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Flank Modifications in Bevel Gears Using a Universal Motion Concept

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American Gear Manufacturers Association



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Abstract

The use of free form bevel gear generators was limited by the processes currently available to cut bevel and hypoid gears with face mill cutter heads. Since a free form cutting or grinding machine has three rotational and three linear freedoms it is possible to perform all possible relative movements between the cutter and the work during the generation process. The trial to use the six axes of the free form machine directly in order to produce new and more advanced flank forms had never a real break through since those axes had no relation to the gear theory. The universal motion concept is applied to axes of the basic gear generation model only. It allows each of them to change the setting during the generation process according a higher order function. This approach enables a free form gear machine to produce an entire variety of modifications to the flank surfaces.

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Flank Modifications in Bevel Gears Using a Universal Motion Concept

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1. Introduction

The development of free-form gear cutting machines was originally based on the idea of designing a machine with a minimal number of freedoms that would allow applying all the existing bevel gear cutting processes with face cutters. This included single-index applications as well as continuous processes (face milling and face hobbing).

The design concept of a six-axis free-form machine met the challenge of today's sophisticated controller and electronic drive technology. A tool can take up any position in space, relative to a workpiece, using only three translatory and three rotational degrees of freedom. This fact fulfilled the basic requirement of a free-form machine, namely to provide the relative movement of a cutter (in space) to a workpiece necessary to produce a bevel gear. The basic design of a free-form bevel gear cutting machine is shown in **Figure 1**.

The simplicity of the concept in Figure 1 eliminates the complex elements of the traditional gear cutting machine. Except for the swinging base pivoting around the machine center, there is no similarity to the traditional cradle-style machine. Geometrical conditions and kinematic processes of the cradle-style machine are transformed into the

motion processes of the free-form machine in such a way that an exactly identical tooth flank geometry is produced. This needs complex transformation calculations [1]. The resulting gear cutting process is completely identical, employing the same process parameters and the same cutting tools.

For the convenience of the designer and manufacturer of gearing familiar with the traditional machines, an operator interface for data input into the controller was developed, featuring settings identical to the cradle-style machine. This way, an angle for cutter tilt or eccentric can be entered into the controller, even though these elements are not physically present. Another benefit of this convention is the fact that only about eight numerical values are necessary to exactly define the complex motions of a free-form machine. This indicates the extraordinary importance of the so-called "basic (machine) setup data" each of which is relevant in the theory of gearing.

An extension of the free-form machine, which had proved to be well suited for all currently known processes, was to utilize it further for developing innovative tooth flank

corrections. Considering individual axes of the free-form machine showed that separate axis motions were not appropriate for significant gear geometry improvements.

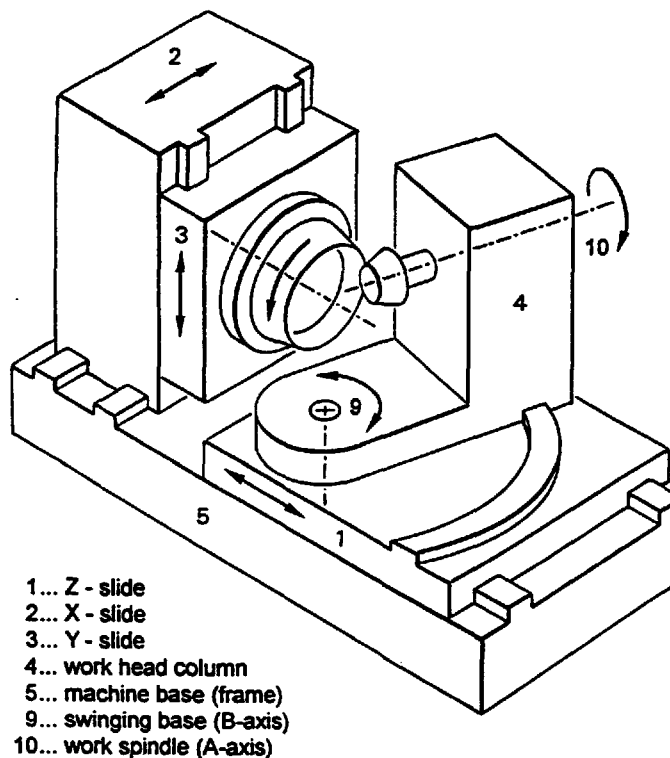


Figure 1: Concept of the free-form bevel gear machine

The influence of corrective motion of a specific axis on the tooth form continuously changes during the generating process. This condition made it necessary to activate a combination of motion freedoms at all times, in order to achieve a useful effect on the tooth flank. To avoid having to "cram" the machine controller with three or more polynomials for correction, the relationship between three or more axes was combined to a corrective effect, addressed by one higher-order polynomial (e. g. radial tilt [2]). This approach, being only partly acceptable with respect to gear theory, lead to a series of problems.

As, for the purpose of analysis and optimization, tooth flank surfaces must be generated by calculation, a virtual gear cutting machine concept exists as computer software, modelled after a basic gear cutting machine. This model possesses all the degrees of freedom of a traditional cradle-style gear cutting machine, the motions of the real machine being simulated by computer. This

allows the calculation of discrete flank surface points for use in tooth contact analysis, coordinate measurement and finite-element calculation.

When corrections are combined, the virtual basic machine - just like the real gear cutting machine - has to activate a combination of several axes according to a mathematical principle with only a single polynomial. Therefore, the object is no longer a mere basic machine without machine constants, where the axes are only theoretically relevant. Auxiliary axes must be defined and formal relationships must be programmed.

An idea of correction and optimization cannot be limited to the correction program itself, but must be extended to the flank generation program and the machine controller software, as well. Likewise, any improvements, changes or additions are not limited to the correction program, but also call for an update of the flank generating software and the machine controller software. This can cause logistics problems and has only limited potential for the requirements of gearing theory.

2. Finding a model for correction

When looking for a suitable model to optimize and correct bevel gear tooth flanks, one can easily come to the conclusion that kinematic processes are involved rather than geometrical ones. All geometrical grades of freedom have been utilized in the traditional gear cutting machine. The question whether there may be other geometrical changes allowing new, still unknown corrections to be realized with the axes of the traditional cradle-style machine, must be answered: no. This is because the traditional cradle-style machine is designed after the coordinate system used for defining gear geometry in which all development calculations are made.

All geometrically relevant degrees of freedom can be addressed in this coordinate system - which is why the real machine was built after it and remained almost unchanged for more than half a century. This fact indicates that the search for new degrees of freedom, with respect to the known coordinate system, points to a kinematic solution.

On the other hand, all geometrical parameters of classical gear cutting theory are transposed by cradle roll into kinematic motions in the free-form machine. When a geometrical setting value of the traditional machine becomes a motion sequence of five to six axes in the free-form machine, a traditional machine's kinematic sequence changes into one overlying another kinematic motion sequence, in a vector space. The vector aspect becomes important, as in the free-form machine, the classical coordinate system is continuously moving, changing its location and orientation. That means that, for instance, a modified movement of the sliding base (helical motion) in the free-form machine is not oriented lengthwise to the machine frame, but is skew in space and changes its direction continuously.

It is evident from the above that new correction effects will always be of kinematic nature and that they are already available in a free-form machine, without additional

mechanical elements. The last paragraph makes clear that the coordinate system of the free-form machine does not offer a mathematically elegant possibility to calculate corrections relevant to tooth geometry.

The solution to this problem is most simple. The best basis of all bevel gear geometry calculation is the basic model shown in **Figure 2**. The model includes the work axis $Z_{1,2}$ with the virtual work gear and the tool representing a tooth of the virtual mating gear, rotating around its axis $Y_{4,5}$ (generating cradle axis). This fact will remain to be important even in alternative flank geometries, because the final product will still be a gear rotating around its axis, meshing with a mating gear. Significant correction effects, which are only possible with free-form machines, must be translatory and rotational changes of the coordinate axes of the basic gear cutting machine model during generation of the tooth form.

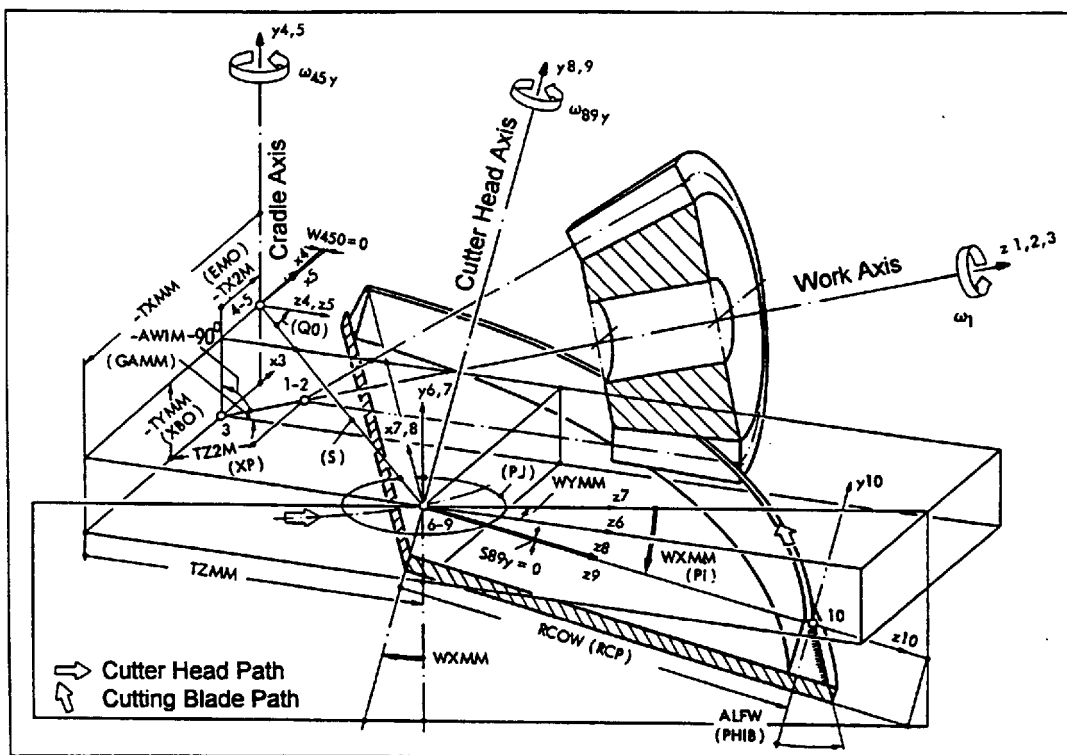


Figure 2: Virtual basic gear cutting machine with its setting parameters

Figuratively speaking, this means changing all machine settings of a cradle-style machine during the generating process - which would not have been possible in a traditional machine, without a realistic effort. The calculation effort, however, is small. After converting the basic machine geometry and **kinematics** into motion coordinates of a free-form machine, it is possible to

manufacture an advanced, optimized tooth form, without additional effort, in the same cutting time and with the same precision as a traditional gear.

These considerations and the statements made in the following paragraphs are equally applicable to single-index and continuous processes, for cutting and grinding.