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Comparison of modeling methods to determine cutting tool profile for conventional and synchronized whirling

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Abstract

The determination of cutting tool profiles for machining operations with coupled rotational kinematics like gear and screw generation can be a complex task which is executed by either numerical or analytical methods. The cutting tool profile for whirling is derived from process parameters and desired workpiece geometry by both a numerical dexel-based model and an analytical model based on the condition of tangential motion. The models are adapted to a process variant of whirling with synchronized rotation of tool and workpiece and compared regarding accuracy, computation time and geometrical flexibility.

Keywords: kinematics; analysis; whirling; meshing; screw

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1. Introduction

Whirling is a variant of milling with a circular tool holder that encompasses the workpiece and the cutting tools rotating internally, see Fig 1. The axis of the workpiece is inclined to the tool holder axis by the tilt angle. The workpiece is positioned at an offset in the ring.

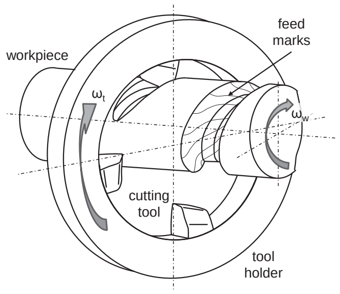

Fig. 1. Machining of a screw geometry by whirling [1]

Whirling is used primarily for the production of thread geometries like screws and worm gears. The resulting workpiece geometry is defined by the cutting tool profile and process kinematics. In processes with two non-parallel axes like whirling, the workpiece is formed in a generation motion. The resulting workpiece geometry complies with the envelope of the generation motion of the cutting tool profile. Thus the cutting tool profile cannot only be derived from the targeted workpiece geometry but has to be determined by taking the process kinematics into consideration. In some process settings the generation motion leads to undercutting of the workpiece. If undercutting is detected early on in the design of the process, it can be compensated by changing the cutting tool profile or process parameters. The cutting tool profile can be determined by different methods both numerical and analytical. The numerical models are based on spatial and temporal discretization of the targeted workpiece geometry and the machining motion. One method is to project the intersection of the workpiece geometry and the cutting tool plane pointwise onto the cutting tool plane for a finite number of steps of the relative motion.

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The cutting tool profile can be constructed by deriving the envelope of all projected points of the workpiece geometry. The envelope method is often used for analysis of gear generation [2] and was successfully applied to whirling [3]. Although the determination of non-convex envelopes is a numerical problem without singular solution [4, 5]. Another numerical method is determining the cutting tool profile by pointwise trimming of a blank cutting tool in each step by detecting intersections with the surface of the workpiece. The intersections are found by elementwise comparison of the point positions. The trimming of intersecting geometries in machining processes can be simulated efficiently by dexel modeling [6, 7]. Analytical models are based on the equation of meshing and solved by methods of differential geometry. This method is used for determining the cutting tool profile for gear grinding processes and milling of screw geometries like pump rotors [2, 8]. While analytical problems can be solved in form of an explicit formula this is not possible in general [9]. When this is the case the set of analytic nonlinear formulae describing the problem can be solved numerically [10].

Nomenclature

ω_t	rotational speed of the tool
ω_w	rotational speed of the workpiece
h_{max}	cutting thickness
v_t	tangential speed of the tool (cutting speed of conventional whirling)
v_w	tangential speed of the workpiece
v_{rel}	relative speed between tool and workpiece (cutting speed of synchronized whirling)
N_w	surface normal of the workpiece

2. Whirling process variants

The performance of thread whirling exceeds other machining processes at meeting high geometric and surface quality requirements under difficult to machine conditions. In contrast to turning the intermittent cut leads to fragmented chips and allows the cutting tool to cool down. At the same time the concave tool motion encompasses the workpiece diameter resulting in steadier cutting conditions and smaller feed marks compared to thread milling. Screws for medical applications are made of biocompatible materials like titanium most of which are considered difficult to machine. Nonetheless surface quality and geometric accuracy has to be high as no consecutive grinding process is applied. These requirements and a high productivity are best met by whirling although the efficiency of the process is limited by the material removal between the major diameter and the diameter of the feedstock necessary for the head of the screw [11]. This material can either be removed by turning before the whirling operation or during whirling with the whirling tool. The first increases the main time of the process, the second increases tool wear. Both may render the process uneconomic.

Synchronized whirling a variant of the whirling process was developed for the generation of multi-start threads in a single pass [12]. Multiple thread starts are cut by increasing the rotational speed of the workpiece so that it revolves around its axis in between the engagement of two consecutive cutting tools. Thus each cutting tool meets a different thread. The rotational speeds of tool holder and workpiece are synchronized in a whole-numbered ratio according to the number of thread starts and cutting tools in the tool holder in order to not remove the crest. Furthermore the tilt angle between the axes of the workpiece and the tool holder is to be adapted. The synchronized whirling process allows the integration of turning operations due to the higher rotation speed of the workpiece. The parallelization of turning and whirling was shown to reduce main time in the production of bone screws and to increase productivity significantly [13].

2.1. Modeling of whirling processes

The kinematics of the conventional whirling process can be modeled by transformations between the tool holder and workpiece coordinate systems in homogenous coordinates [3]. The tool holder axis is moved out of the workpiece axis by the eccentricity and rotated around the eccentricity by the tilt angle. The tilt angle corresponds with the lead angle of the workpiece. The cutting tool rotates around the tool holder axis. The workpiece shifts along its axis by the feed rate and rotates accordingly as the zone of engagement moves along the thread. The synchronized whirling process differs from conventional whirling by an additional rotation of the workpiece. The process variant sets different constraints to the process parameters like a fixed ratio of rotational speeds between tool and workpiece and a different tilt angle. The adaptation of the tilt angle is necessary to align the resulting vector of relative motion between cutting tool and workpiece with the lead of the thread, as illustrated in figure 2.

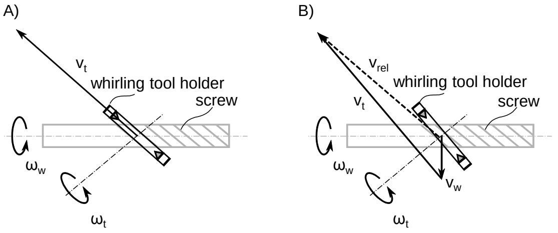

Fig. 2. Kinematics of (A) conventional whirling and (B) synchronized whirling with the combination of speed vectors

The synchronized whirling process with two rotating axes can be modeled by attaching the observing coordinate system to the workpiece. Thus the additional rotary motion of the workpiece is projected to the tool holder. Effects of the modified process parameters on the cutting conditions can be derived easily by this modeling approach, as illustrated in figure 3. For example the positive impact of the additional rotation on cutting thickness. The projection of the workpiece rotation to the tool holder shifts the axis during cutting tool engagement and the motion encompasses the workpiece closer. The additional motion stretches the chip geometry and decreases cutting thickness while feed per tooth and chip volume stay constant.