General Tool Correction for Five-Axis Milling

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In this paper a method is presented by which cutter location data can be determined for any type of milling tools defined according to DIN 66215 whereby any point of the tool can be defined as the contact point. In addition, the cutter location point for 5-axis milling can be determined using a single formula for any type of milling tool.

Keywords: CAD/CAM; Cutter location data; Five-axis milling; Tool correction

1. Introduction

Most current CAD/CAM systems contain a module for 3- and 5-axis milling in which the cutter location data can be calculated. However, not all types of milling tools which are used in manufacturing are covered by these modules, which results in restrictions in the selection of a milling tool.

In order to optimise the milling process this module should cover as many types of milling tools as possible for 3- and 5-axis milling and allow any point of a tool to be defined as the contact point for 5-axis milling. In addition, it may be desirable that the calculation of cutter location point of any tool can be done using a single generalised formula. The determination of cutter location data from the workpiece geometry and tool data is usually designated as tool correction.

2. Geometric Description of Milling Tools

According to DIN 66215 [1] a milling tool can be described as in Fig. 1, where

- \( d \) = tool diameter
- \( r \) = fillet radius
- \( e \) = horizontal distance
- \( f \) = vertical distance
- \( a \) = angle between horizontal and face
- \( b \) = angle between vertical and generating line
- \( h \) = cutter length

This description covers both milling tools and drills and can be used as a general geometric description of tools. In Fig. 2 possible tool types for 5-axis milling [2] are displayed. Their definitions are:

1. Cylindrical milling cutter:  
   \( d, r = 0, e = \frac{1}{2}d, f = 0, a = b = 0, h \)

2. Toroidal milling cutter:  
   \( d, r, e = \frac{1}{2}d - r, f = r, a = b = 0, h \)

3. Ball end milling cutter with cylindrical shank:  
   \( d, r = f = \frac{1}{2}d, e = a = b = 0, h \)

4. Ball end milling cutter without shank:  
   \( d, r, f = r, e = a = 0, b, h \)
5. Barrel milling cutter:
\[ d, r, e, f, a = 0, b, h \]
6. Conical milling cutter:
\[ d, r = f = a = 0, e = \frac{1}{3}d, b, h \]
7. Ball end milling cutter with conical shank:
\[ d, r = e = a = 0, f = r, b, h \]

For a milling tool to be correctly defined according to DIN 66246 [1] the above parameters must fulfill the following constraints (see Fig. 3):

\[ d, r, a, f, h \geq 0 \]
\[ 90 - b > a \]
\[ h \geq h_{\text{min}} = y_c \]
\[ x_b, x_c \geq 0, y_c \geq y_b \geq 0 \]

Point \( B = (x_b, y_b) \) and \( C = (x_c, y_c) \) can be calculated as follows:

\[ x_b = - \frac{F_b + \sqrt{(F_b^2 - 4E_bG_b)}}{2E_b} \]
\[ y_b = x_b \tan a \]

where

\[ E_b = 1 + \tan^2 a \]
\[ F_b = -2e - 2f \tan a \]
\[ G_b = e^2 + f^2 - r^2 \]

and

\[ y_{c1}, y_{c2} = \frac{-F_c \pm \sqrt{(F_c^2 - 4E_cG_c)}}{2E_c} \]
\[ y_c = \min (y_{c1}, y_{c2}) \]
\[ x_c = \frac{1}{2}d + (y_c - \frac{1}{2}d \tan a) \tan b \]

where

\[ E_c = 1 + \tan^2 b \]
\[ F_c = \tan b (d - 2e - d \tan a \tan b) - 2f \]
\[ G_c = f^2 + \frac{1}{4} (d - 2e - d \tan a \tan b)^2 - r^2 \]

A milling tool is not correctly defined, if \( F_b^2 - 4E_bG_b < 0 \) or \( F_c^2 - 4E_cG_c < 0 \). The transition at \( B \) or \( C \) is tangential if \( F_b^2 - 4E_bG_b = 0 \) or \( F_c^2 - 4E_cG_c = 0 \).

3. Tool Axis Orientation in 5-Axis Milling

The workpiece surface is usually defined in a CAD system and has the following form

\[ P = P(u, v) \]

where \( u \) and \( v \) are parameters of a parametric surface. The following describes any contact curve \( P(w) \) of the surface:

\[ u = u(w), v = v(w) \]

The unit normal vector \( n \) and the unit tangent vector \( t \) at any point with respect to \( w \) can be determined by

\[ n = \frac{P_u \times P_v}{|P_u \times P_v|} \]

and

\[ t = \frac{P_u \frac{du}{dw} + P_v \frac{dv}{dw}}{|P_u \frac{du}{dw} + P_v \frac{dv}{dw}|} \]

where \( P_u \) and \( P_v \) are partial derivatives at the point on the surface.

In the determination of the cutter location data it is useful to define a contact point coordinate system (CPCS) \( (t, q, n) \) [3] at the contact point \( P \), where \( q = n \times t \). The CPCS and the unit tool axis vector \( v_a \) are given in Fig. 4. The relation between \( n \) and \( v_a \) can be described with the following two angles: fall angle \( \alpha \) [2, 3] and rotation angle \( \beta \) [3] (Figs. 4 and 5). The concept of both angles is generally used in 5-axis milling of curved surfaces.

In the case of 3-axis milling the tool axis remains constant. Five-axis milling has two additional degrees of freedom by which the tool axis can be varied. With the help of two angles \( \alpha \) and \( \beta \), the tool axis vector \( v_a \) can be obtained as follows.

From the reference position, which is the surface normal \( n \), \( v_a \) is firstly rotated \( \alpha \) degrees about the axis \( q \) and then \( \beta \) degrees about the axis \( n \). Therefore we can write

\[ v_a = R_{\alpha} \cdot R_{\beta} \cdot n \]

where

\[ R_{\alpha} = \cos \alpha - \sin \alpha \]

\[ R_{\beta} = \cos \beta - \sin \beta \]

\[ n = \frac{P_u \times P_v}{|P_u \times P_v|} \]

\[ t = \frac{P_u \frac{du}{dw} + P_v \frac{dv}{dw}}{|P_u \frac{du}{dw} + P_v \frac{dv}{dw}|} \]

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\[ R_{\alpha} = \cos \alpha - \sin \alpha \]

\[ R_{\beta} = \cos \beta - \sin \beta \]

\[ n = \frac{P_u \times P_v}{|P_u \times P_v|} \]

\[ t = \frac{P_u \frac{du}{dw} + P_v \frac{dv}{dw}}{|P_u \frac{du}{dw} + P_v \frac{dv}{dw}|} \]

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