Prediction of thrust force and torque in tapping operations using computer simulation

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General cutting mechanics approach, successfully used for different machining operations using cutting tool with complex geometry, was here applied for prediction of cutting forces in tapping with machine taps. Basic idea was to exploit data obtained from orthogonal cutting tests and relations for oblique cutting forces to obtain force components on discretized parts cutting edges. Developed simulation program calculates instantaneous positions of tap in hole and undeformed chip area of each engaged tooth. Integration along all engaged teeth provides actual values of torque and thrust force in every simulation step in the whole tapping cycle.

Keywords: *Cutting forces, model, tapping, computer simulation*

1. INTRODUCTION

There is a small number of texts in literature which deals with technology of tapping. In small-batch production it is partly clear. This method is used for machining of features which sometimes are not frequent, and in whole required time and energy resources contributes in small percentage. On the other hand, permanent interest in tapping technology could be explained by two facts. The first, it is safety required for threaded joints in many products, which is related to quality of manufacturing of threaded pairs.

The second, there is specific philosophy of large volume production, where optimisation of each operation, including tapping, leads to significant benefits. As the third reason is the fact that threading operations in holes are often at the end of machining process for numerous parts in practice. Failrues made during tapping make waisted all previous work on such part.

Actual research activities in tapping technology are concerned on new materials for taps, optimizaton of tap geometries and cutting parameters and new techologies for manufacturing of taps. It is useful to have reliable model for cutting forces required for various calculations in technology design. Model which is oriented to simulation, for obtaining profile of tapping thrust force and torque is presented in this paper.

2. CUTTING FORCES IN TAPPING

Taps are a kind of cutting tools with very complex cutting geometry. International and national standards, [6] describe a number of constructions, especially of cutting part of taps for different purposes.

In the context of cutting forces it is well known that chamfer section (Figure 1) of tap generates a major part of resulting cutting force, because of larger chip cross section related to teeth of chamfer.

Machining with calibrating section does not contribute significantly to resulting force because friction effects are dominant in this phase. For several practical reasons it is useful to decompose resulting cutting force acting on tap to axial (F_3) force and torque (M). Tapping process is also followed by the so called side force which arises from unbalanced sum of tangential (F_t) and radial (F_r) forces acting on all engaged teeth of tap. Complex cutting geometry of taps and rapid change in engagement of particular teeth make calculations of cutting forces pretty different.

During the tapping cycle, cutting forces are drastically changing. Thrust force and torque by full immersion of chamfer section of tap are used as representative values for such operations. Dynamic change of torque, for example, is shown in figure 2 for two cases of tapping operations (tapping in a blind hole and in a through hole).

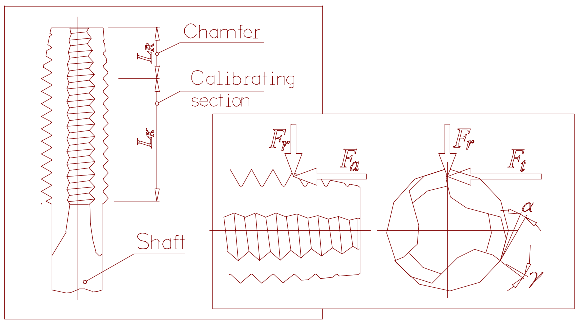

Figure 1. Basic elements of tap and forces on elementary tooth

Graphs in figure 2 describe expected tapping dynamics from basic observations [3]. In real situations this dynamics seems more "live" as shown in figure 3. Maximum values that appear in phase B (the same situation is for axial thrust force) are important for phases in technology design process, which are related to the choice of fixture, tool and tooling (holder with coupling).

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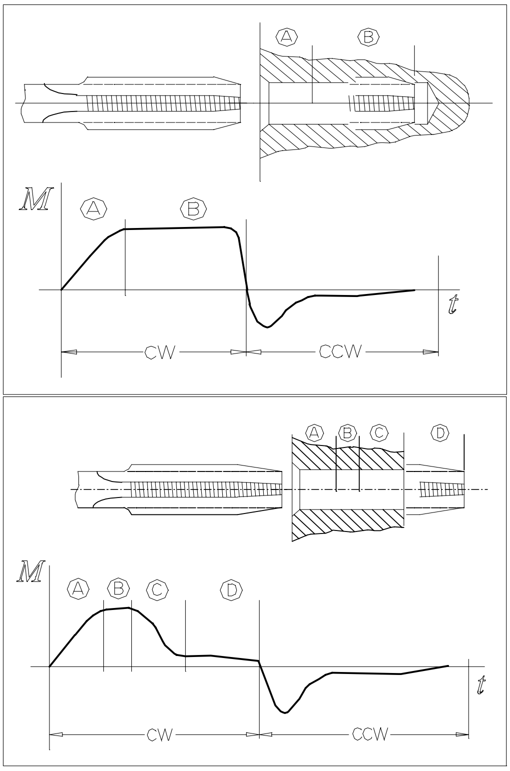

Figure 2. Change in torque during the tapping cycle

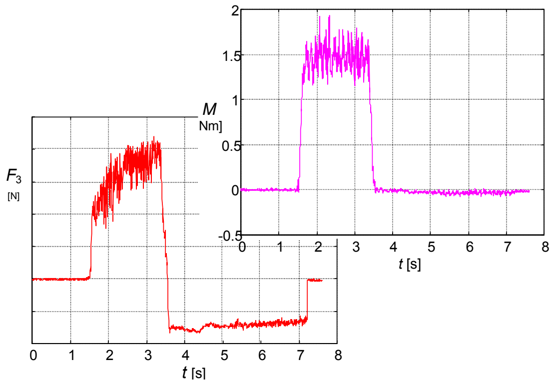

Figure 3. Signals of torque and thrust force in time - domain in one example of tapping

Besides maximum values, it is useful to predict the change of thrust and torque in the whole tapping cycle for implementation of automatic monitoring of process [7] in high volume production.

This paper presents a model for axial thrust force and torque derived from the model of cutting forces in orthogonal cutting and their transformations in oblique cutting [8].

Such approach was called general (unified) cutting mechanics. This model was developed for obtaining profiles of thrust force and torque for specified geometry of tap (cutting section and calibrating section; figure 4) through simple computer simulation.

3. GENERAL CUTTING MECHANICS – BASIC

In modelling of cutting forces, in the last decade, the approach named Unified (general) cutting mechanics it was widely used [8], [9]. Motive for developing such approach was to solve the problem of prediction of cutting forces for operations which assume complex tool geometry.

A variety of modern cutting tools, their materials and geometry [1], [2], [5] made unuseful the popular the approach of orthogonal experimaental plan. Basic idea in general cutting mechanics is that complex tool geometry should be divided into segments of cutting edge.

Such segments should be chosen in such a way so that they can be treated as tools with simple geometry with straight edges (Figure 4).

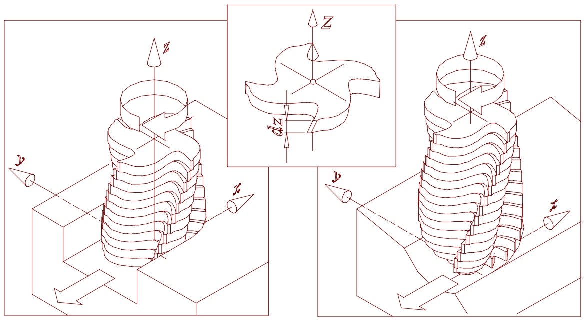

Figure 4. Slicing of cutting tool on discs with simple cutting geometry

It can be assumed that on each elementary cutting edge we have classic oblique cutting. To determine force components acting on a whole tool, this approach gives procedure consisting of three steps:

STEP1. Using machining tests with orthogonal cutting to obtain: shear angle (ϕ_c) , average friction angle (β_a) and shear yield stress(τ_s).

STEP 2. For each engaged elementary cutting edge (tool is sliced along z-axis) of rotating tool to calculate force components acting on it: tangential force ($\mathrm{d}F_t$), feed force ($\mathrm{d}F_f$) and radial force ($\mathrm{d}F_r$). Calculations in this step are based on transformations from orthogonal to oblique cutting (K_{tC}, K_{fC}, and K_{rC}), actual chip load on elementary edge and several assumptions.

STEP 3. To calculate sums F_t, F_f and F_r integrating the contributions $\mathrm{d}F_t$, $\mathrm{d}F_f$ and $\mathrm{d}F_r$ along all cutting edges (flutes).

Assumptions made in deriving transformations in step 2 are as follows [8]:

- The orthogonal shear angle (ϕ_c), in oblique cutting, is equal to the normal shear angle (ϕ_n) in oblique cutting.
- Chip flow angle (η) is equal to the rake angle (i) in oblique cutting.
- Normal rake angle (α_n) is equal to the rake angle (α_r) in orthogonal cutting.

For the same conditions (workpiece material, tool material, tool geometry, speed and chip cross section), for both orthogonal and oblique cutting , friction coefficients (β_a) and shear stress (τ_s) are the same.

4. MODEL OF THRUST FORCE AND TORQUE IN TAPPING

In order to make basics for simulation of cutting forces in tapping, it is presented here the approach for calculation cross section of undeformed chip (Fige 5), which is necessary to apply in general cutting mechanics.

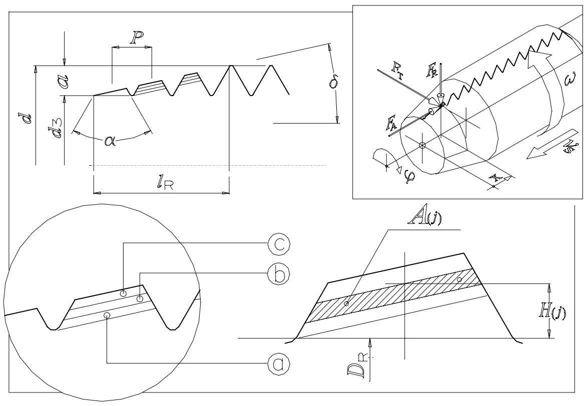

Figure 5. Undeformed cross section of chip in tapping (Parameters of tap and tapping operation: α-angle of thread profile; η - thread helix angle $\mathrm{tg}\eta = P/d\pi$; δ - inclination of cutting section; L_R - cutting section length of tap; z - number of flutes; d_3 - root diameter of tap; a - cutting depth, $a = (d - D_R)/2$; D_R - diameter of a hole; b - max. width of undreformed, $b = 2a\,\mathrm{tg}(\alpha/2)$; x - axial position of cutting edge)

If the undeformed chip area $A(j)$ on a particular tooth of cutting section is approximated with regular trapezoid, then it will be:

$$A(j) = b\left(1 - \frac{H_j}{2a}\right)(H_j - H_{j-1}), \qquad (1)$$

$$H(j) = x(j)\,\mathrm{tg}(\delta), \qquad (2)$$

$$x(j) = a\,\mathrm{tg}(\frac{\alpha}{2}) + \frac{(j-1)P}{z}, \qquad (3)$$

$$H(j) = (a\,\mathrm{tg}(\frac{\alpha}{2}) + (j-1)\frac{P}{z})\,\mathrm{tg}\,\delta, \quad j = 1,2,\ldots,N_R. \qquad (4)$$

Equations for force components in oblique cutting are derived from transformations of orthogonal to oblique cutting [8]:

$$F_1 = K_{tC} \quad A + K_{tE} L, \qquad (5)$$

$$F_3 = K_{fC} \quad A + K_{fE} L, \qquad (6)$$

$$F_2 = K_{rC} \quad A + K_{rE} L, \qquad (7)$$

where cutting coefficients are:

$$K_{tC} = B\left[\cos(\rho - \gamma) + \quad \mathrm{tg}^2\eta \quad \sin\rho\right], \qquad (8)$$

$$K_{fC} = B\frac{\sin(\rho - \gamma)}{\cos\eta}, \qquad (9)$$

$$K_{rC} = B\,\mathrm{tg}\,\eta\left[\cos(\rho - \gamma) - \sin\rho\right], \qquad (10)$$

where are

$$B = \frac{\tau_S}{\sin\phi\sqrt{\cos^2(\phi + \rho - \gamma) + \mathrm{tg}^2\,\eta\,\sin^2\rho}}. \qquad (11)$$

Edge forces (related to friction effects by small depth of cut) F_{iE} ($i = 1,2,3$) are proportional to the length of a particular immersed cutting edge $L(j) \approx (1/a)(a - H(j))(b + 2a/\cos(\alpha/2))$ for edges on cutting section and $L(j) \approx 2a/\cos(\alpha/2))$, or calibrating section. There is: ϕ - shear angle in cutting zone, τ_s - shear stress, γ -rake angle, ρ - friction angle. There are two ways to obtain constants $K_{i\mathrm{C}}$ i $K_{i\mathrm{E}}$ ($i = t, r, f$). One is to use the results from tests (turning of tube) with orthogonal cutting (used for verification in this research).

The second procedure assumes the so called mechanistic approach, also based on experiments. Cutting speed has direction of tangent on thread helix and , in case of tap with straight flutes, contribution of cutting edge of particular tooth to tangential and axial component of cutting force will be:

$$F_t(j) = \left[K_{tC} \quad A(j) + K_{tE} L(j)\right]\cos\eta + \\ + \left[K_{tC} \quad A(j) + K_{rE} L(j)\right]\sin\eta, \qquad (12)$$

$$F_a(j) = \left[K_{tC} \quad A(j) + K_{tE} L(j)\right]\sin\eta - \\ - \left[K_{rC} \quad A(j) + K_{rE} L(j)\right]\cos\eta. \qquad (13)$$

For cutting edges on calibrating section of a tool, it is assumed that there exists just edge component of cutting force. At a given moment, the resulting thrust force and resulting torque are sums of contributions of all immersed cutting edges:

$$F_a = \sum_{j=1}^{N_R} F_a(j), \quad M = \frac{d}{2}\sum_{j=1}^{N_R} F_t(j). \qquad (14)$$

4.1 Experimental setup

As a part of a wider research in the field of machining of threaded holes with tap a large number of experiments were conducted. From the necessity to work with different cutting speeds and have appropriate feed speed according to actual tap pitch, experiments were conducted on numerically controlled machine tool (horizontal machining center LOLA HMC500).

Installation which was used with piezoelectric force+torque transducer, components for conditioning, acquisition and digital signal processing is shown in figure 6.

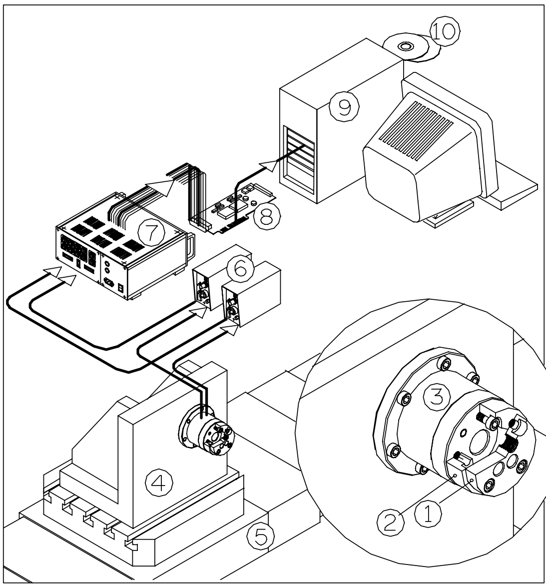

Figure 6. Experimental setup for acquisition of thrust forceand torque during the tapping cycle 1-Work piece (disc); 2-Distant ring; 3-Two component piezoelectric dynamometer KISTLER 9271A; 4-Fixture; 5-Table of machining centerHMC500; 6-Amplifiers KISTLER 5007; 7-Module forconditioning and isolation ED 1778AP; 8-PC module fordata acquisition ED2000; 9-PC; 10-DAQ software

4.2 Model verification

Figure 7 shows graphs of thrust force and torque in tapping operations, for two tap with metric normal profile (M8 and M10). Workpiece material was Č.1730 (JUS). Through hole depths were 20 mm for both examples. Tapping cycle was programmed to ensure that cutting section of tap pass as through the end of a hole, in a working stroke. Taps are with straight flutes both with 3 flutes. Geometry and dimensions of taps are according to DIN 376(1) Form C (tap with thin shaft, short cutting section, $\delta = 20°$). Simulation [11] is based on a previously described model. There are shown, in the same graphs, the results of experiments and the results obtained through simulation for equal conditions. Conditions for these two examples are listed in table 1.

Remarkable deviations between experimental and simulation results are expected. The nature of tapping process and cutting forces in tapping is more complex compared to proposed model. Part of inaccuracy of the model results from experimental obtaining of model constants (specific cutting forces) used in calculations of forces for every particular cutting edge. Also there are details related to coolant and cooling, orientation of tapping axis, small deviations of diameter of previously machined holes, use of specific tool holders, and so on [4], [10].

As most important, a proposed model does not a consider the real mechanism of chip forming in tapping operations. During the tapping each particular tooth on cutting section of tap has three cutting edges (one longer than two others) with different orientation, acting on workpiece material. There is no relief edge in a traditional manner. This results in higher cutting forces as well as in edge forces. As a rule, such chip forming process, similar to threading operations on lathe, with radial approach of tool, should be avoided in machining whenever it is possible. Good results, tested in experiments, were obtained through simulation for taps with straight flutes. For different geometries of taps it is necessary to modify calculation of underfomed chip thickness and, during simulation, modify calculating of triggering moments for each particular cuting edge.

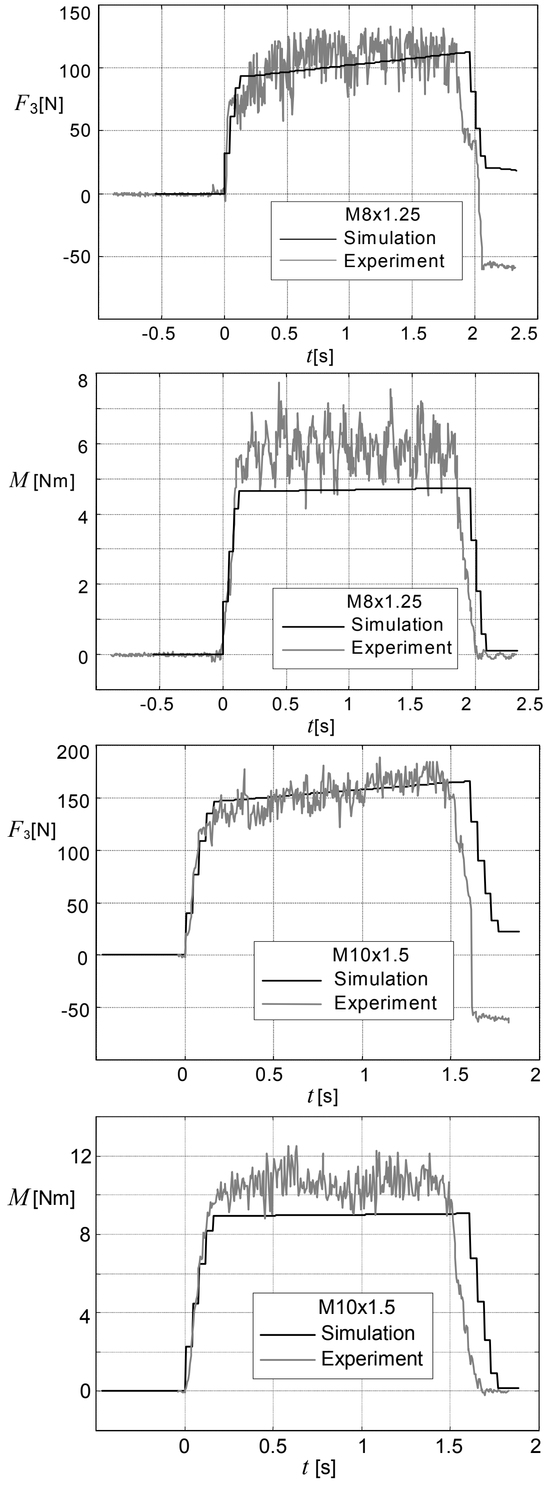

Figure 7. Comparing of experimental and simulation results for thrust force and torque during the tapping operations M10x1.5 and M8x1.2.

Table 1. Parameters of two examples for model verification

		Example #1	Example #2
Tap geometry		According to DIN376(1)	
Tap material		HSS	
Nominal dia.	d [mm]	8	10
Pitch	P [mm]	1.25	1.5
Chamfer length	L_R [mm]	2.5	3.0
No. of flutes		3	3
Workpiece material		Č.1730 (JUS)	
Premachined hole diameter	D_R [mm]	6.7	8.4
Through hole length	H_R [mm]	20	20
Start tap position	x_S [mm]	-5	-5
End tap position	x_E [mm]	25	15
Spindle speed	n_S [mm]	500	300
Simulation steps per revolution		20	20

5. CONCLUSION

Presented model is based on approach which was succesfully used for modelling of cutting forces in turning, milling and drilling operations. This approach includes integration of force components acting on discrete parts of cutting edge, which are engaged into workpiece material, and project them on directions of main force components acting on the entire tool. Presented model of thrust force and torque is suitable for simulation.

Besides simulation of regular condition in tapping operation this model allows insight in to the influence of particular disturbing factors, such as breakage of some cutting edges or tool wear. This could be used in the training of systems for automatic monitoring of tapping process. Current research is expected to provide better model which would respect specific mechanism of chip forming in tapping and its influence on cutting forces, and accuracy and quality of machined internal threads.

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ПРЕДВИЋАЊЕ СИЛЕ И МОМЕНТА КОД ОПРЕРАЦИЈЕ УРЕЗИВАЊА НАВОЈА КОРИШЋЕЊЕМ КОМПЈУТЕРСКЕ СИМУЛАЦИЈЕ

Радован Пузовић, Бранко Кокотовић

Приступ опште механике резања, успешно је примењиван за различите захвате обраде алатима сложене геометрије. Овде је примењен за предвиђање аксијалне силе и момента при урезивању навоја машинским урезником. Основна идеја је да се подаци одређени кроз тестове са ортогоналним резањем и изрази за силе при косом резању искористе за одређивање компоненти сила резања на дискретизованим деловима сечива. Развијени програм за симулацију израчунава тренутну позицију урезника у односу на рупу, пресек недеформисане струготине за сваки зуб. Интеграцијом по свим зубима у захвату добијају се тренутне вредности моментаи и аксијалне силе за сваки симулациони корак у укупном циклусу урезивања навоја.

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