[1.]Vasil VLASEV

DETERMINATING THE CUTTING FORCES IN CIRCULAR CUTTING MACHINES WITH REGARD TO THE EFFECT IN THE RADIAL RUN-OUT OF THE CUTTING MECHANISM

[1.]University of Forestry, Faculty of Forest Industry, Department Woodworking Machines, BULGARIA

Abstract: The cutting forces in circular cutting machines have been determined by calculating the cumulative radial run-out, according to known normative documents about the cutting mechanism. The radial run-out in this mechanism is seen as a periodic movement, towards and away of the cutting body to the workpiece. As a result, the velocity of this movement is summed with the feed rate. It is found, that its velocity is comparable to the feed rate, and it is approximately 25% of its size. The cutting forces are also equally greater than the traditionally calculated ones and within one full rotation of the cutting tool, they are changed in an asymmetric cycle. For a better perception, this approach and offset can be represented as a periodic shift of the cutting body in the direction and against the direction of feed. For strength calculations, it is sufficient to calculate the feed rate only with its increase. Research in this regard has not been found in any literature known to the author. Therefore, the purpose of the present work is to determine the movement velocity of the tooth line of the circular saw to the workpiece as a result of the radial run-out, and whether it is comparable to the feed rate. This would, consequently, determine how this affects the cutting forces.

Keywords: circular cutting machines, cutting forces, radial run-out

INTRODUCTION

The cutting forces, for circular as well as other woodworking machines, are the basis for the strength dimensioning of the elements of their cutting mechanisms as well as other machine elements. These forces need to be known for the proper operation of the machines.

The cutting forces are tangential and radial [3], [4], [8]. According to A. L. Bershadskiy's [3] famous theory the tangential force of cutting is determined by the formula /the radial force of cutting is calculated by means of the tangential force.

$$P = \frac{KbhU}{V}, N, \tag{1}$$

where:

- P is the tangential force of cutting,
- N; b – width of the slot,
- m; h – height of the slot,
- m; U – feed rate, m.s^{-1};
- V – cutting velocity, m.s^{-1}.

As it can be seen from formula (1), the tangential force of cutting is in direct proportion to the feed rate, which, according to known literary sources [3], [4], [8] is assumed to be uniform within a complete rotation of the cutting tool /figure 2a/.

In these machines, as well as in many others, the geometric accuracy of some of the cutting mechanism's elements is essential to their operation. One of the geometrical inaccuracies of this mechanism is the radial run-out [5]. Such run-out can occur on the shaft of this mechanism [2], as well as on the circular saw [7].

The specified geometrical inaccuracies in practice can occur in any probable situation, but for certain calculations they are summed up unambiguously and with their maximum values [6]. Therefore, it is possible to have a maximum radial run-out equal to the sum of the radial run-out of the shaft and circular saw. As a result of this radial run-out, a part of the circular saw's teeth are periodically moving away and towards the processed material, thereby the speed of the approach is summed with the feed rate and the offset speed is subtracted from it.

For a better perception, this approach and offset can be represented as a periodic shift of the cutting body in the direction and against the direction of feed. The latter means that the feed rate by which the cutting force in formula (1) is to be calculated, needs to be increased or decreased in accordance with the rate of the periodic approach or offset of the circular saw to the processed material. For strength calculations, it is sufficient to calculate the feed rate only with its increase. For the convenience of expression, the term "tooth line" will be used in the article since it does not coincide with the circumference of a geometrically accurate circular saw.

Considering the explanation given above, the cutting forces in circular machines would be different in size compared to those in the formula (1), if the radial run-out is taken into account. Research in this regard has not been found in any literature known to the author.

Therefore, the purpose of the present work is to determine the movement velocity of the tooth line of the circular saw to the workpiece as a result of the radial run-out, and whether it is comparable to the feed rate. This would, consequently, determine how this affects the cutting forces.

THEORETICAL FORMULATION

In order to achieve this goal, it is necessary to determine the two velocities defined above. The first is the movement velocity of the tooth line of the circular saw in the direction of feed. The method of determining this velocity is illustrated in Figure 1.

Position 1 shows the workpiece that moves in the direction indicated by U. Position 2 is the circular saw. The total radial run-out is shown along the η axis, which passes through the circular saw's tooth line and through the middle of the workpiece. For axis η this space is determined, as the power calculations are made for it [3].

The magnitude of the cumulative radial run-out of the figure corresponds to the distance A_1B where the workpiece is, and on the opposite side (at 180^0) - AB_1. The center of rotation is point O around which the circular saw rotates eccentrically. Its center of rotation is displaced by the geometry at a distance equal to half of the total radial run-out, which in the figure corresponds to the distance AA_1.

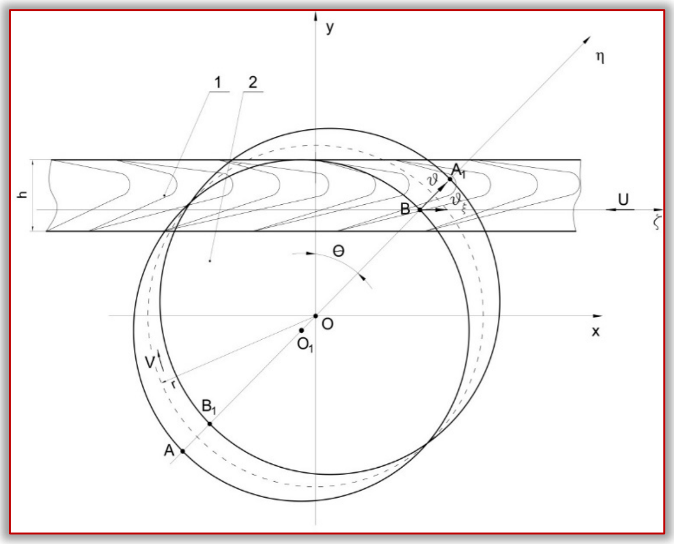

Figure 1: Scheme for determining the speed of movement of the circular saw in direction of the feed rate

In figure 1, points A and B show two end positions of the radial run-out of the tooth line along the axis η when the circular saw circles around point O. Point A is the most convex part, and point B is the most concave part. When rotating the circular saw by 180^0, point A moves to point A_1 and point B to point B_1. From this it is seen how the tooth line moves along the axis η from point B to point A_1, i.e., the circular saw is periodically moving towards and away from the workpiece within a complete rotation. The latter means that the feed of the tooth will also change within one turn and hence the cutting power.

Once the tooth line moves along the axis n, it does that at some velocity **ϑ**. The law associated with the changes in this velocity cannot be accurately determined. The reason for this is that the shape of the geometrical inaccuracies of individual elements and their surfaces are of a random nature, as well as their summing. Therefore, assuming that the circular saw after mounting and tightening it to the shaft, with its geometrical inaccuracies is rotating around a displaced geometric center of rotation, it can be assumed that the movement of the tooth line is harmonious and thus this velocity changes by a harmonious law. The projection on the axis η is determined by the formula [1], [9]

$$\boldsymbol{\vartheta} = A\omega\cos(\omega t+\boldsymbol{\varphi}),\ m.s^{-1}, \qquad (2)$$

where:

- **ϑ** is the movement speed of the tooth line to the workpiece, $m.s^{-1}$;
- A – the amplitude of vibration of the tooth line, m;
- ω – angular velocity, $rad.s^{-1}$;
- t - time, s;
- **φ** - initial phase of motion, $rad.s^{-1}$.

As it can be seen from the formula above, the tooth line's movement velocity is variable and it is determined by the angle of rotation of the circular saw.

To calculate the cutting forces in strength dimensioning it is necessary to know the maximum velocity, which is determined by the formula [1], [9]

$$\boldsymbol{\vartheta}_{max} = A\omega,\ m.s^{-1}, \qquad (3)$$

where: $\boldsymbol{\vartheta}_{max}$ is the maximum speed of movement of the tooth line on the axis η, $m.s^{-1}$;

In order to determine the magnitude of this velocity, it is necessary to know the magnitude of the amplitude, which is determined by the sum of the radial run-out of the shaft and the radial run-out of the circular saw.

The radial run-out of the shaft according to BDS 4297 [2] is 0,04 mm for machines with normal precision and 0.02 mm for machines with higher precision and according to Obreshkov [7] the radial run-out of the teeth of the circular saw is 0,06 mm to 0,1 mm after sharpening. The magnitude of the amplitude, considering the measurement method of the radial run-out [6], [2], is half of the total radial run-out and is determined by the formula:

$$A = \frac{\delta}{2},\ m, \qquad (4)$$

where: δ is the total radial run-out of the tooth line, m.

In order to determine whether the magnitude of the movement speed of the tooth line is comparable to the feed rate, it is necessary to determine the rate at which the tooth line moves in the direction of feed, i. e. along the axis ζ (Figure 1).

Thus far, the maximum velocity along the axis η is determined, and the velocity along the axis ζ, according to Figure 1 is determined by the formula.

$$\vartheta_{\zeta max} = \vartheta_{max}\cos(90-\theta),\ m.s^{-1} \qquad (5)$$

where:

- $\vartheta_{\zeta max}$ is the maximum speed at which the tooth line moves at the direction of feed, m.s^{-1};
- θ - cinematic angle of encounter, ^{0}.

By replacing equations (3) and (4) in (5) it is obtained:

$$\vartheta_{\zeta\,max} = \frac{\delta}{2}\omega\cos(90-\theta),\ m.s^{-1} \qquad (6)$$

RESULTS AND DISCUSSION

In order to determine whether the speed of movement of the tooth line $\vartheta_{\zeta\,max}$ is comparable to the feed rate U, it is necessary to make specific calculations for both speeds. The calculations to be made for the feed rate are for a case in which the circular shaft is heavily loaded at a low feed rate /to be comparable to the movement speed of the tooth line / and with a large slot height.

The aim is to maximize the kinematic angle of encounter as the movement speed of the tooth line in the direction of feed is determined by it. This is one of the possibilities that can be encountered in practice and during which a maximum shaft load is obtained.

The cutting mode selected to determine the feed rate is based on the following parameters:

- Circular Saw Diameter - 400 mm;
- Rotation speed - 75 s^{-1};
- Number of teeth - 48;
- Slot width - 4 mm;
- Slot height – 0,1 m;
- Wood type - beech.

The calculations are based on a methodology developed by Bershadskiy [3]. Since the feed rate is also dependent on the dulling of the cutting edges, it has been found that feed rates of less than 0,096 m.s^{-1} are obtained when dulling of the same above 39 μm.

The maximum movement speed of the tooth line in the direction of feed is calculated by the summed radial run-out δ = 0.14 mm / A = 0.00007 m / and a kinematic angle of encounter $\theta = 46^{0}$. It has been determined that at these values its magnitude is 0.0235 ms^{-1}.

From the calculations made, it can be seen that the movement speed of the tooth line in the direction of feed is a quantity which can be comparable to the feed rate. It can have values approximately 4 times lower (24.6%), and as it can be seen from formula (6) it changes approximately within the range of ± 0.25U by a harmonious law, within one complete rotation of the cutting tool.

Considering the above and formula (1) it follows that the cutting force is also changed by a harmonious law, as shown in Figure 2b, i.e by an asymmetric cycle [5].

The analysis made shows that a circular machine which is within its geometric precision can be loaded with cutting forces over the traditionally computed and with a variable sign.

Here, a question can arise regarding the cutting speed in the more protruding and recessed part of the circular saw's tooth. Calculations have been made for these two regions, and it was found that the cutting speed varied by ± 0.033 m.s^{-1}. Concerning the cutting speed for case above, this change is 0.035%, which indicates that it would practically not change the results of this study.

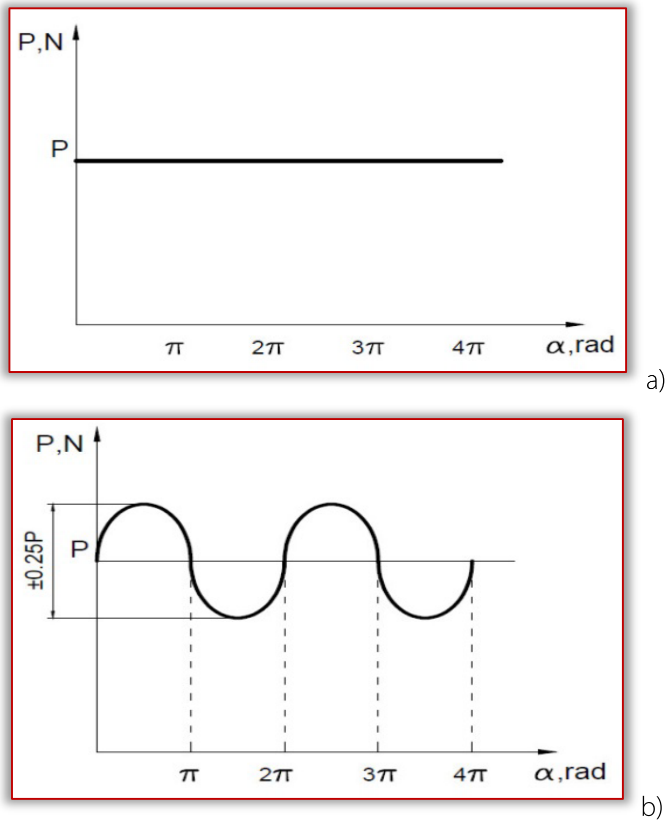

Figure 2. Graphical dependencies for loading of the circular shaft:
a - at constant magnitude of the cutting force;
b- cutting force, with regard to the radial run-out.

CONCLUSIONS

- The tangential and radial cutting force in strength dimensioning of the shafts in circular machines, taking into account the radial run-out in the cutting mechanism, is approximately 25% greater compared to the traditional calculation method;
- In strength dimensioning of the shafts in circular machines which operate at high loads, the unsymmetrical dynamic load cycle must be considered;
- The analysis made indicates that the radial run-out is the greatest as a result of the inaccuracies when sharpening the circular saw. From the latter it follows, that the

sharpening machines for these saws need to be with high accuracy.

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Faculty of Engineering Hunedoara,
5, Revolutiei, 331128, Hunedoara, ROMANIA
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