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MILLING MACHINE FOR SPUR GEARS WITH CIRCULAR ARC DIRECTRIX

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Abstract: While general awareness exists in the engineering environment of spur (cylindrical) gears with curved directrix, of the corresponding cutting procedures, machines and tools, as well as of their evident potential benefits, particularly in mechanical power transmissions, the amount of information available in relation to this type of gears is limited and scarce in literature. The paper presents results of recent research [11] finalized by the development of the kinematic structure of a machine for cutting spur gears with circular arc directrix by face milling, the cutter teeth being located along a circular contour at a uniform pitch. The teeth are cinematically generated based on the principle of fixed rack rolling, the cutting being achieved "space by space", thus by discrete indexing. The paper further presents the limitations of gears of the considered type, as well as subsequent directions of study and research.

Key words: *machine-tools, gear cutting, circular arc directrix gears.*

1. INTRODUCTION

The utilization of spur cylindrical gears has known a long history, and at the same time is highly up to date and of significant future potential. The continuous development of machines manufacturing industry and of mechanical transmissions in particular has over the years motivated a large number of specialists to study and contribute to knowing spur gears and their applications.

A frequently addressed topic is increasing spur gear performance and developing machine, tools and procedures for their machining. Significantly less frequent however, is the appearance of new machining procedures and of adequate machines.

From the viewpoint of their directrix, at present frequently utilized are straight, tilted, V-shaped spur gears, and somewhat less frequently W-shaped spur gears.

From the viewpoint of the generatrix conjugated [7], reciprocally envelopable curves [1] need to be utilized. The majority of spur gears are involute with symmetrical teeth. However numerous other curves are used for a generatrix, mostly complex curves like the ones composed of epi- and hypocycloid arcs (cycloid gears) or of circular arcs (Novikov gears) [2, 3].

Effective machining of spur gears is achieved either by kinematical generation or by copying. Kinematical generation is often conducted by metal cutting, particularly by milling with hobs, disk cutters or vertical broaches. Generation by copying employs various procedures, like cutting (e.g. broaching), stamping, volume plastic forming or syntherizing.

2. RESEARCH OBJECTIVES AND PREMISES

The central objective of the presented research concerned the identification of minimum dimensions spur gears, sufficiently precise, relatively easy to generate, and more importantly, capable of transmitting high loads.

Of the known gears, these requirements are sufficiently satisfied by those with tilted or V-shaped teeth, the selection of the generatrix being, however, a secondary objective.

Conducted studies have also shown that the bevel gears most frequently utilized in power transmissions have curved directrix in the plane reference wheel, and that these gears are machined by milling.

The comparison to bevel gears has actually generated both subject and object of the presented research, conducted by means of the techniques of inventics [4, 5, 6], two of the currently employed methods being comparison and extrapolation. Answers were sought to the following formulated:

- Is curved directrix spur gear generation possible?
- From the viewpoint of the transmitted load and overall dimensions is a curved directrix spur gear superior to one with tilted teeth?
- What is the recommended nature of the directrix?
- Which is the most adequate one of the possible directrix curves?
- Which machining procedure is preferred?

It has to be remarked that the author already had information on poly-hypocycloid gears [8, 9] as well as on spur gears with elongated cycloid arc directrix [10], cinematically generable by milling with face cutters.

Considering that:

1) the circular directrix is the simplest and probably easiest to achieve, and that
2) the generation of curved bevel gears is milled with face cutters,

the immediately subsequent objective of the research could be formulated with sufficient accuracy: "study of the possibility of curved directrix spur gear generation by milling with face cutters and development of the kinematic structure of such a gear milling machine based on the principle of rolling".

3. MOTIONS AND CONDITIONS REQUIRED FOR THE GENERATION BY MILLING OF SPUR GEARS WITH CIRCULAR ARC DIRECTRIX

The directrix is obtained by the main motion, sometimes also with the participation of one and rarely with the participation of several of the feed motions.

As the considered directrix is a circle, the main motion needs to be a rotation, without the requirement of an additional motion. The main motion however requires adjustment, hence the main linkage needs to include a speed regulator, with continuous or incremental operation, as the case my be.

The utilized tool is a face cutter, the teeth being located along a circle, the directrix being thus materialized on the tool. Due to the tool rotation the cutting edges of the teeth will shape a tooth of the reference rack, that can fixed or mobile, translatable.

In this case the obtaining of the teeth generatrix requires simulation of the meshing of the teeth to be cut and the reference rack, thus a rotation of the part by its axis and a translation motion carried out either by the reference rack or the tool axis. The two motions need to be strictly correlated, ensuring together the rolling motion. Consequently two feeds are required: a circular feed of the part and a tangential feed achievable by either the tool or the part. The linkages ensuring these two motions need to have "a rigid kinematic link".

The teeth are machine "space by space" (or "tooth by tooth", depending on the configuration of the tool teeth), thus an indexing motion is required. This is achieved by an additional rotation of the part during each idle phase following upon the machining of a space between the part teeth. It follows that the indexing linkage utilizes part of the part circular feed linkage. Although it is possible to use an indexing mechanism, it is recommended to include a differential mechanism in the indexing linkage.

After the machining of each space, a relative distancing of tool and part is required, in order to ensure their safe return to the initial position. Before resuming machining a reverse motion is carried out, i.e. a nearing of tool and part, thus restoring the preset distance between the part axis and the reference rack.

The machining of gears of various overall dimensions, determined by the number of teeth and module, calls an adjustment of the distance between the part axis and the reference rack. The face plane of the cutter can be used as a base.

In relation to a setting base, the teeth median plane of various gears to be cut is positioned at different distances. In order to prevent the generation of axial forces in the meshed gears with teeth of the considered type, the centre of the directrix needs to be included by the median plane of the teeth. Consequently a relative positioning motion between tool and part has to be ensured, in order to position the tool rotation axis in this median plane.

In conclusion a milling machine designed to cut circular arc directrix spur gears by rolling, employing a cutter with teeth located at a uniform pitch along a circle, needs to have at least the following linkages:

- main linkage with rotation motion, for tool driving;
- part circular feed linkage, for generation by rolling of the teeth generatrix;
- tangential feed linkage, for slippage free rolling of the part over a plane of the reference rack;
- rolling linkage for simulating the meshing of the cut gear with the reference rack. The rolling linkage consists of the final elements of the part circular feed and the tangential feed linkage; between these two linkages there are a rigid kinematic link and adjustment gear pairs;
- indexing linkage for the (discrete) machining of all teeth (spaces);
- linkage for the relative nearing-distancing of tool and part. This linkage operates discretely and ensures a short stroke, slightly larger than the height of the tooth;
- linkage for adjusting the distance between part axis and a plane of the reference rack;
- positioning linkage of the tool rotation axis in the median plane of the cut teeth.

4. KINEMTIC STRUCTURE OF MACHINE FOR MILLING BY ROLLING OF CIRCULAR DIRECTRIX SPUR GEARS

Based on the above requirements the kinematic diagram of a milling machine for circular arc directrix spur gear was developed [11], Fig. 1. The selected generation principle employs a fixed rack, ensuring a rolling motion of the part.

The main motion is carried out by cutter 9, driven by the main spindle 8. The source of energy and motion is motor 2, driving shaft 6 via the belt and pulley transmission (4 and respectively 3 and 5). Shaft 6 is the input shaft of a speed regulator 7, with continuous or incremental operation, as the case my be. The output shaft of speed regulator 7 is exactly the main spindle 8. The transversal slide 10 supports all mechanisms responsible for the main motion and can move transversally along the guides *f* on vertical slide 92.

Slide 10 carries a fixed nut, 91. The translation of slide 10 is achieved by manual rotation of screw 90 by hand wheel 89, thus (pre)adjusting the distance between the axis of the gear to be cut and the pitch plane of the reference rack. Teeth profile with zero shift is obtained when the reference rack pitch plane is tangent to the rolling cylinder of the cut teeth 46. Shifted profile teeth are obtained by adjustment of the distance between the cut gear axis and the reference rack pitch plane to other values than previously mentioned.

The relative nearing-distancing motion between the cut gear and the tool is achieved by means of a linear hydraulic motor (93), the bilateral rod (94) of which is attached to screw 90.

The amplitude of the nearing-distancing motion needs to be slightly greater than the height of the cut teeth. When cutting teeth with different module to the previously machined one the amplitude of this motion has to be adjusted. Consequently the possibility of adjusting the piston stroke of hydraulic motor 93 needs to be ensured.

The adjustment motion for positioning the axis of main shaft 8 in the median plane of the cut teeth is achieved by a translation of vertical slide 92, via a screw

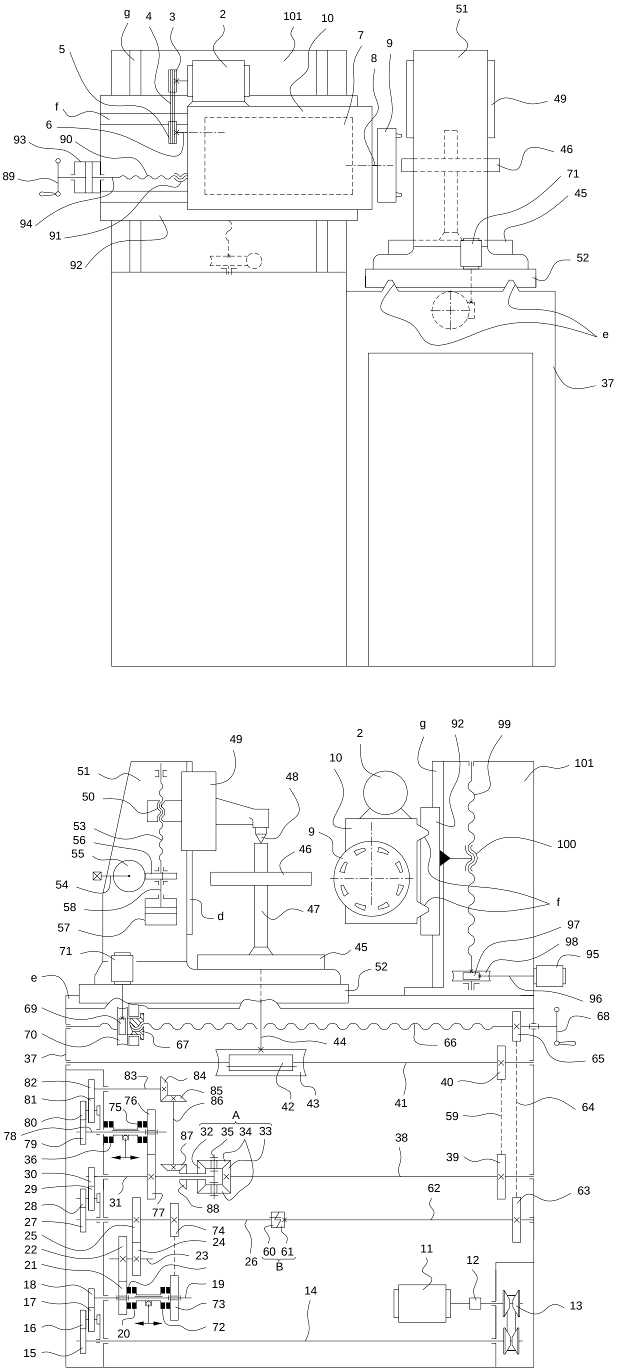

Fig. 1. Kinematic diagram of a machine for milling by rolling of circular directrix spur gears [11].

and nut mechanism. Nut 100 is attached to vertical slide 92 and drives its translation motion. The rotating and non-translatable screw 99 is driven by a worm gear (97–98) via an electric motor 95. The motor can be replaced by a hand wheel.

The translation motion of vertical slide 92 is achieved over the guides *g* of standard 101.

The position of part 46 at the starting moment of the rolling motion depends on its overall size. This adjustment is achieved by a screw and nut mechanisms (66-67). The rapid motion of slide 52 close to this position is achieved by motor 71 via a worm gear (69–70), the nut 67 being attached to the gear. Fine adjustment is achieved by manual driving of screw 66 via hand wheel 68. During these adjustments coupling *B* is released.

The translation motion of the part axis parallel to the plane of the reference rack – a motion of working tangential feed as part of the rolling – is obtained also by the screw and nut mechanism 66–67. Coupling *B* is connected, and screw 66 is driven by chain transmission 64. The feed rate is achieved by adjustment gear pairs 15–16–17–18. One direction of motion is achieved if coupling 20 is activated, while the opposite direction via coupling 72, the latter being active during the return phases of the part to its initial position, immediately after the machining of each space between the teeth.

The tangential feed and circular feed linkages share the part between the electric motor 11 and shaft 26, inclusively.

The circular feed linkage of the part branches out starting from shaft 26, through adjustment gear pairs 27–28–29–30, shaft 31, differential mechanism A, shaft 38, chain transmission 59, shaft 41, worm gear 42–43 and shaft 44, the latter driving the rotation of plate 45 and implicitly of cut part 46. Worm 42 is movable along shaft 41, while attached to it during rotation. In the machining phase of a space between the teeth of part 46, one of the inputs of differential mechanism A is blocked, detail in Fig. 2, namely gear 32. For this coupling 36 is activated, the effect being the lack of motion of shafts 78, 83 and 86, thus of bevel gear 88 to which gear 32 is attached.

If the circular feed rate adjustment requirements are reduced, either continuous speed regulator 13 can be eliminated, or adjustment gear pairs 15–16–17–18, as the two subsystems participate jointly in the achievement of this function.

During the kinematic generation phase of a space between the cut teeth 46 the rolling linkage connects rotation and translation of the part. The rolling linkage includes a portion of the circular feed linkage of the part comprised between part 46 and shaft 26 and a portion of the longitudinal feed linkage comprised between shaft 26 and longitudinal slide 52. This linkage is adapted by adjustment gear pairs 27, 28, 29 and 30.

During the return phase of longitudinal slide 52 to its initial position, also indexing is achieved, as well as the additional rotation by one or a multiple of teeth of the cut part 46 in one or the other direction.

For this coupling 75 is activated and consequently shaft 78 is driven into rotation by meshing gears 76 and 77. Shafts 83 and 86 are driven into rotation, thus also gear 88 to which gear 32 is attached.

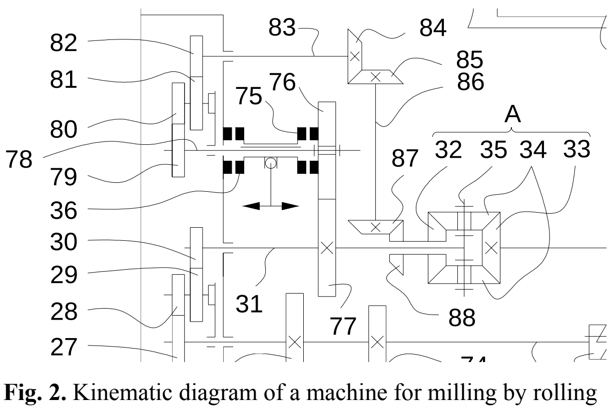

Fig. 2. Kinematic diagram of a machine for milling by rolling of circular directrix spur gears. Detail.

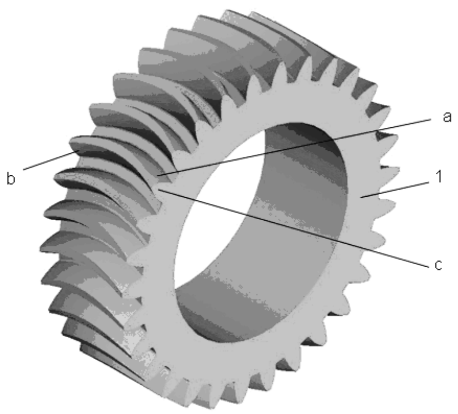

Fig. 3. Circular arc directrix and involute generatrix spur gear [11]. A 3D image generated in ProEngineer.

Differential mechanism A is active and ensures the necessary additional rotation of shaft 38. The transfer ratio of the indexing linkage is adapted by adjustment gear pairs 79, 80, 81 and 82.

Typically the clamping of part 46 on rotating plate 45 (of longitudinal slide 52) is achieved by an intermediary part 47.

In order to increase the rigidity of the clamping system of part 46, the element 47 can be supported by a conical tip 48 placed on a slide 49. Slide 49 is vertically mobile on guides *d* on a standard 51 attached to the longitudinal feed slide 52.

The positioning in the vertical plane of slide 49 is achieved by a screw and nut mechanism 53–50, the nut 50 being attached to slide 49. Screw 53 can de driven manually by means of a shaft 54 and two gears – 55, 56.

Rapid release and clamping of part 47 is ensured by a linear hydraulic motor 57 generating a short stroke, its unilateral and partially grooved rod 58 being attached to screw 53.

5. CIRCULAR ARC DIRECTRIX SPUR GEAR

A circular arc spur gear 1 as shown in Fig. 3, has opposing flanks a and b of any circular arc tooth c of different radii, but equal to the corresponding display radii of the cutter teeth.

For meshing gears of the considered type the radii of the contacting flank directrix need to be equal. Consequently the teeth of the two meshing gears need to be machined with different cutters. Moreover, motion is transmitted correctly only in one direction.

Motion is transmitted correctly in both directions only if the circular arc directrixs of both opposite flanks of a tooth have the same radius. For this machining has to be conducted with more complex cutters, of the type used for cyclo-paloid bevel gears [2]. In such a case the teeth of both meshing gears can be machined with the same cutter.

Ongoing study focuses on the design of a machine and cutter for this purpose.

6. CONCLUSIONS

General awareness exists in the engineering environment of spur (cylindrical) gears with curved directrixs, as well as of the corresponding cutting procedures, machines and tools.

Curved directrix spur gears either benefit from a loading capacity superior to other types of spur gears, or ensure a slight rise of the teeth along the directrix, what contributes to a favourable location of the contact spot.

Spur gears with arc shaped directrix can be kinematically generated by milling with face cutters with teeth located at a uniform pitch along a circular contour and incremental indexing.

Meshed circular directrix spur gears do not generate axial loads.

The presented kinematic structure of a milling machine of circular directrix spur gears is explicit, such a machine being achievable at any time.

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