THEORETICAL ASPECTS OF WOOD CROSS MILLING
KINEMATICS AND DYNAMICS

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Abstract
A key-factor in the milling process is the chip thickness. Its configuration and values determines the quality of milling and thus the cutting process dynamics.

INTRODUCTION

In order to analyze the kinematics and dynamics of solid wood cross milling it is necessary to analyze the milling process phenomenon for two consecutive rotations of the milling cutter while the cutter forward horizontally on distance \( u_z \) and the calculation of chip (cutting) thickness depending on maximum milling depth \( a_{\text{max}} \).

MATERIAL AND METHOD

To determine the chip thickness at a certain time, two positions of the milling cutter are considered. The equation of the two circles centred \( M_1 \) and \( M_2 \) will be as follows:
- For the circle with the centre in \( M_1 \): \((x + u_z)^2 + y^2 = R^2\)
- For the circle with the centre in \( M_2 \): \(x^2 + y^2 = R^2\)

![Figure 1 - Chip formation.](image)

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These circles cut cross a beam of straight lines passing through \( M_2 \)

\[ x = -y \tan \varphi \]

and one obtains the ordinate lines of two points that limit the chip thickness \( M_2A \) by right side. Thus by crossing the straight line with the circle centred in \( M_1 \) one obtains the ordinate line of the 1\(^{\text{st}} \) point and the following equation:

\[ y^2 \tan^2 \varphi - 2yu_x \tan \varphi + u_x^2 + y^2 = R^2 \]

or

\[ y^2 (\tan^2 \varphi + 1) - 2yu_x \tan \varphi + u_x^2 - R^2 = 0 \]

By replacing \( 1 + \tan^2 \varphi = \cos^2 \varphi \) one obtains:

\[ y^2 - u_x \sin 2 \varphi y + (u_x^2 - R^2) \cos^2 \varphi = 0 \]

It results the following equation:

\[ y_{1,2} = \frac{1}{2} u_x \sin 2 \varphi \pm \sqrt{\frac{1}{4} \sin^2 2 \varphi + (R^2 - u_x^2) \cos^2 \varphi} \]

By crossing the straight line \( M_2A \) with the \( M_2 \) centre circle one obtains:

\[ y^2 (1 + \tan^2 \varphi) = R^2 \]

or

\[ y^2 = R^2 \cos^2 \varphi \]

\[ \sin \gamma_{1,2} = \pm R \cos \varphi \]

of which

\[ \gamma_2 = R \cos \varphi \]

Chip thickness corresponding to angle \( \varphi \) resulted is:

\[ a_{\varphi} = \frac{y_2 - y_0}{\cos \varphi} \]
\[ a_{\phi} = u_{z} \sin \phi + R - \sqrt{R^2 - u_{z}^2 \cos^2 \phi} \quad [\text{mm}] \quad (1) \]

As shown in Figure 1 and 2, the chip thickness varies from zero to the maximum value \( a_{\text{max}} \). Thus the maximum chip thickness corresponding to \( \phi_{\text{max}} \) angle is as follows:

\[
a_{\text{max}} = a_{\phi_{\text{max}}} = u_{z} \sin \phi_{\text{max}} + R - \sqrt{R^2 - u_{z}^2 \cos^2 \phi_{\text{max}}} \quad [\text{mm}] \quad (2)
\]

where

\[
\cos \phi_{\text{max}} = \left( R - \bar{h} \right) \left( R - a_{\text{max}} \right)
\]

By replacing the angle expression \( \phi_{\text{max}} \) one obtains:

\[
a_{\text{max}} = R - \sqrt{R^2 + u_{z}^2 - 2u_{z} \sqrt{2R \bar{h} - \bar{h}^2}} \quad [\text{mm}] \quad (3)
\]

Maximum chip thickness can be set approximately by the report resulted from the Figure 1 and 2, as follows:

\[
a_{\text{max1}} = u_{z} \sin \frac{\phi_{k}}{2} - 2u_{z} \frac{h}{D} \quad [\text{mm}] \quad (4)
\]

One can also establish as twice the average chip thickness, the later being considered for angle \( \phi_{k} : 2 \), namely:

\[
a_{\text{max1}} = 2a_{m1} - 2u_{z} \sin \frac{\phi_{k}}{2}
\]

\[
= 2u_{z} \sqrt{\frac{h}{D}} \quad [\text{mm}] \quad (5)
\]

The average chip thickness can be determined approximately from the surface equality:

\[
a_{m} \cdot l_{c} = u_{z} \cdot h_{c} \]

\[
a_{m} = \frac{u_{z} \cdot h_{c}}{l_{c}} \quad [\text{mm}] \quad (6)
\]

where \( l_{c} \) is the length of arc circle representing the chip length

\[
l_{c} = \sqrt{h_{c} \cdot D}.
\]
To determine the average thickness of the chip the following may be also used:

\[ a_m = \frac{v_z \cdot \sin \theta}{2} + \frac{h}{D} \]  \[\text{[mm]} \ (7)\]

As a result of calculations made to determine the chip thickness of wood milling one results:

- The value of chip thickness at a certain time is set by the 2nd equation;
- The maximum chip thickness can be determined accurately by the 3rd equation but also accepting a normal approximation with the 4th and 5th equations;
- The average chip thickness may be determined by 6th equation 6, but usually one uses the 7th equation.

Chip thickness is a key element in the study of milling dynamics for cross milling, since in this milling method the main parameter is the cutting forces and power.

The study of chip thickness size variation can be done by means of PC software.

In the milling process, throughout the length of contact \( L_c \) between the cutter tooth and wood a cutting force is generated on the tooth, which at a certain moment reaches the following value:

\[ F_a = K_i \cdot A_i \]  \[\text{[N]} \ (8)\]

where \( K_i \) is the specific cutting strength during milling at a particular chip thickness and \( A_i \) is the chip cross section at that time.

For the milling machines and tools design calculations and checking purposes the international standards recommend a maximum cutting force of 1 mm per blade according to the formula: \[ F_{\text{calc}, i} = \frac{50 \text{N}}{\text{mm/blade}} \]

Thus for a milling cutter, for example, with a blade width of 20 mm, the working force calculated for the cutting machine and tool is: \[ F_{\text{calc}} = 50 \times 20 = 1000 \text{N} = 100 \text{daN} \]. In the point of view of the author of the present paper takes into consideration a safety factor (overloading) therefore that the recommended value is: \[ F_{\text{calc}, \text{real}} = 1.5 \times 100 = 150 \text{daN} \].
Figure 3. Graphical representation of cutting dynamics. Legend: “dintele” 1, 2, 3 is the tooth 1, 2, 3.

Based on the average cutting force $F$ one determines the cutting power when milling as follows:

$$P = \frac{F \cdot v}{1000} [\text{KW}]$$  \hspace{1cm} [N] (9)

where $v$ is the cutting speed expressed in m / s

The calculation of the milling cutting speed is determined by the relation:

$$P = \frac{KV}{1000} [\text{KW}]$$  \hspace{1cm} [N] (10)

where $K$ is the specific cutting work expressed in Nm/cm$^3$, and $V$ is the volume of material milled per time unit expressed in cm$^3$/s, which is

$$V = \frac{A_T \cdot u}{60} \text{ cm}^3/\text{s}$$

where $A_T$ is the crossing surface of the milled wood, perpendicular to the feeding direction and $u$ is the feed rate, expressed in m/min.

If the milled section has a height $h$ and width $b_1$, then $V = bh_u/60 \text{ cm}^3/\text{s}$.

RESULTS AND DISCUSSIONS

Given the complexity of wood cross milling and the lack of data on correct values for the dynamic parameters, in this paper we chose the following method for setting them:
- experimental setting of cutting power P according to various factors of milling regime by means of using a precision power meter recorder;
- identifying specific cutting strength specific to cutting forces K, of average equivalent forces F and F_R, and the maximum cutting forces per tooth by using the equations 8, 9 and 10;
- generalization of experimental data on dynamic parameters values by preparing tables, graphs and setting reports calculation.

CONCLUSIONS

Chips formation at cross milling differs significantly from those which occurs in other longitudinal or tangential milling. Thus, for the cross milling with the positive rake angle, the chip formation occurs as follows:
- first phase - the wood fibbers slicing by blade under \( \psi = 90^\circ \) angle;
- second two - wood particles shearing according to a longitudinal plan (in fibers plan) normally according to the plan between the early and late wood; this shearing is generated by the teeth raking force;
- third phase – the tangential shearing which is generated by the side blades of raking face; this occurs only in closed cross milling, namely to the manufacturing of joining articles.

REFERENCES

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