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Cutting Forces Calculation and Experimental Measurement for 5-axis Ball End Milling

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Abstract

Calculation technique for cutting forces prediction in 5-axis ball end milling is worked out and realized as computational program. The curvilinear cutting edge is divided into small segments, and the path for each segment is defined. The local cutting forces are than calculated from local chip thickness using mechanistic approach. Total cutting force is a sum of local forces, acting on each of the elements. The influence of tool orientation in 5-axis milling on the cutting force amplitude and impulse shape is investigated. Series of cutting tests with cutting force measurement for various tool orientations are carried out to validate the calculations. The results are applicable for optimization of 5-axis finishing of flexible workpieces such as turbine blades.

1. Introduction

Metal cutting requires significant force to be applied by tool on workpiece. The value of cutting force determines a number of important issues, such as spindle torque and power, deflections and vibrations of tool and workpiece, cold-hardening and residual stresses in workpiece surface layer. As a result, cutting force value can influence on dimensional form accuracy and surface finish obtained.

For finish milling of a flexible workpiece such as turbine blade some of the most important isuues are workpiece deflections and vibrations during machining. Excessive workpiece vibrations can instantly cause workpiece spoilage because of heavy overcut. Cutting process parameters are to be optimized carefully to reduce cutting forces and avoid workpiece vibrations [1], [2]. With five-axis machining one can also choose tool orientation to achieve the best result. However, it may not be clear which tool orientation is preferable in this or that particular situation.

This paper is dedicated to cutting force computational prediction and investigation of tool orientation influence on cutting force value. Five-axis ball end milling with any given tool orientation is considered.

2. Cutting force calculation

According to mechanistic approach, one can evaluate cutting forces for given chip thickness using cutting force coefficients for the specified material [3], [4]:

$$F_t = k_{tc}ah + k_{te}a \quad (1)$$

$$F_n = k_{nc}ah + k_{ne}a$$

Here F_t and F_n are tangential and normal cutting forces (figure 1), h is undeformed chip thickness, a is chip width, k_{tc}, k_{te}, k_{nc} and k_{ne} are cutting force coefficients. One can get cutting force coefficients values for the material in hand from reference data or refine them from cutting tests with dynamometer.

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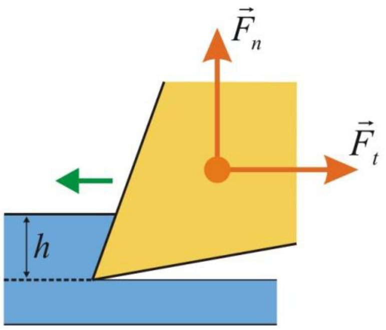
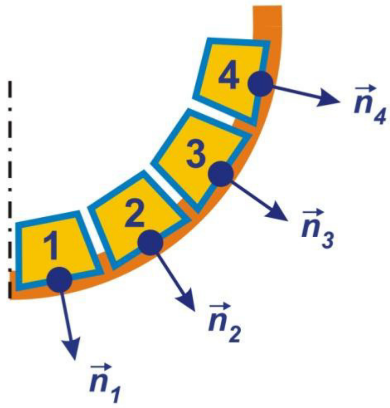
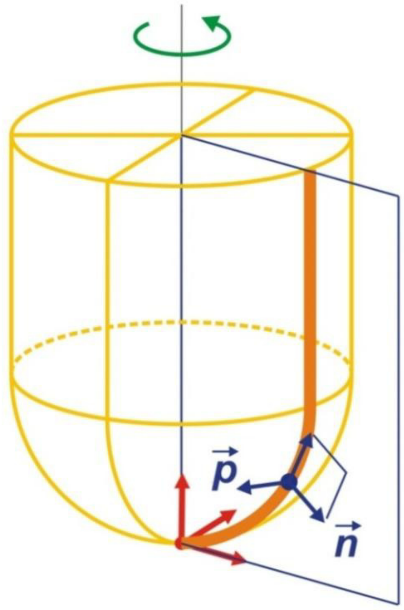


Figure 1: Tangential and normal cutting forces.



(a)



(b)

Figure 2: Cutting edge model. (a): cutting edge representation as a number of small segments. (b): segment directing vectors.

For ball end milling the chip thickness varies significantly along the curvilinear cutting edge [5], [6]. To calculate cutting forces using mechanistic approach the cutting edge is divided into a number of small similar segments (Figure 2a). Each segment is considered to have a strait cutting edge of certain length, and the instant segment spatial position is specified by segment central point coordinates and two unit directing vectors giving segment orientation (Figure 2b). Travel of all segments is traced during rotation and feed-motion of the tool considering its complex 5-axis orientation, and cutting edge trajectory is obtained as a cloud of points. The local chip thickness for the certain segment and certain time moment is than calculated as a distance from the segment current position to the trajectory of cutting edge previous pass.

Workpiece boundaries should be kept in mind to indicate whether the segment is in cut. A simple rectangular workpiece is considered in this paper. One can use a triangular stock model to simulate complex part machining [7-11].The vectors of local cutting forces, acting on the segment are than calculated. Segment directing vectors are used to indicate cutting forces directions. The vector of total force, acting on cutting edge is than calculated as a sum of local cutting forces.

3. Implementation of the calculation technique developed

The influence of tool orientation on cutting forces is investigated using the calculation technique described. Cutting force component normal to workpiece surface is mainly under consideration, as namely that component causes deflections and vibration of a flexible workpiece.

Finish milling of compressor blade is considered as an example of operation where one of four main tool orientations can be used (Figure 3). Milling across blade span downwards or upwards corresponds to negative or positive lead angle respectively and zero lean angle (Figures 4, (a) and (b) tool orientations). Milling along blade span downwards or upwards corresponds to negative or positive lean angle and zero lead angle (Figures 4, (c) and (d) tool orientations). The designation of tool orientation variants by letters (a, b, c, d) on Figure 4 is kept identical hereinafter through all the paper.

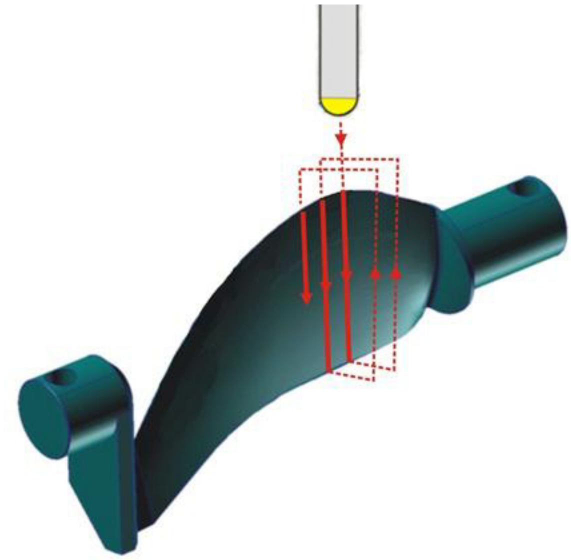


Figure 3: Finish milling of compressor blade.

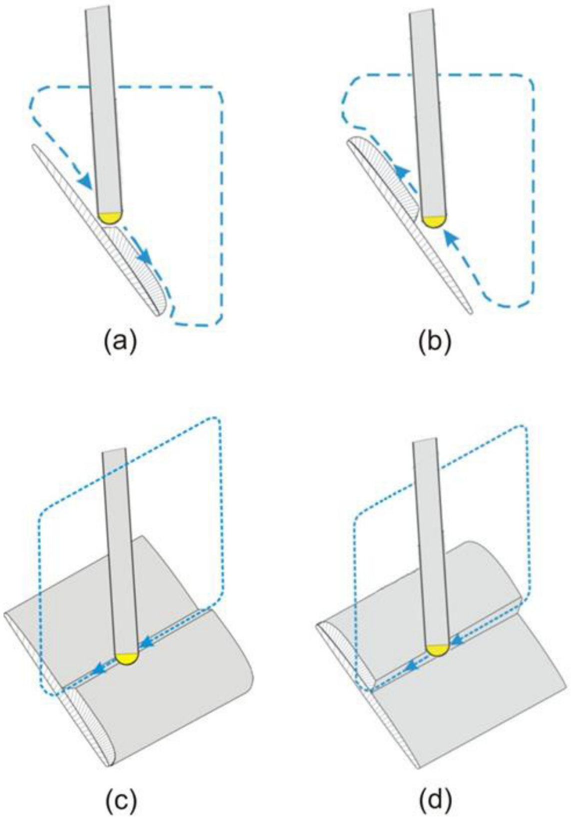


Figure 4: Four main tool orientation variants for compressor blade milling.

Calculated cutting force impulses (the component normal to workpiece surface) for regarded tool orientations and down milling with all other cutting process parameters equal are shown on Figure 5. The results are nearly the same for downward and upward milling, but significant differences in force impulses amplitudes, durations and shapes are observed for milling across or along blade span.

The corresponding cutting force impulses for up milling (tool orientations (a) and (c)) are shown on Figure 6. Significant reduction in cutting force amplitude (the force component normal to workpiece surface) as compared to down milling is observed. This is due to counteraction of tangential and normal cutting forces why the force component normal to workpiece surface is significantly smaller for up milling than for down milling. For up milling the force vector is of the same amplitude but it is orientated mainly along workpiece surface.

4. Cutting test validation

Series of cutting test were carried out to validate the results of calculations. 5-axis ball end milling of a rectangular workpiece for various tool orientation and cutting parameters were made and cutting forces were measured with dynamometer. Good coincidence with calculated data and experimental confirmation of theoretical issues stated above were obtained. On Figure 7 the measurement results for selected cases are shown to demonstrate that the cutting force (the component normal to workpiece surface) is influenced by tool orientation (compare (1) and (2)) and is much smaller for up milling rather than for down milling (compare (2) and (3)).

5. Conclusion

Calculation technique for cutting forces prediction in 5-axis ball end milling is worked out and validated by cutting tests. The influence of tool orientation in 5-axis milling on the cutting forces is investigated. Different cutting force impulse shapes and amplitudes are obtained for various tool orientations and machining strategies. It was learned by means of calculations and experimentally confirmed that the cutting force component normal to workpiece surface can be significantly reduced by using up milling with negative lead angle, which normally corresponds to milling across blade span downwards. Thus, flexible workpiece vibrations can be significantly reduced by using such machining strategy. Further investigations including time domain workpiece vibrations simulation are to be carried out to explore precisely how tool orientation can influence workpiece vibrations amplitude and resultant dimensional form error and surface finish.

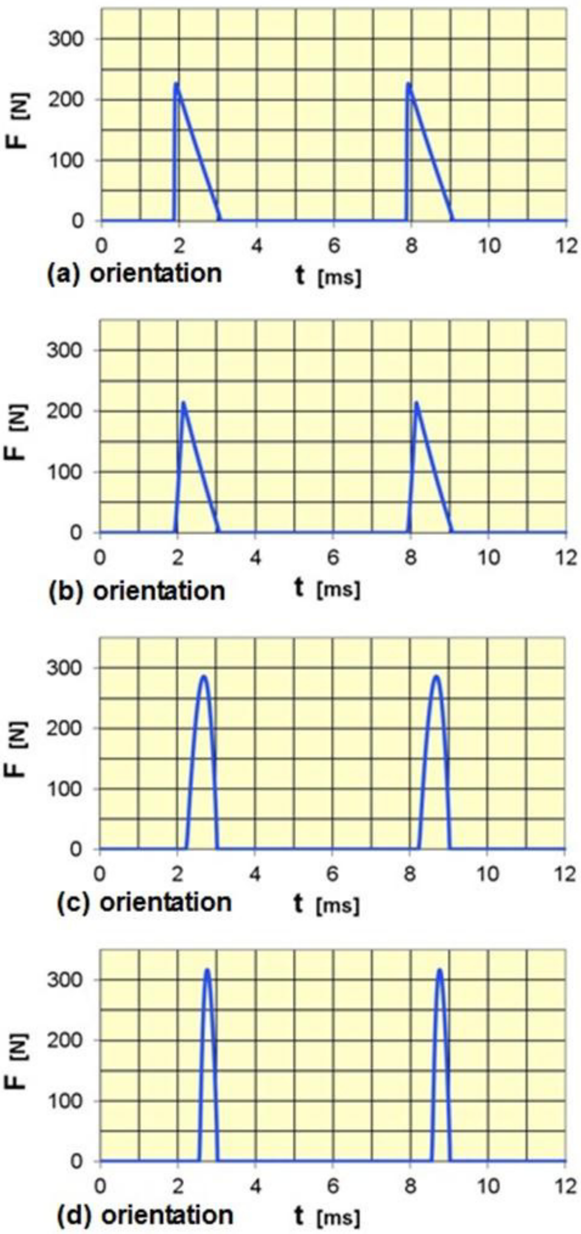


Figure 5: Calculated cutting force impulses for down milling with various tool orientations.

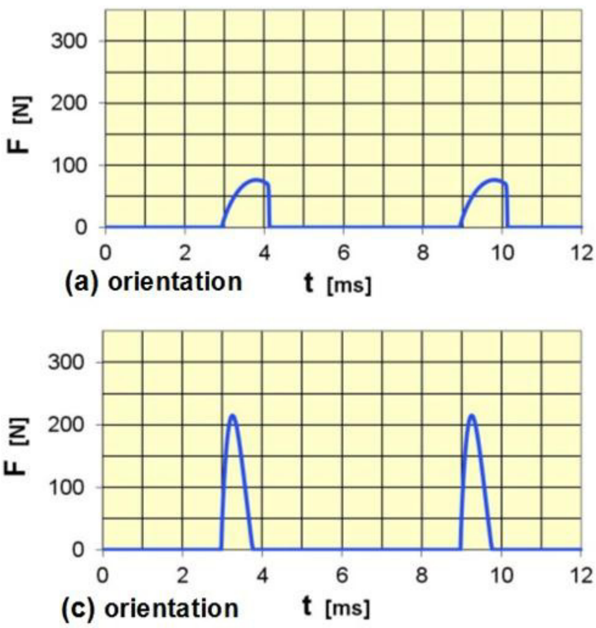


Figure 6: Calculated cutting force impulses for up milling with tool orientations (a) and (c).

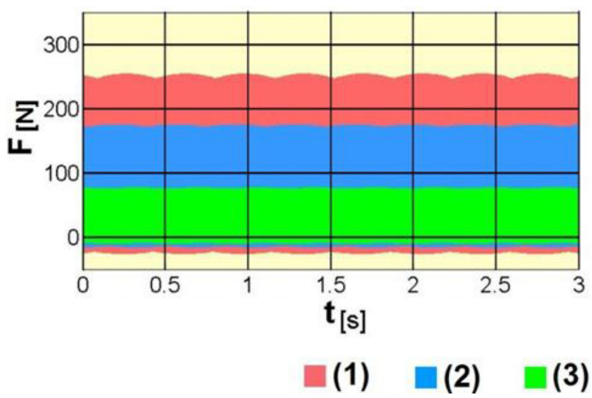


Figure 7: Comparison of experimentally measured cutting force values for (1) - down milling with tool orientation (c); (2) - down milling with tool orientation (a); (3) - up milling with tool orientation (a).

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