

Theoretical and actual feed per tooth during wood sawing on an optimizing cross-cut saw

Kazimierz A. ORŁOWSKI^{1*}, Wojciech BLACHARSKI¹,
Daniel CHUCHALA¹ and Przemysław DUDEK²

¹ Department of Manufacturing Engineering and Automation, Faculty of Mechanical Engineering, Gdansk University of Technology, 11/12 Narutowicza Street, 80-233 Gdansk, Poland

² REMA S.A., 5 Bolesława Chrobrego Street, 11-440 Reszel, Poland

* Corresponding author. E-mail address: kazimierz.orlowski@pg.edu.pl

Abstract: The work presents the geometries of circular saw teeth, whose task is to divide the cross-cut of the cutting layer. For efficient machining on a cross-cut saw with high feed speed values (about 1 ms^{-1}) maximal theoretical feeds per tooth are determined. These values were compared with the actual values determined during transverse cutting of pine wood on a special test stands in industrial conditions. In the experiment the rotational speed of the main driving motor and the feed speed of the saw blade were simultaneously measured. Unique experimental results revealed that the feed driving system with the crank mechanism driven with the rotary servo motor only the phenomenon of the decrease in the spindle rotational speed was present, which caused a slight increase of the feed per tooth. In the case of the pneumatic actuator applied in the feeding driving system its flexibility together with larger changes in feed speed additionally were observed. For that reason in a new cross-cut saw for the feeding system driven by the crank mechanism with the rotary servo motor ought to be recommended.

Keywords: optimizing cross-cut saw, circular saw blade, feed per tooth, cutting.

1. Introduction

Optimizing cross-cut saws, also called optimizers, belong to the group of cross-cut sawing machines often used in wood processing plants, and their purpose is to align the ends of lumber, trim to length and fast and precise cut out the anatomical defects during cross-cutting of single boards in solid wood. Thanks to the use of modern cross-cut saws and effective optimization for defect removal, it is possible to expect a reduction of raw material waste up to 8% [1].

Modern optimizing cross-cut saws are very dynamic machine tools, in which circular saw blades work with cutting speeds of about $80 \text{ m}\cdot\text{s}^{-1}$, and average feed speeds can exceed $2 \text{ m}\cdot\text{s}^{-1}$ (maximum up to $3.7 \text{ m}\cdot\text{s}^{-1}$). The latter gives the cycle time of cutting approximately 0.085 s in the Opti Cut 450 Quantum model [1]. On the other hand, tool manufacturers report about cycle times in the range from 0.3 s to 1 s [2]. In the fastest sawing machines, the raw material movement system allows speeds of up to $415 \text{ m}\cdot\text{min}^{-1}$, and exact positioning from full speed followed by re-acceleration is performed at up to $50 \text{ m}\cdot\text{s}^{-2}$. This kind of machine cuts with an accuracy of up to $\pm 0.8 \text{ mm}$ [1]. It should be emphasize that in printed materials as well as internet sources of many manufacturers, the speed of material movement is erroneously called the feed speed, which is in contradiction with the definition of this movement in the standard ISO 3002-3 [3].

Nasir and Cool [4] investigated the effect of feed speed, rotation speed, depth of cut, and the average chip thickness on the power consumption and waviness during the circular sawing process of green Douglas-fir wood. On the other hand, Mohammadpanah and Hutton [5] examined a stability analysis of spinning disk, an idealized representation of circular saw, for collared and splined arbor saws, when subjected to radial and tangential in-plane forces. Although the results described in works [4, 5] are valuable they cannot be utilized in the machine tools, which are the subject of this paper, since, in optimizing cross-cut saws fixed length cutting, defect cutting and optimization is conducted with extremely fast saw strokes, therefore, some saw blades producers call this method cutting “a punching method” [6]. The method for determining energetic effects for cross-cutting of wood is presented in the paper [7]. Furthermore, the method of selecting the desirable angular position of the cutting aggregate arm in the structural layout of the machine is also explained [7].

The Polish manufacturer of machine tools for woodworking Rema SA (Reszel, PL) offers an optimizing cross-cut saw with an automatic pusher (Fig. 1), in which a feed movement is realized by means of a pneumatic actuator. Nevertheless, latterly the company has been financially supported by the European Regional Development Fund, and the improvement of the feeding system of the machine is one of the project goals. Hence, in this paper the theoretical and actual values of the feed per tooth for two feed systems for the pneumatic and the crank mechanism driven with the rotary servo system are compared.



Fig. 1. The optimizing cross-cut saw with an automatic pusher CASTOR 500 currently produced by Rema SA

Theoretical background

In the modern feed systems of optimizing cross-cut saws the pendulum systems are mainly applied, in which the spindle moves on a curved trajectory [8-10]. The feed motion can be realized by means of a pneumatic actuator (Fig. 2a) [11] or in newer solutions due to crank mechanisms driven with the rotary servo motor (Fig. 2b) [1, 12], which are called as ultra-rapid cutting units.

Circular saw blades with sintered carbide inserts or stellite tipped teeth are usually used in woodworking machines. The exemplary teeth shapes are shown in Fig. 3. Figure 4 presents the geometry of alternate top bevel teeth (cutting tool geometry according to ISO standards [13]), which is commonly used in saw blades for efficient cutting on optimizing cross-cut saws.

Feed speed v_f for this kind of circular saw blades (Fig. 4) can be defined as follows:

$$v_f = f_z \frac{z}{2} n_s \quad (1)$$

where:

f_z – feed per tooth,

z – teeth number of the circular saw blade,

n_s – rotational speed of the circular saw blade.

After the transformation of equation (1) the feed per tooth is expressed as:

$$f_z = \frac{2v_f}{z \cdot n_s} \quad (2)$$

The theoretical maximal value of feed per tooth could be determined from equation (2) under assumption that the working feed speed $v_f = v_{fmax}$ and simultaneously rotational speed of the circular saw blade n_s is constant.

During sawing the value of feed per tooth might change as a result of:

- an effect of the feed system sensitiveness, which in case of the pneumatic actuator probably smaller values of feed speed could appear. Nevertheless, larger stiffness in case of the system with the crank mechanism driven with the rotary servo motor the mentioned effect is not expected;
- decrease in the spindle (circular saw blade) rotational speed caused by changes in feed speed. If the electric motor is controlled with the variable speed drive VSD (frequency converter) the behaviour of the driving system could be affected by the motor control mode either the V/f (Voltage/frequency) mode or the SLVC (Sensor Less Vector Control) mode. The latter should be applied if the application requires more dynamic and speed assurance.

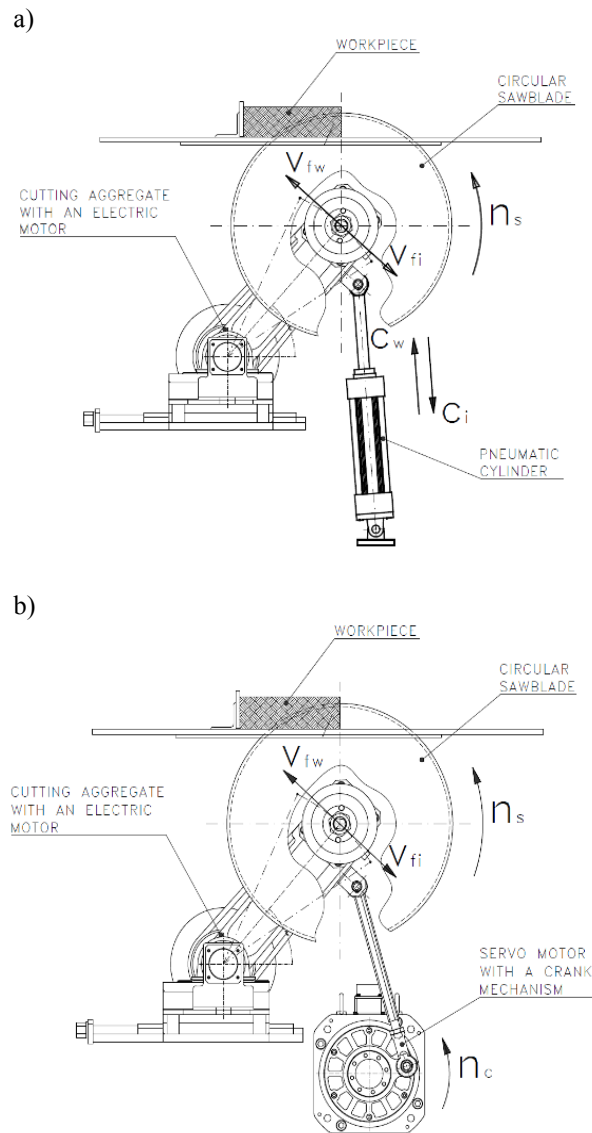


Fig. 2. The pendulum systems of optimizing cross-cut saws with the feed motion realized by means of a pneumatic actuator (a) and due to the crank mechanism driven with the rotary servo motor (b), where: v_{fw} – working feed speed, v_{fi} – idling feed speed, n_s – rotational speed of the circular saw blade, n_c – crank rotational speed, c_w – piston rod speed in the working stroke, c_i – piston rod speed in the idling stroke

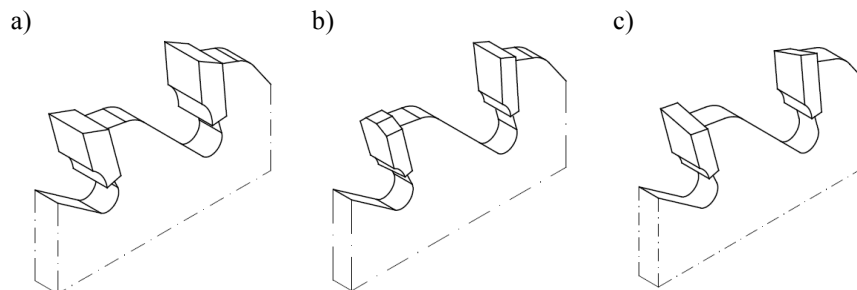


Fig. 3. The exemplary shapes of teeth of circular saw blades for wood cutting, where: square teeth regular shape, b) square / trapezoidal teeth, c) alternate top bevel teeth

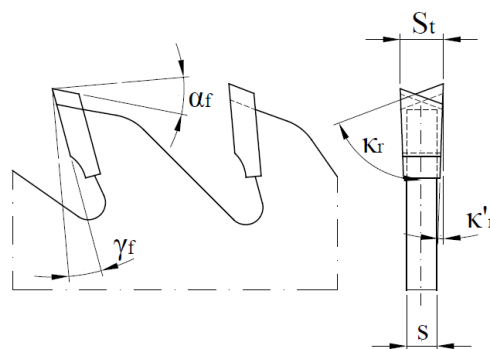


Fig. 4. Geometry of the alternate top bevel teeth, where: S_t – overall set (theoretical kerf), s – blade thickness, α_f – side flank angle, γ_f – side rake angle, κ_r – tool cutting edge angle, κ'_r – tool minor cutting edge angle

3. Materials and method

The tests of the cross-cutting process were carried out on two prototype stands under industrial conditions at REMA S.A. in Reszel (PL). The pendulum systems of optimizing cross-cut saws with the feed motion realized by means of a pneumatic actuator (Fig. 2a) and due to the crank mechanism driven with the rotary servo motor (Fig. 2b) were under investigations. On the both prototype stands rotational speeds of the electric engines were measured with the use of the incremental encoders type DFS60B-S4UA08192 (f. Sick (D)) (Fig. 5a). the same types of encoders were applied for measurement of the rotational speeds of the arms of the sawing aggregates (Fig 5b). The encoder shafts were joined with the examined systems by bar couplings made of the glass fiber-reinforced polyamide (in the foreground in Fig. 5a).

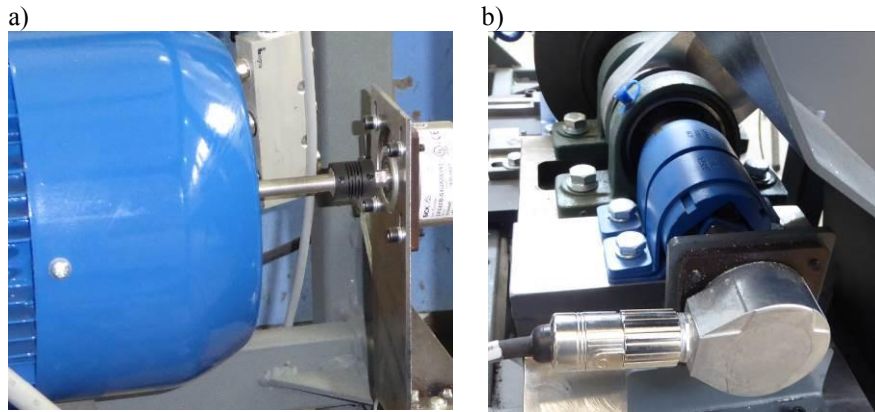


Fig. 5. Mounted incremental encoders for measurements of the both rotational speeds of the electric engine of the main drive (a) and the arm (in the background) of the sawing aggregate (b)

The spindles of the cutting aggregates are driven by the electric motors (nominal power $P_n = 7.5$ kW, nominal speed $n_n = 2830$ rpm, f. Tamel (PL)) by the toothed belt transmission with the ratio equal to $i = 1.26$. Therefore, the circular saw blade could rotate with the rotational speed equal to $n_s = n_n \cdot i = 3565.8$ rpm. The electric motor is controlled with the variable speed drive VSD type VLB3 7.5 kW (f. Lovato, Italy), and could be controlled either in the V/f (Voltage/frequency) mode or the SLVC (Sensor Less Vector Control) mode.

The crank mechanism was driven by the servo motor (three-phase synchronous motor) type 8LSA75DA030S000-3 (f. B&R, Austria) with technical data: nominal speed of the motor $n_n = 3000$ rpm, the nominal torque $M_n = 30$ Nm and maximum torque $M_{max} = 187$ Nm.

In experiments pine (*Pinus sylvestris* L.) samples of moisture content MC 15.7%, with dimensions in the cross section of $200 \text{ mm} \times 60 \text{ mm}$, were sawn. Technical data of the circular saw blade applied is as follows: outside diameter $D = \text{Ø}450$ mm, hole diameter $d = \text{Ø}30$ mm, blade thickness $s = 3.5$ mm, total overall set (theoretical kerf) $S_t = 4.8$ mm and teeth number $z = 138$. Sintered carbide teeth have had geometry shown in Fig. 4, with angle values: flank side angle $\alpha_f = 15^\circ$, rake side angle $\gamma_f = 10^\circ$ and tool cutting edge angle $\kappa_r = 70^\circ$. The circular saw blade was clamped on the spindle by collars with the diameter equal to $\text{Ø}112$ mm. For comparison purposes, the maximum feed speed for two examined feed drive systems was expected to be $1 \text{ m} \cdot \text{s}^{-1}$. Hence, the estimated maximal theoretical value of feed per tooth, for this cutting conditions, was equal to $f_{zmax} = 0.004$ mm.

In the experiments a software, which controlled cooperation of the USB measurement modules and incremental encoders, designed in the LabVIEW SignalExpress environment has been applied. Sampling rate in the experiment was equal to 2 kHz.

4. Results and discussion

Figure 6 presents the spindle rotational speed and feed speed in a function of time while the feed motion was realized by means of a pneumatic actuator.

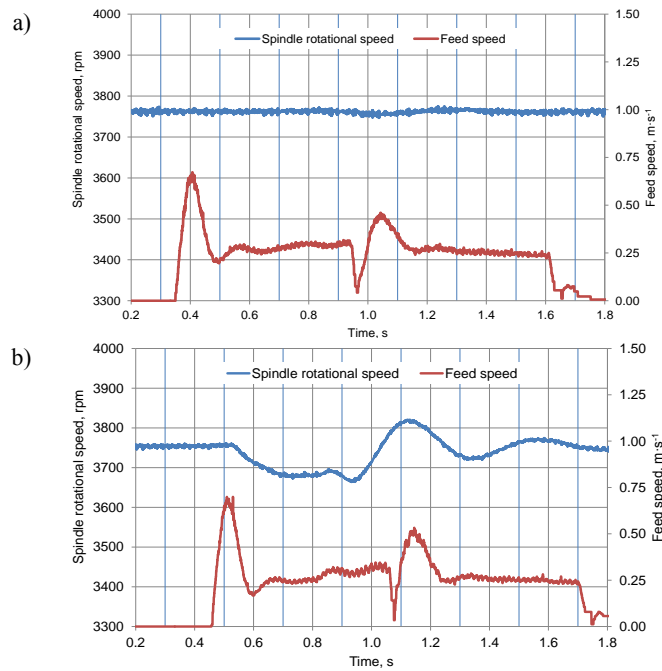


Fig. 6. Spindle rotational speed and feed speed while the feed motion was realized by means of a pneumatic actuator, where: a – idling, b – during cutting of pine lumber (200 mm × 60 mm)

In Fig. 6a courses of the spindle rotational speed and the feed speed are shown. The plot of the feed speed (Fig. 6a) consists of two parts, the first presents changes of feed speed while the arm of the cutting aggregate (Fig. 2a) moves up with the working feed speed v_{fw} , and the second part when the is the idling stroke with the feed speed v_{fi} . On the other hand, Figure 6b shows courses of the spindle rotational speed and the feed speed during cross cutting of the pine lumber of dimensions in the cross section 200 mm × 60 mm. In this experiment the main electric motor controlled with the variable speed drive VSD type VLB3 7.5 kW (f. Lovato, Italy) worked in the V/f (Voltage/frequency) mode. For that reason, even for a small value of the feed speed equaled during cutting $v_{fw} = 0.23 \text{ m}\cdot\text{s}^{-1}$, the spindle rotational speed rapidly decreased at the begging of sawing and at the time of leaving the workpiece the dynamical changes of the spindle rotational speed are observed.

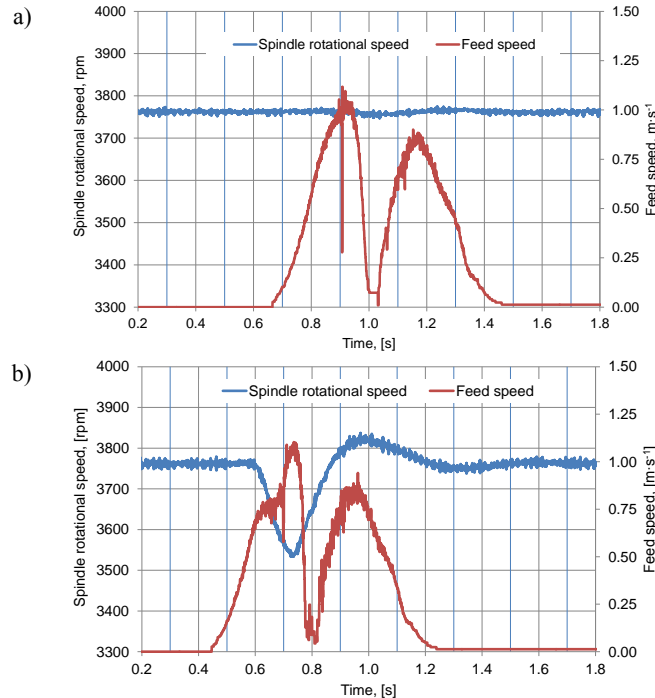


Fig. 7. Spindle rotational speed and feed speed while the feed motion was realized by means of the crank mechanism driven with the rotary servo motor, where: a – idling, b – during cutting of pine lumber (200 mm × 60 mm)

Moreover, the comparison of feed speed changes revealed that the relative drop in the feed per tooth f_z caused by the flexibility of the pneumatic actuator was equal to about 9.6%, whereas the reverse phenomenon was observed in case of the spindle rotational speed decrease. For the latter, the drop in the spindle rotational speed caused increase of the feed per tooth equal to 2.2%. The resultant change in the relative feed speed was -7.4%.

Figure 7 presents the spindle rotational speed and the feed speed in versus time while the feed motion was realized by means of the crank mechanism driven with the rotary servo motor. In this case the feed drive requires more dynamic and speed assurance, hence, the SLVC (Sensor less Vector Control) mode for the variable speed drive VSD was applied. In the working stroke some kind of deformation of the feed speed course at the time of the circular saw blade entry into the workpiece was observed (Fig. 7b), and simultaneously at this time the drop in the spindle rotational speed is noticed. This phenomenon caused an increase in feed per tooth equal to 6.36%. A comparison between maximal feed speeds during the idling (Fig. 7a) and working cycles (Fig. 7b) shown that the speeds are at the same level (1.09 m·s⁻¹).

For an assessment of the quality of the feed drive system it is proposed the use of the specific change in feed speed, which might be defined as a ratio of the fixed nominal (idling) feed speed to the relative change of feed per tooth. The carried out assessment revealed that the specific change in feed speed for the feed system with the pneumatic actuator was $-0.035 \cdot \text{m} \cdot (\text{s} \cdot \%)^{-1}$, whereas in the case of the drive system with the crank mechanism was $+0.171 \text{ m} \cdot (\text{s} \cdot \%)^{-1}$. The latter result is a proof that the feed drive with the crank mechanism driven with the rotary servo motor together with the SLVC mode applied in the spindle drive is a better solution in comparison to the feed drive with the pneumatic actuator.

5. Conclusions

The carried out analyses allowed us to discover undesired effects in the form of cutting conditions changes while sawing on the optimizing cross-cut saw.

- It was observed that the actual feed per tooth value could be affected by the flexibility of the both the feed drive system and the applied mode of the variable speed drive VSD. The both phenomena were simultaneously noticed during cutting while the cutting aggregate was driven by the means of a pneumatic actuator, and the resultant change in the relative feed speed was -7.4%.
- In the case of the feed drive system with the crank mechanism driven with the rotary servo motor only the phenomenon of the increase of the feed per tooth was observed. The latter was caused by a decrease in the spindle rotational speed. This phenomenon caused an increase in feed per tooth equal to 6.36%.
- Since, in the case of the feeding system driven by the means of a pneumatic actuator the set-up of the feed speed is difficult and its changes are unpredictable because of the system flexibility, hence, in the future in a new cross-cut saw the crank mechanism driven with the rotary servo motor should be applied. Furthermore, for the latter driving system feed speeds during the idling (Fig. 7a) and working cycles (Fig. 7b) have shown that the speeds are at the same level ($1.09 \text{ m} \cdot \text{s}^{-1}$).

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