Kinematic Structures for Processing of Surfaces with a Circle Directrix and a Straight-Line Generatrix (Part V)

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Abstract
In modern industrial society, maximum importance comes to machines manufacturing with machine tools manufacturing as one of its main pillars. The machine tools are used for producing the majority of components of various industrial equipment and consumer goods, including the components for building new machine tools. Each part is characterised by one or more surfaces, simple or complicated, as the case may be. A well-known theory of surface generation asserts that any surface is characterised by a directrix and a generatrix, as well as by at least one modality of their physical achievement by means of the tools and machines deployed for processing. The evolution of industrial knowledge and practice over the last decades calls for the further development of this theory, such as to eliminate certain inadvertencies or limitations bound to create confusion, as well as to include an essential part that addresses the kinematics of machine-tools in a systematic and explicit manner. At present this latter part is not found either as integrated into the theory of surface generation, or as a distinctive theory, what determines but a weak connection to the theory of linkages and in general to the theory and practice of machine-tools. The present paper, as well as previous ones on similar topics, proves the kinematic synthesis of machine tools to be a necessary development and a natural part of the theory of surface generation. The paper exemplifies a set of particular cases, characterised by a programmed circle directrix and a straight-line generatrix obtained by any known modality of generation.

Keywords
directrix, generatrix, kinematic structure, linkages, machine-tool, kinematic synthesis

1. Introduction

A body of a given geometry can be obtained by various processing modalities, however with different surface qualities, dimensional precision and (especially) productivity. Among other attributes, each of the processed parts is characterised by one or more surfaces, simple or complex, as the case may be. It is known [1, 2, 3] that a surface is characterised by a directrix and a generatrix, as well as by at least one modality of their physical achievement by means of the tools and machines used for processing.

Without excluding the possibility of identifying also another modality of generation, the theory of surface generation on machine tools [2, 3, 4] asserts that the directrix (D), as well as the generatrix (G) can be:

1) materialized (M; m);
2) generated by copying (Co; co);
3) kinematically generated as the trajectory of a point (Ci_{tp}; ci_{tp});
4) kinematically generated as the envelope of a family of curves (Ci_{fc}; ci_{fc});
5) generated by rolling (R; r);
6) programmed (P; p).

It needs be pointed out that the directrix and the generatrix are generated non-kinematically only if they are materialized. In all cases motion is needed in order to obtain the directrix, even if it is materialized, the motion being known as “primary”.

Further it needs mentioned that in literature [2] generation of the generatrix and the directrix is not approached distinctively as by “copying” and “programming”, as they are considered as being of the same type. The increasingly widespread use of numerically controlled machine tools calls, however, for a clear differentiation between their structure and that of machines (still) using generation by copying from a template.

The set of possibilities for obtaining a surface characterised by a certain directrix and a certain generatrix is given by the set of possible combinations of the obtaining modalities of the respective directrices and generatrices [4÷7]. Table 1 features this aspect, where, for example, Ci_{tp}&co is to be read as D(Ci_{tp})&G(co), that is a modality of surface generation where directrix D is obtained kinematically as the trajectory of a point (Ci_{tp}), and the generatrix G is obtained by copying (co).

Table 1. Possible combinations of surface generation depending on the modalities used for obtaining the directrix and the generatrix

		Directrix					
		M	Co	Ci_{tp}	Ci_{fc}	R	P
Generatrix	m	M&m	Co&m	Ci_{tp}&m	Ci_{fc}&m	R&m	P&m
	co	M&co	Co&co	Ci_{tp}&co	Ci_{fc}&co	R&co	P&co
	ci_{tp}	M&ci_{tp}	Co&ci_{tp}	Ci_{tp}&ci_{tp}	Ci_{fc}&ci_{tp}	R&ci_{tp}	P&ci_{tp}
	ci_{fc}	M&ci_{fc}	Co&ci_{fc}	Ci_{tp}&ci_{fc}	Ci_{fc}&ci_{fc}	R&ci_{fc}	P&ci_{fc}
	r	M&r	Co&r	Ci_{tp}&r	Ci_{fc}&r	R&r	P&r
	p	M&p	Co&p	Ci_{tp}&p	Ci_{fc}&p	R&p	P&p

For the various types of directrices and generatrices, some combinations are found in practice and are described by literature, as illustrations of known modalities of surface generation [1÷3, 8÷11]. The author asserts the conviction that while any directrix-generatrix combination is theoretically possible, only relatively are also practically efficient. The systematic approach explores the entire set of generation possibilities [4], applied or not (yet) in practice, hence being oriented towards discovery and even inventics [12, 13].

In history, three modalities of obtaining a material body have been identified and used:

a) by material removal/subtractive manufacturing (in order to obtain a certain body excess material is removed from an initial body of greater volume),

b) by material redistribution (the matter of an initial body of the same volume as the desired body is redistributed; or the matter of a body of larger volume is redistributed, thus obtaining the desired body plus excess material that is removed), and

c) by adding material/additive manufacturing (matter is added, for example layer-wise, to an initial body of smaller volume, possibly even starting "from scratch"; or matter is added – often in excess – in order to fill a cavity of identical form and volume with that of the desired body).

Various processes of cutting, plastic forming and non-conventional technologies are utilized [4].

In industry, various bodies are obtained by using various machine tools, equipped with adequate tools and devices. The destination of a machine tool, as given in various definitions [2, 14], is to manufacture the components of future, previously defined technical systems. Manufacturing a part entails a deliberate action consisting of a sequence of certain motions such as to obtain the body of desired geometry and characteristics.

Each motion is the result of the action (the final effector) of a generating or auxiliary linkage, as the case may be. Depending on how they are connected, linkages can be independent or partially overlapping.

It is important to point out that:

- The directrix is obtained as a result of a primary motion and possibly one or more secondary motions;
- The generatrix is obtained as a result of one secondary motion, rarely more. If the generatrix is materialized on a tool, then a secondary motion is not necessary;
- In addition, one or more auxiliary motions are needed.

This paper deals only with those generation cases characterised by a programmed circle directrix and a straight-line generatrix. The examples given in the paper are exclusively of the subtractive manufacturing type. The presented kinematic diagrams were devised by using type-linkages [15].

2. Generation with a Programmed Circle Directrix and a Materialized Straight-Line Generatrix

Any of the machining diagrams with a materialized straight line generatrix and a circle directrix obtained by copying [5], obtained kinematically as the trajectory of a point [6], obtained kinematically as the envelope of a family of curves [7] or obtained by rolling can be converted into a machining diagram with a materialized straight line generatrix and a programmed directrix. The discussed example is a fairly simple one, namely contour milling, as shown in Figure 1.

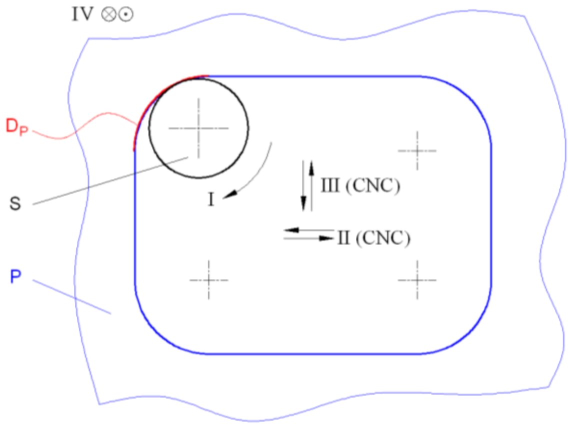

Fig. 1. Machining diagram for milling a cylinder surface,
with a programmed directrix and a materialized straight-line directrix (case P&m)

The primary motion I is a (single direction) rotation and is carried out by the tool.

The feed motions for generating the directrix D_P of the part are motions II and III, both translations and both numerically controlled. They can be carried out by either the tool S, or the part P, or one of the motions by tool S and the other one by the part P.

The generatrix of the part, a straight line, is materialized by the generatrix of the tool S. Consequently, the tool S can be a cylinder mill (or a cylinder-face mill) with a straight-line generatrix, parallel to or tilted in relation to the tool axis, corresponding to a desired generatrix of the part P perpendicular on or tilted in relation to the plane of motions II and III. As the generatrix is materialized, no motion is required for its obtaining.

The machining diagram requires only one auxiliary motion, namely translation IV perpendicular on the plane of motions II and III. The role of motion IV is positioning. Besides the machining process, motions II and II can also ensure positioning.

Figure 2 shows a kinematic diagram of principle corresponding to the machining diagram of Figure 1. The linkages ensuring motions II and III are numerically controlled type-linkages for translation motions. As the considered machining operation is milling, a classical structure main linkage was selected in order to highlight this possibility, even if the primary motion participates in obtaining the programmed directrix.

A manually driven minimalist structure linkage is provided for the one necessary auxiliary motion.

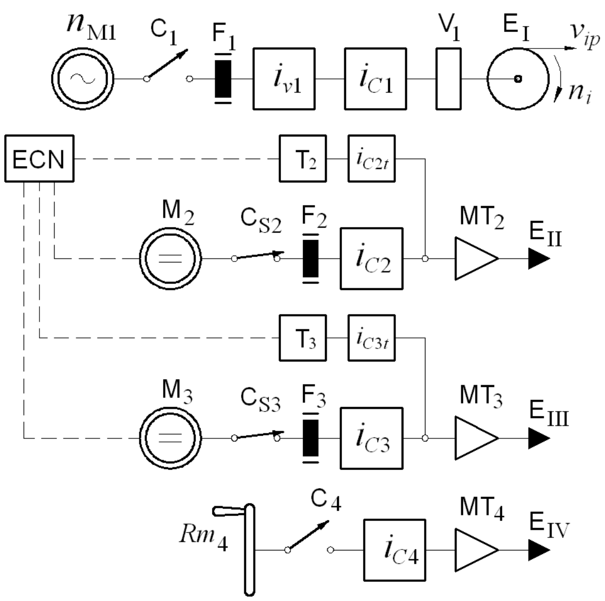

Fig. 2. Kinematic diagram of principle minimum necessary for the case P&m presented in Fig. 1

3. Generation with a Programmed Circle Directrix and a Straight-Line Generatrix Obtained by Copying

The machining diagram that is an example for the case Ci_{fc}&co ([7], fig. 3) can be converted easily into a diagram corresponding to the machining of a surface with a programmed circle directrix and a straight-line generatrix obtained by copying. However, a slightly different diagram, Figure 3, exemplifies the discussed case.

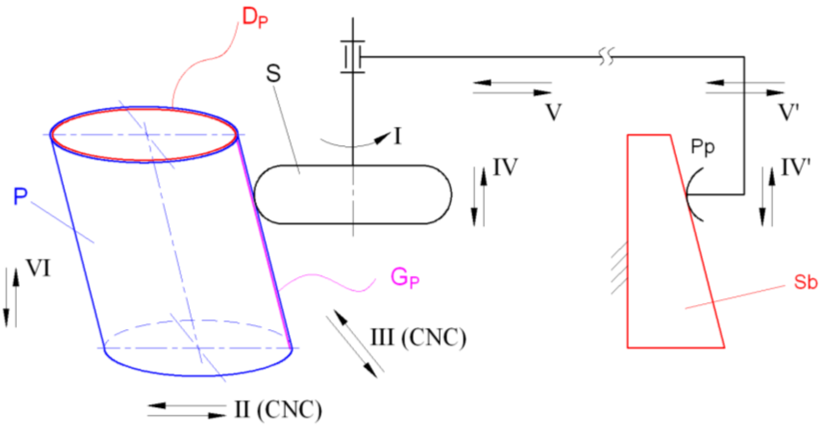

Fig. 3. Machining diagram for the milling of a (tilted) cylinder with a programmed circle directrix and a straight-line generatrix obtained by copying from a template (case P&co)

Tool S carries out the primary motion I, rotation.

In order to obtain the circle directrix D_P of the part, by the combined generation feed motions II and III, both numerically controlled, part P carries out a planetary type motion around the tool S, however without changing its orientation.

After a complete revolution of the part around the tool, the tool S together with the follower P_p carries out a pitch of translation motion IV, and remains in that position until the part carries out the next revolution around the tool. The interruptor INT_4 in the kinematic diagram of principle, Figure 4, associated to the machining diagram of Figure 3, fulfils this very function of fragmenting feed motion IV. Motion IV induces motion IV' of the follower; motions IV and IV' are identical. Motion IV' of the follower determines motion V', carried out also by the follower, however perpendicularly to the direction of motion IV' and in the median plane of template S_b profile. The motion V' is transmitted to the tool a translation V, here of natural magnitude. Also transmission by a proportionality factor is possible, denoted by i_{C5} in the kinematic diagram of principle (Fig. 4).

Under the mentioned circumstances, the generatrix G_P of the part is obtained by copying, but as the envelope of a family of curves, actually of the set of tool generatrices left behind successively along the generatrix of the processed part.

According to the machining diagram of Figure 3 involving milling, the directrix D_P of the part – even if programmed – is also obtained as the envelope of a family of curves, in this case a family of epicycloids described by points on the cutting edges of the tool teeth.

The frame of reference adopted for the machining diagram of Figure 3 is Cartesian, tri-orthogonal and rectangular. In such a frame, typically three auxiliary positioning motions are necessary along the directions of the coordinate axes. Two of the motions are already provided, namely motions II and III, the numerically controlled ones, and can be used for this purpose outside the actual machining process. The third auxiliary motion is provided by motion VI, parallel to motion IV carried out by the part.

4. Generation with a Programmed Circle Directrix and a Straight-Line Generatrix Obtained Kinematically as the Trajectory of a Point

The example used to present this case is the machining diagram of Figure 5, namely the milling of a tilted cylinder surface using a disk cutter as a tool with a circular arc shaped convex generatrix (of relatively large radius) and using the "two feed" method for describing generatrix G_P of the part.

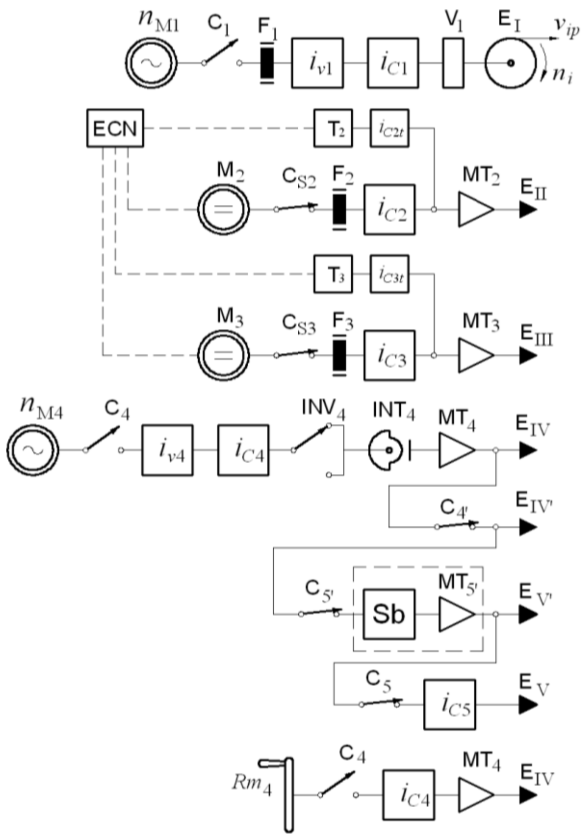

Fig. 4. Kinematic diagram of principle for the case P&co presented in Fig. 3

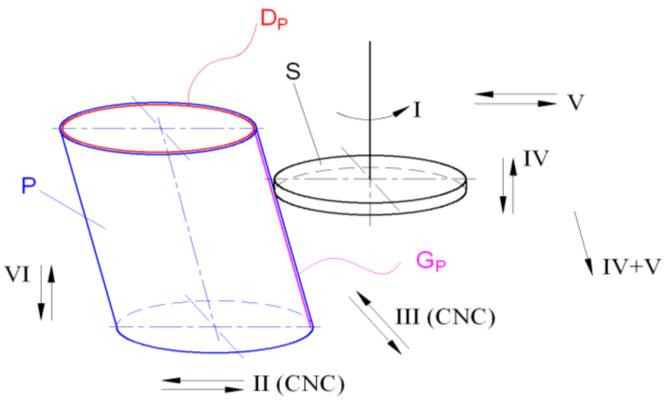

Fig. 5. Machining diagram for the milling of a (tilted) cylinder surface with a programmed circle directrix and a straight-line generatrix obtained kinematically as the trajectory of a point (case $P\&ci_{tp}$)

The tool S carries out the primary motion I, an independent rotation.

The part P carries out the translation motions II and III, numerically controlled, both participating simultaneously in achieving the circle directrix D_P of the part.

In order to achieve the straight laine generatrix G_P of the part, motions IV and V of the tool S are provided, so that their simultaneous action ensures a feed "IV+V" parallel to the generatrix G_P tilted in relation to the plane of motions II and III. The values of motions IV and V form a constant ratio, possibly adjustable (by i_{v5}), what is reflected in the kinematic diagram of principle associated to the machining diagram, Figure 6.

The machining process is evidently of the type "straight line generatrix kinematically obtained as the trajectory of a point" if the feed by direction "IV +V" is sufficiently small in relation to a complete rotation of the tool S around part P consequently to the simultaneous and correlated action of motions II and III. From this point of view the comparison to turning is evident.

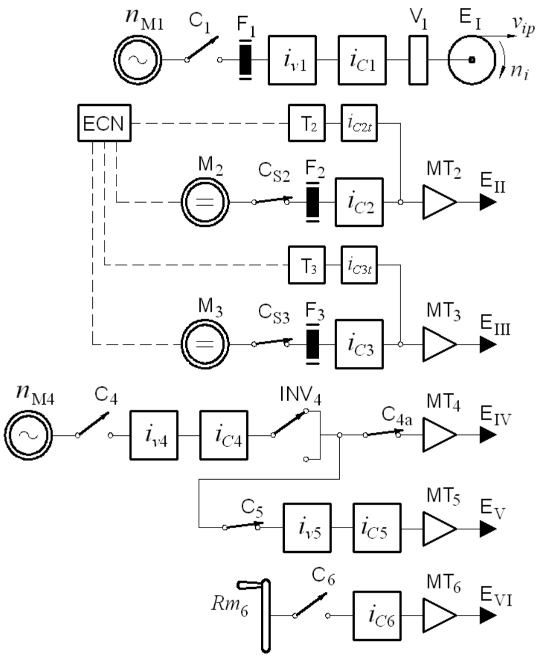

Fig. 6. Kinematic diagram of principle for case P&ci$_{tp}$ presented in Fig. 5

Outside the machining process, motions IV and V operate independently as auxiliary positioning motions.

It needs pointed out that a dedicated motion “IV+V” can be provided along an adequate direction in relation to the plane of motions II and III, motion carried out by a slide, the orientation of that can be adjusted by rotating it by an axis simultaneously perpendicular on the directions of motions IV and V. In this case another linkage is required, motions IV and V retaining only their role as auxiliary positioning motions.

Although redundant in relation to motion IV, an auxiliary motion VI is also necessary, namely a positioning translation carried out by the part P.

5. Generation with a Programmed Circle Directrix and a Straight-Line Generatrix Obtained Kinematically as the Envelope of a Family of Curves

The machining diagram of figure 5 can be easily adapted such as to correspond to a case of machining with a straight-line generatrix obtained kinematically as the envelope of a family of curves: motion “IV +V” simply becomes a discrete translation, Figure 7. In addition it is preferable for the tool S to have an evident curved (convex) generatrix.

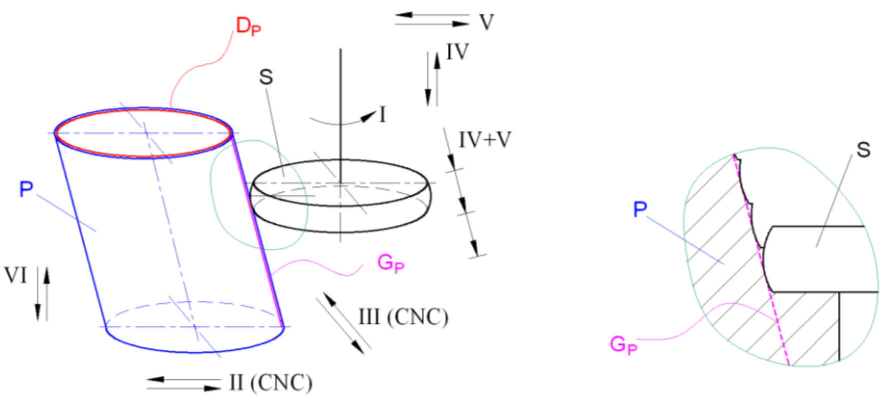

Fig. 7. Machining diagram for the milling of a (tilted axis) cylinder surface with a programmed circle directrix and a straight-line generatrix obtained kinematically as the envelope of a family of curves (case P&ci$_{fc}$)

The directrix D_P of the part is obtained consequently to the primary motion I – the rotation of the tool, and to translation motions II and III, numerically controlled, also carried out by the tool S (motions II and III van also be carried out by the part P).

The generatrix G_P of the part is obtained as the envelope of the tool generatrix segments remaining as traces on the part upon its successive discrete repositioning along the direction of motion "IV+V", motion obtained by the simultaneous action of motions IV and V. In the kinematic diagram of principle, Figure 8, the presence of the interruptor INT_4 indicates that the repositioning motion of the tool in view of obtaining generatrix G_P of the part as an envelope is made intermittently. This is the only necessary difference in relation to the diagram of Figure 6.

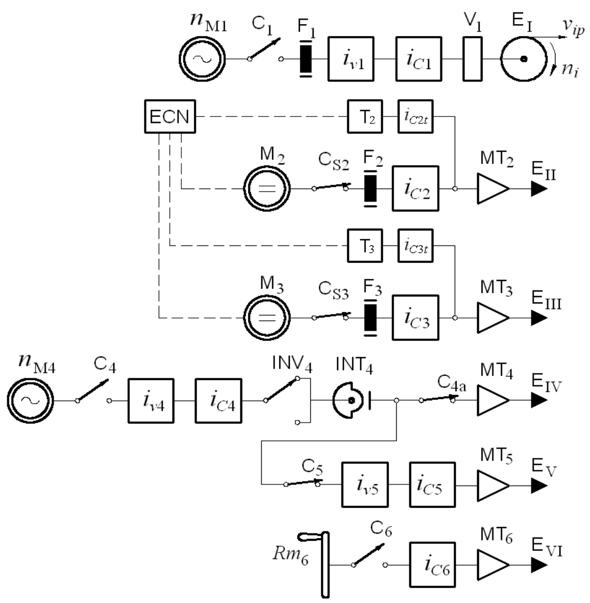

Fig. 8. Kinematic diagram of principle for the case P&ci$_{fc}$ presented in Fig. 7

Manually conducted translation VI is the only exclusively auxiliary motion. It is to be carried out by the tool and appears to be redundant in relation to motion IV.

Outside the working cycle, motions IV and V have independently the role of auxiliary repositioning motions of the tool in relation to the part.

6. Generation with a Programmed Circle Directrix and a Straight-Line Generatrix Described (Kinematically) by Rolling

Figure 9 shows a possible (but most probably not efficient!) machining diagram to exemplify the discussed case. In this milling operation the utilised tool S is a barrel cutter, a profiled cylinder milling cutter with a circular arc generatrix.

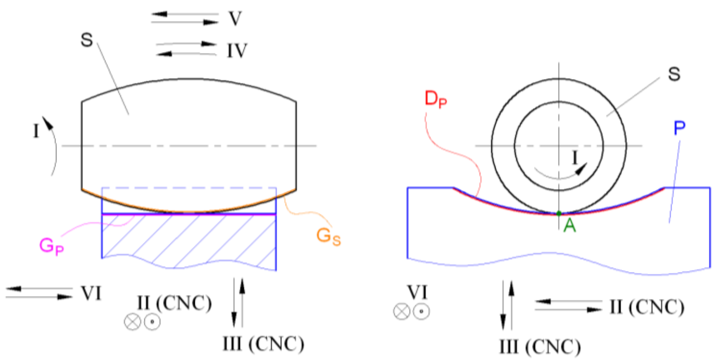

Fig. 9. Machining diagram for the milling of a cylinder surface with a programmed circle directrix and a straight-line generatrix obtained kinematically by rolling (case P&r)

Although the directrix D_P of the part P is "programmed" and the primary motion I – the rotation of tool S participates directly in its achievement, this motion needs not be controlled numerically. As generating motions, translations II and II contribute to the obtaining of directrix D_P. The directrix being "programmed", the generating motions II and III need be numerically controlled.

The generatrix G_P of the part is obtained by rolling the generatrix G_S of the tool (a circular arc) over the generatrix G_P of the part (a straight-line segment). This rolling is obtained by the simultaneous and correlated action of motions IV (rotation) and V (translation). The contact point A between the tool and the part has to be in the plane of motions IV and V, which includes also the axis of the tool S.

Motions IV and V are significantly slower than motions II and III. If motions IV and V were significantly more rapid than motions II and III, the diagram would correspond to generation with a straight-line directrix obtained by rolling and a programmed circle generatrix.

Ensuring an adequate relative positioning of the tool and the part entails also the existence of adequate auxiliary motions. This role can be fulfilled outside the working process by the motions II, III and V, oriented along the directions of coordinate axes of the reference frame adopted for the machining diagram. Also auxiliary motions distinctive from the generation motions can be provided, even if redundant as to the directions of action. An example in this sense is auxiliary motion VI.

Figure 10 shows a kinematic diagram of principle in complete accordance with the machining diagram of Figure 9 described above.

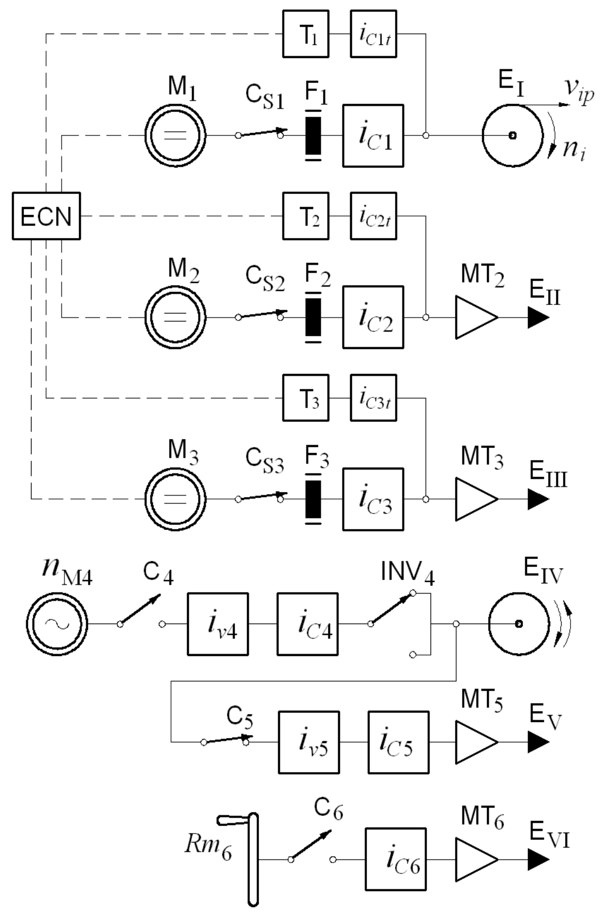

Fig. 10. Kinematic diagram of principle for the case P&r presented in Fig. 9

Motions I, II and III are numerically controlled, *i.e.* all motions participating in the achievement of the directrix on the processed part surface, even if NC is not imperative for motion I.

Motions IV and V have a rigid kinematic link and ensure the obtaining of the generatrix by rolling. According to the diagram, motion V cannot be carried out independently, but only once with motion IV, while the presence of coupling C5 allows conducting motion IV also in the absence of motion V.

7. Generation with a Circle Directrix and Straight-Line Generatrix, both Programmed

Being programmed, the directrix and the generatrix can be any curves, 2D or 3D, simple or complex, analytical or non-analytical. Consequently, any surfaces can be generated, as long as the adequate relative positions and orientations of tool and part are ensured. This being pointed out, it is evident that generation with a circle directrix and a straight-line generatrix, both programmed, is a relatively simple particular case.

A good example can be the machining of conical surfaces by milling with ball nose cutters (Figure 11) (or with a face cutter with disk inserts, Figure 12), according to the diagram of Figure 13.

The diagram is minimalist, at least in the sense that the axis of the tool is parallel to the axis of the processed conical surface, what ensures the maintaining of the tool orientation in relation to the part in any point of the directrix D_P of the part (and in any point of it generatrix G_P). If the axis of the tool were tilted in relation to the axis of the part, then the tool should also carry out a pivot motion, for example by an axis parallel to the axis of the part, its purpose being to ensure the (optimum) orientation of the cutter's spherical ball nose in relation to the machined surface of the part.

The primary motion I is a rotation, carried out by the tool by its axis. It needs not be numerically controlled, but is preferable in this case.

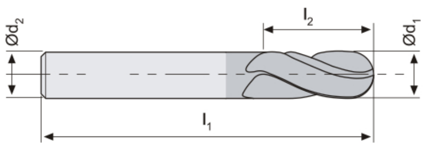

Fig. 11. Ball nose milling cutter [16]

Fig. 12. Face milling cutter with disk implements [17]

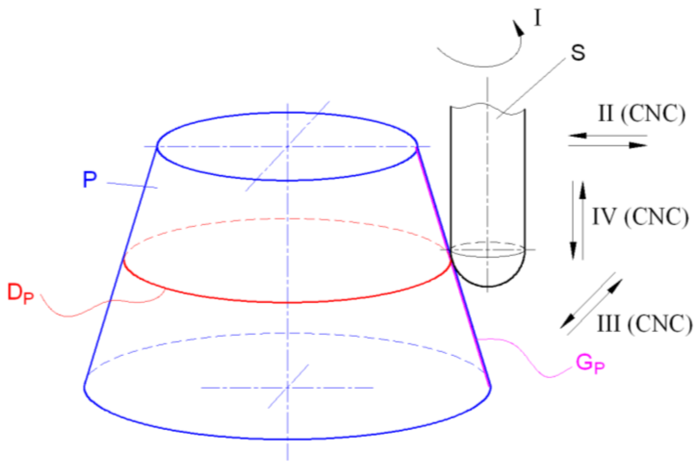

Fig. 13. Machining diagram for the milling of a conical surface with a circle directrix and a straight-line generatrix, both programmed (case P&p)

In order to obtain the directrix D_P of part P, which is a circle of variable diameter depending on its position along the axis of the machined part, required are (in addition to the primary motion I) the generation feed motions II (longitudinal translation) and III (transversal translation), both numerically controlled.

In order to obtain the generatrix G_P required are motions II and IV (vertical translation), both numerically controlled. Motions II and III are continuous and variable. Motion IV can be discrete with a small pitch (in which case the tangency point between the tool generatrix and the part generatrix describes a family of circles, directrices of the machined surface) or continuous, with a very small velocity in relation to motions II or III (in which case the mentioned tangency point describes a small pitch conical helix).

The presented case allows the highlighting of a rather rare situation, when one of the generation feed motions participates simultaneously in the obtaining of both the directrix and the generatrix. In the present case this motion is motion II, at least when motion IV is continuous.

Figure 14 shows a kinematic diagram of principle corresponding to the machining diagram of Figure 13.

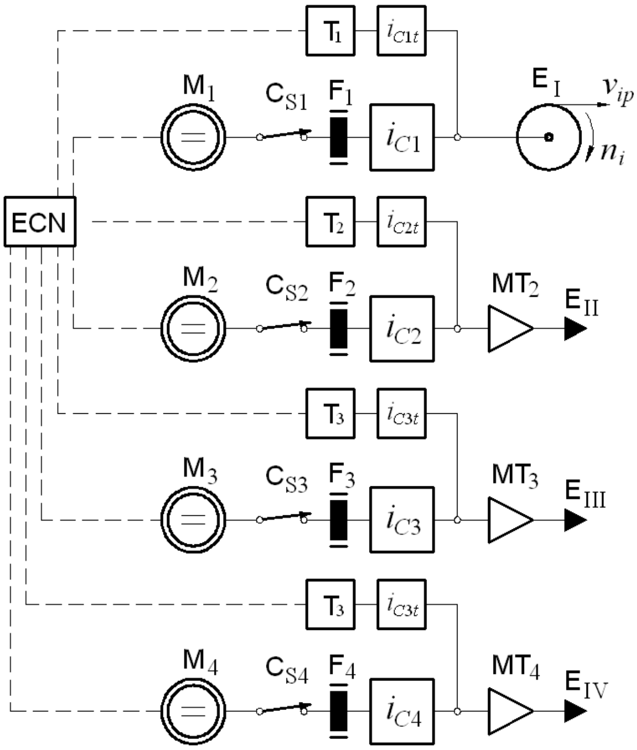

Fig. 14. Kinematic diagram of principle for the general case P&p, in particular for the one presented in Fig. 9

No auxiliary positioning motion is provided, motions II, III and IV (oriented along the axes of the frame of reference) being the ones that can fulfil this role outside the actual machining process.

8. Conclusions

A body of a given geometry can be obtained by various processing modalities, however with different surface qualities, dimensional precision and (especially) productivity.

The set of possibilities of achieving a surface characterised by a certain directrix and a certain generatrix is given by the set of possible combinations of the obtaining modalities of the respective directrices and generatrices. Any directrix-generatrix combination is theoretically possible, however only relatively few are also practically efficient. The systematic approach explores the entire set of generation possibilities, applied or not (yet) in practice.

The evolution over the past decades of industrial knowledge and practice call for the further development of this theory of surface generation, mainly to include an essential part that addresses the kinematics of machine tools in a systematic and explicit manner. At present this latter part is not found either as integrated into the theory of surface generation, or as a distinctive theory, what determines but a weak connection to the theory of linkages and in general to the theory and practice of machine-tools. The present paper, as well as previous ones on similar topics proves the kinematic synthesis of machine tools to be a necessary development and a natural part of the theory of surface generation.

The paper exemplifies a set of particular cases, characterised by a programmed circle directrix and a straight-line generatrix obtained by any known modality of generation. Each of the six theoretically possible cases is exemplified by both machining and kinematic diagrams of principle based on the utilisation of type-linkages. The given examples are aimed mainly at proving that what is technically possible is not necessarily efficient.

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