Congress on Gearing and Power Transmission (Paris, 1999) and other.

Professor G. I. Sheveleva and her colleagues were taking an active part in international conferences during the considered period; their presented works were devoted to analysis and synthesis of spiral bevel gears. Papers of S. A. Lagutin considered synthesis and application of general type worm gears. Contributions of Prof. V. N. Syzrantsev and his co-authors discussed the issues of theoretical and experimental research of different types of gears.

A special attention should be paid to the active participation of Professor V. I. Goldfarb in international events. Along with his colleagues he made contributions on investigation and implementation of spiroid gears in practice of mechanical engineering, as well as on general issues of the theory and practice of gearing. Merits of Prof. V. I. Goldfarb in the development of international cooperation of gear experts were noted by his two elections for the position of the Chair of the Gearing Committee of IFToMM, then the Vice-President of this Federation (2011–2015) and finally the Dedicated Service Award in IFToMM (2017).

Being the Chair of the IFToMM Gearing Committee, V. I. Goldfarb was publishing the International Journal "Gearing and Transmissions" twice a year in 1994–2004. It included publications of Russian and foreign experts in Russian and English. Such parallel publication in two languages promoted the increase in the level of mutual understanding between scientists from different countries. As a rule, works of Russian authors published in this journal had the fundamental character and were mentioned above in different paragraphs of this review.

Here is the list of the most fundamental publications in English within the described period:

Airapetov, E. L., Goldfarb, V. I., Novosyolov, V. Yu. (1999). "Analytical and Experimental Assessment of Spiroid Gear Tooth Deflection." Proc. 10th World Congress on TMM. Oulu, 6, 2257–2262.

Goldfarb, V. I., Isakova, N. V. (1995). "Variants of spiroid gearing from pitch realization point of view." *J Gearing and Transmissions*, 1, 25–34.

Goldfarb, V. I., Kuniver, A. S., Koshkin, D. V. (2000). "Investigation of Spiroid Gear Tooth Tangency under Action of Errors." *Proc. Int. Conf. "Gearing, Transmissions & Mechanical Systems"*. Nottingham, 99–108.

Goldfarb, V. I., Russkikh, A. G. (1991). "Skew Axis Gearing Scheme Synthesis." *Proc. MPT'91 Int. Conf. on Motion and Power Transmissions (JSME)*. Japan, Hiroshima, 649–653.

Goldfarb, V. I., Trubachev, E. S. (1997). "Peculiarities of Non-orthogonal Spiroid Gears Parametric Synthesis." *Proc. Int. Conf. on Mechanical Transmissions and Mechanisms*. China, Tjanjin, 613–616.

Goldfarb, V. I. (1995). "The Nondifferential Method of Geometrical Modeling of the Enveloping Process." *Proc. 9th World Congress on the ToMM*. Milan, 1, 424–427.

Goldfarb, V. I. (1994). "The Synthesis of Nontraditional Kind of Skew Axes Gearing." *Proc. Int. Gearing Conference "BGA Transmission Technology"*. Newcastle—London, 513–516.

Goldfarb, V. I. (1995). "Theory of Design and Practice of Development of Spiroid Gearing." *Proc. Congress "Gear Transmissions'95"*. Sofia, 2, 1–5.

Lagutin, S. A. (2000). "Envelope Singularities and Tooth Undercutting in Rack and Worm Gearing." *Proc. Int. Conf. "Gearing, Transmissions & Mechanical Systems"*. Nottingham, 99–108.

Lagutin, S. A. (1999). "Local Synthesis of General Type Worm gearing and its Applications." *Proc. 4th World Congress on Gearing and Power Transmissions*. Paris, 1, 501–506.

Lagutin, S. A. (1999). "Synthesis of Gearings Transmitting a Screw Motion." *Proc. 10th World Congress on the Theory of Machines and Mechanisms*. Oulu, Finland, 6: 2293–2298.

Litvin, F. L., Krylov, N. N., Erikhov, M. L. (1975). “Generation of Tooth Surfaces by Two-Parameter Enveloping,” *Chapter in “Mechanism and Machine Theory”*, 10(5), 365–373.

Litvin, F. L., Petrov, K. M., Ganshin, V. A. (1974). “The Effect of Geometrical Parameters of Hypoid and Spiroid Gears on its Quality Characteristics.” ASME J of Engineering for Industry, 96, 330–334.

Lopatin, B. A., Tsukanov, O. N. (1999). “Design Cylindrobevel Gears in Generalizing Parameters.” *J Gearing and Transmissions*, 2, 24–35.

Sheveleva, G. I., Gundaev, S. A., Volkov, A. E. (1988). “Analysis and Synthesis of Conical Gearing.” *Proc. World Congress INTER-GEAR’ 88*, China, 1, 1025–1028.

Sheveleva, G. I., Medvedev, V. I., Volkov, A. E. (1995). “Mathematical simulation of spiral bevel gears production and processes with contact and bending stressing.” *Proc. 9th World Congress on the ToMM*, Milan, 1, 509–513.

Syzrantsev, V. N., Golofast, S. L., Syzrantseva, K. V. (1999). “Gearing serviceability diagnostic with the help of integral strain gauges.” *Proc. 4th World Congress on Gearing and Power Transmission*. Paris, 2, 1845–1850.

Syzrantsev, V. N., Shteen, O. A. (1997). “Research of contact and bending durability of cylindrical gears with arch-shaped teeth with two-point contact.” *J Gearings and Transmissions,* 1, 17–29.

Syzrantsev, V. N., Erikhov, M. L., et al. (2000). “Novikov-Wildhaber Gearing. New Methods of Geometrical Analysis, Technology of Manufacturing and Control. Experimental Studies of Load Capacity and Service Life.” *J Gearing and Transmissions*, 1, 29–37.

Syzrantsev, V., Kotlikova, K. (2000). “Mathematical and program provision of design of bevel gearing with small shaft angle.” *Proc. Int. Conf. on Gearing, Transmissions, and Mechanical Systems*. Nottingham, 13–18.

Syzrantsev, V., Seelich, A. (2000). “Theoretical and experimental research of Novikov gear shaving.” *Proc. Int. Conf. on Gearing, Transmissions, and Mechanical Systems.* Nottingham, 143–150.

Syzrantsev, V. N., Golofast, S. L., et al. (1995). “New Methods for Experimental Research of Gear Transmissions.” *Proc. of Congress “Gear Transmissions’95”*, Sofia, 1, 71–73.

Volkov, A. E., Gundaev, S. A., Sheveleva, G. I. (1985). “Load-carrying capacity and quality of gear transmissions and reduction unit elements of a CAD system for gear-cutting processes.” *J Soviet Engineering Research*, 5(10), 9–12 (translation from *J “Vestnik mashinostroyeniya”*).

Volkov, A. E., Sheveleva, G. I. (1990). “Computer calculation of tooth-broaching heads for machining of straight-tooth bevel gears.” *J Soviet Engineering Research*, 10, 11, 97–101 (translation from *J “Machine-tools and Tooling”*).

Appendix 2: Theory of Gearing in Persons

The first part of this review was called "Russian School of the Theory and Geometry of Gearing: Its Origin and Golden Period (1935–1975)". In this part, the authors wrote that after the publication of the first edition monograph "Theory of Gearing" by Professor Litvin in 1960, the 1960s became the period of the formation of this theory as an independent science.

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, V. N. Kudryavtsev, 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. Erikhov, I. I. Dusev, E. B. Vulgakov, M. G. Segal et al. already began to create their own scientific schools.

Most of them continued to work in those years, which are considered in the second part of our review. Paying tribute to the memory of our predecessors, we present below essays for some of them.

Yakov Samuilovich Davydov (1914–2003)

Yakov Samuilovich Davydov entered the Gorky mechanical engineering (later polytechnic) institute in 1933 after three years of working experience. In 1937 he was assigned to Moscow State Technical University named after Bauman and graduated from in1939. That autumn he was accepted to the post-graduate course at the MMS department.

In the first days of the Great Patriotic War Ya. S. Davydov was enrolled as an engineer at the Armored repair plant in Moscow. There he got acquainted with gears of the company Fellow that comprised the involute spur pinion and its paired face gearwheel. When returned to the post-graduate course in autumn 1945, he made an analytical investigation of these gears under the supervision of V. A. Gavrilenko. After completing postgraduate studies, he came to the Gorky institute of water transport engineers where had worked continuously till 1987 as the assistant, associate and full professor at the department of the theory of mechanisms and machine parts.

Ya. S. Davydov summarized the ideas stated in the Ph.D. thesis as the monograph "Non-involute gearing" (Mashgiz, 1950). This book played a great role in the development of the theory of gearing not only due to a new class of gears investigated and discussed there, but due to the kinematic method proposed there by the author (simultaneously with V. A. Shishkov and F. L. Litvin and independently of them). This method became the main technique for analysis and synthesis of gearing in the second part of the XX century.

A number of papers published at the 1960s had no less importance for the theory of gearing. In these works Ya. S. Davydov showed that in order to generate conjugated gearing with the point contact of active flanks (such as W-N gearing), it is not obligatory to reject Olivier's principles inextricably related to the gear-cutting technique. It is just necessary and enough to spread these principles for application of rigid non-congruent pairs of generating surfaces and curve lines.

Brilliant erudition, tactfulness, carefulness in his work and assessment of other works acquired the great authority of Ya. S. Davydov in the gear expert society. At the end of 1990s he emigrated to the USA where lived till the end of his days.

Kalman Malkielevich PISMANIK (1914–1990)

Kalman Malkielevich Pismanik was born in Saint-Petersburg on August 24, 1914. In 1933 he graduated from the railway college. In 1935 he tested out the exams for the first two courses and was accepted to the third year of Leningrad Polytechnic Institute. In 1939 he graduated with honors from the evening department of this institute with the major "Cold machining of metals". At the end of 1939 he entered the post-graduate course and held the study with the work of the chief designer first at the Kirov plant of lifting equipment, then at the Special Designing Bureau 19. During the Great Patriotic War K. M. Pismanik was working as the head of the designer group at the plant #174 of the Ministry of armored vehicle industry.

In 1948 K. M. Pismanik presented his Ph.D. thesis on "Fundamentals of the kinematic theory of spatial gearing and its application for investigating the technique and meshing of hypoid gears". By this time the applicant had 12-year experience in industrial plants.

The further working activity of K. M. Pismanik was closely related to education. Since 1948 he had worked at Saratov road transport institute as the senior lecturer first, then as the associate professor of "Mechanical engineering" department. Since 1960 he had worked as the associate professor of "Metal cutting machines and tools" department. In 1973 K. M. Pismanik presented his DSc thesis on "Theoretical fundamentals of tooth profiling for bevel and hypoid gears". After awarding him the professor title in 1973 he became the head of "Mechanism and machine science" department of Saratov polytechnic institute.

Professor K. M. Pismanik contributed much to the generation of the Russian gear cutting science. He published 118 scientific papers, including 5 books. His monograph "Hypoid Gears" (1964) remains today the reference book of any engineer engaged in the production of these gears. He supervised 10 Ph.D. theses. A number of very urgent theoretical issues on the geometry of gearing and gear machining technique for hypoid and worm gears had been solved under his leadership. His works with V. N. Kedrinskiy became the foundation for the development of a whole range of Russian machine-tools for machining bevel and hypoid gears at the Saratov plant and the Special Designing Bureau of heavy gear cutting and shaping machine tools. The last book with him as the first author was published in 1993 [152].

Scientific activity of professor K. M. Pismanik was specific by his high integrity, insistence on quality and practical focus of works that gained the worthy tribute and wide popularity among scientists and experts in this field of science and production both in Russia and abroad.

Lev Vasilyevich KOROSTELEV (1923–1978)

As a rule, a fundamental discovery appears in a rather complex and confused way. The founder involuntarily reproduces the thought passing through the labyrinth of accumulated knowledge prior to the light of a new Truth and enriches the statement by the variety of formulas, calculations and details that promoted the obtained conclusions. The author presents all the known facts and proofs as if in front of a trial jury in order to convince them to reach the only right, to his opinion, verdict. The works by Ch. I. Gochman and E. Wildhaber are the visual examples of such an approach. And there is some “period of information settling” during which juridical riots are calming down, random features are vanishing and the truth appears as a perfectly simple statement, transparent as the main law of meshing in the form $\mathbf{n} \cdot \mathbf{V} = \mathbf{0}$. The more serious the discovery is, the longer this period is. And usually only representatives of the next generation manage to bring the simplicity and importance of fundamental discoveries to wide recognition.

But there are rare exceptions to this rule. The history of science knows scientists of Kepler’s type, capable of intuitively conceive the truth in the last resort at once and state the information so simply and evidently as the verdict is final without appeal. Prof. L. V. Korostelev had this lucky ability to the full extent, being the bright representative of the second generation of scientists who developed the theory of gearing in Russia.

Lev Vasilyevich Korostelev was born on September 15, 1923 in a hereditary intelligent family. During the Great Patriotic War, he was working as a gear cutter at the military plant. In 1946 he entered the Moscow Machine-Tool Institute (Stankin) and devoted all his further life to it. In 1950 he graduated from the machine-tool department and entered the post-graduate course in this specialty. In 1954 he presented the Ph.D. thesis on development and production of bevel gears.

Having worked a little at Izhevsk mechanical institute, he returned to his Alma-Mater as the associate professor of MMS department. In 1964 he presented his DSc thesis on “Geometrical and kinematical characteristics of load-carrying capacity of spatial gearing”. In 1968 he was award the professor title. Since 1971 he held the head of MMS department position with the responsibilities of Vice-rector for Research. He died in the road accident on August 9, 1978.

During a short period of his scientific activity, L. V. Korostelev published works on: investigation of curvature of mutually enveloping surfaces, kinematic sensitivity of gears to errors of mutual arrangement of gearwheel axes, synthesis of spatial gearing by means of screw generating wheel and investigation of general-type worm gears. He discovered the analog of the Willis theorem for spatial gearing. The worm gears with closed lines of contact are among his 30 inventions.

He passed away painfully early. His papers and reports are scattered within different journals. He did not have time to write a monograph. He did not publish any of his works abroad. All this does not promote the knowledge of his scientific heritage for new generations of researchers. But he is worth to be studied at least not to apply numerical methods for solving those issues that are evident from general laws determined by him, to find grains of further investigations in his works and, finally, to inherit his simplicity and clearness of the line of thoughts .

Edgar BorisovichVulgakov (1928–2006)

Education: 1952—Moscow Automobile and Road and Institute, 1963—Ph.D. degree at Moscow State Technical University, Thesis—“Gears with modified basic rack profile”, 1974—Dr.Sci degree at the same University, Thesis—“Gears with improved characteristics. Generalized theory and design”.

Main employment: 1956–1962 –VNIINMASH (Russian Research Institute of Standardization and Certification in Mechanical Engineering), Research sector chief, 1962–2006—CIAM (Central Institute of Aviation Motors), Gear department chief.

In the 1960s E. B. Vulgakov researched a new basic rack profile that improved gear quality characteristics. He had developed the unique block-contour album and defined the local bending stresses for gears with different basic contours. Later, he created the Gear Theory in Generalized Parameters that describes the involute gear mesh independently of gear fabrication technology and tooling generation profile. This theory is an outstanding contribution by E. B. Vulgakov to involute gearing that breaks the dogma about the necessity of using a preselected basic (or generating) rack profile to define involute gear parameters and gear design. In traditional gear design, the typically standard tooling generating gear rack is primary, and gear parameters and performance characteristics are secondary. In a fact, Vulgakov’s theory makes gear drive performance parameters primary—where completely defined gear geometry dictates tooling proportions and dimensions—just like when designing practically any other mechanical parts and components. This approach allows for gear geometry to be fully optimized for gear drive performance for a particular application.

In his theory, Prof. E. B. Vulgakov defined the functions and parameter limits of the involute mesh of cylindrical gears and introduced their areas of existence. He described the generalized rack generating tooling profile, its area of existence and shaping of the gear tooth root fillet by the protuberance hobs. He also extended his theory to asymmetric tooth gears and epicyclic gears.

The Gear Theory in Generalized Parameters was ahead of its time and, unfortunately, despite the many publications of Vulgakov and his followers, it did not find deserved understanding and application in Russia. In the USA it became a foundation for the development of the Direct Gear Design method that is used to design high-performance custom gear drives.

E. B. Vulgakov was an editor of the handbook “Aviation Gearboxes” that became very popular among aerospace gear engineers in Russia. In 1993, E. B. Vulgakov founded the “Conversion in Machine Building” journal and became its chief editor. This magazine published articles about the restructuring and conversion of Russia’s defense industries and enterprises for production of civil goods.

(The essay about E. B. Vulgakov was prepared by his follower A. L. Kapelevich).

Galina Ivanovna SHEVELEVA (1929–2005)

Galina Ivanovna Sheveleva graduated with honors from Moscow Machine-Tool Institute (Stankin) in 1952. In 1955 she entered the post-graduate courses of the same institute and in 1957 she was enrolled as the assistant at the department “Theoretical mechanics” where she had been working till her death. There she presented her Ph.D. (1960) and DSc Theses (1969) became the Assistant Professor (1965), Professor (1973) and the holder of the award by the Council of Ministers of the USSR (1985).

Already in the 1960s she proposed new methods for solving the problems of the theory of gearing by decomposing the functions into power series; that allowed carrying out the synthesis of Revacycle bevel gears for Soviet and Polish enterprises. She developed the theory of covering lines; on its basis the algorithm was developed for metal removal from the workpiece by multi-point cutting tools. This allowed for efficiently eliminating such a generating defect as the tooth flank cutting-off by one of the cutters of the broaching mill.

During the age of computerization these methods proved to be high-demanded; and they became the foundation of a new trend in solving the problems of synthesis and analysis of gears by numerical simulation of gear-machining processes and meshing gearwheel pairs. She proposed a new solution for the contact problem of the elasticity theory by consequent loading as applied to gears.

The main practical outcome for scientific studies of G. I. Sheveleva is the software system “Expert” developed under her leadership and at her direct participation. It is intended to master the production of spiral bevel and hypoid gears. “Expert” is competitive with the best world-wide analogs developed by the world leaders of gear machining equipment (Gleason, USA and Klingelnberg, Germany); and it is widely used at aviation and mechanical engineering plants.

Being the eminent and miscellaneous teacher, she had been unchallenged for many years as the best lector of Stankin. Her lectures on theoretical mechanics, computer science and programming captivated and admired the audience, acquainting the students to the flawless logical process developed from the very beginning of narration to the final conclusions.

She created her own scientific school, published the monograph, several textbooks, about 200 scientific and guidance manuscripts. She was the research advisor of successfully presented theses: two DSc and 11 Ph.D., including in Poland. Galina Ivanovna paid much attention to her followers and was proud of them. She was strict and fair. No disingenuous motives and nobody’s authority could make her change the exam mark of student’s work or the Ph.D. presentation.

Mark Gerasimovich SEGAL (1931–2000)

Mark Gerasimovich Segal was born on December 19, 1931 in Latvia, Rezekna. In 1954 he graduated from the mechanical and mathematical department of Saratov State University on the major “Mechanics”. He started his working activity as the teacher of physics at school.

From 1956 till 1984 he was working at Saratov Plant of Heavy Gear-cutting Machines (SPHGM), at the department on development of heavy gear-cutting and gear-grinding machines. He made a career from the senior designing engineer to the Chief Designer and Head of the Department of theoretical investigations. In 1964 M. G. Segal presented the Ph.D. thesis and in 1979 the DSc thesis.

Since 1981 he headed the department of Metal-cutting machine-tools at Saratov Polytechnic Institute. In 1987 he was awarded the title of Professor. He is the author of 120 scientific works and 8 inventions.

The main contribution of Prof. M. G. Segal to the theory of gearing is that unlike his predecessors he introduced the concept of the ease off between the nominal and theoretical surfaces of the gear tooth for the analysis of contact condition of active tooth flanks. The line of the level of reduced clearances that corresponds to the thickness of the paint layers compressed at gear running-in at the testing machine is the contour of the theoretical area of contact. This idea is being commonly used nowadays in the world.

M. G. Segal was also the first to state the issue of determining the value of undercut in bevel and hypoid gears. Before him there were efficient methods for determining the fact of the presence or absence of undercut rather than its value. Segal showed that the requirement for the complete absence of the undercut is often unjustified; and he introduced the concept of the allowable value of undercut by proposing the distance h_Q to the axis of the pinion rotation from the point Q of jog, that is, from the point of intersection of the enveloping and the transient surfaces in the chosen section.

Professor M. G. Segal headed the development of the program system for solving the problems of manufacturing synthesis and analysis of contact conditions, first of all, for bevel teeth with circular teeth. The last version of this system "Volga 5" is being still actively applied at many mechanical engineering plants for analysis of gear-cutting machine-tool settings at the SPHGM enterprise.

At the same time, M. G. Segal developed the mathematical model for the process of tooth generation at CNC machine-tools based on the theory of envelopes. At any assigned laws of motion of CNC machine-tools elements this model allows for analyzing all criteria of the quality of the gear cut at these machine-tools, the criteria characterizing the conjugacy of tooth flanks and their geometrical shapes.

In 1990s M. G. Segal was invited to work in Germany where he became the ideologist and chief developer of the program system "Kimos" for Klingelnberg gear-cutting machine-tools. His results on the choice of optimal schemes of multi-coordinate CNC machine-tools for gearwheel machining were also applied by Klingelnberg Company.

He died on October 29, 2000 in the hospital in Israel and he was buried there.

Maks L'vovich Erikhov (1937–2002)

Maks L'vovich Erikhov was one of few encyclopaedists in the field of gearing theory and practice of gearbox engineering. He had the competency to thoroughly discuss fine mathematical nuances of the theory of envelopes, logics of the structure of a higher educational course on MMS, geometry of double-enveloping gears with ground worms, kinematics of machine-tools for cutting the arch teeth, the system of tolerances for W-N gears, and any issues of the theory and practice of real gearing. Maks L'vovich was born in 1937 in Velikie Luki, Pskov region. He graduated from the mechanical engineering department of LPI—Leningrad Polytechnic Institute (now Saint-Petersburg Polytechnic University—SPU) in 1960. He started his working activity in the same year at the design department of Khabarovsk enterprise named after Gorky, where he was working up to entering the post-graduate course at MMS department of LPI in 1962.

Having presented the Ph.D. thesis, he was working since the end of 1965 to 1975 at Khabarovsk Polytechnic Institute as the senior lecturer of the “Machine parts” department, and since June 1966 he was the head of this department. During this period Prof. M. L. Erikhov managed not only to re-establish the staff of the department by captivating the most talented graduates of the institute by scientific investigations, but to organize the scientific laboratory at the department to carry out the experimental investigation of gears and methods of gear generation. By continuing and developing the investigations started during the post-graduate course, he obtained a number of new results in the theory of gearing that became the subject of DSc thesis presented in 1972 at the age of 35.

In 1975 Prof. M. L. Erikhov along with his few followers moved to work at Kurgan Mechanical Institute (now Kurgan State University) where he was the head of the “Machine parts” department and in 1986–1990 he was the vice-rector of the institute on the scientific work. In Kurgan M. L. Erikhov continued his intense scientific activity. During a short period, he managed to re-organize the work of the department and create laboratories for experimental research where investigation of new types of gears and methods for gear machining were continued and fundamentals of new scientific directions were laid.

Thanks to the authority and organizational efforts of M. L. Erikhov, in 1979 Kurgan became the venue for the 3rd All-Union Symposium “Theory and geometry of spatial gearing”. After three symposia “Theory of real gearing” were held there in 1988, 1993 and 1997. The change of the title of the Symposium represented the increase in the number of considered issues and main trends in the development of the gearing science at the advanced level.

Since 1998 and till the end M. L. Erikhov worked as the professor of SPU.

Professor M. L. Erikhov was one of the founders of a new scientific direction in the theory of gearing—the application of the principle of enveloping with two parameters to analysis and synthesis of gearing. Introduction of two-parametric models into the classical theory allowed for reconsidering the whole theory of conjugate gearing generation and to give it the logical structure and completeness.

Original methods of gearing synthesis developed by Erikhov allowed for developing and investigating a number of new types of advanced gears and methods for gear generation, including gears with arch and barrel-shaped teeth.

M. L. Erikhov was one of the first in Russia to understand that further development of methods for gear analysis and optimization was impossible without complex consideration of such factors as manufacturing errors and deformation of teeth and other gear elements. Such an approach allowed him and his followers to state and solve a number of problems of complex investigation of the loaded state of gears with arch teeth, W-N gears, double-enveloping gears and, above all, to refine the design experimental methodology of solving the spatial problems of the theory of real gearing.

It was stimulated by mastering the method for assessment of the loaded state of gear elements by means of an integral type strain gauge—a new direction in experimental mechanics that has been successfully developed by the followers of M. L. Erikhov and the followers of his followers.

M. L. Erikhov did his best to prepare the skilled experts in the field of gears and to assist young scientists. He was the supervisor of more than 30 Ph.D. and two DSc theses. He is the author of more than 130 publications. Papers published by the staff of the scientific school created by M. L. Erikhov are widely known in Russia and abroad.

Maks L'vovich had the natural Saint-Petersburg commitment with respect to people and ability to spread positive emotions around him. This wonderful ability along with the versatility of his knowledge promoted the uniting of the gearing society of our country.

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