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Calculation of cutting force by book-edge trimming with disk knives

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Introduction

The process of cutting paper stacks and books with a circular knife is relatively poorly researched. Anyway, some of known cutters are used for book-edge trimming and brochure cutting. In order to speed up the process and to select its optimal parameters, some additional researches needed. The paper proposes formulas for theoretical calculation of forces when trimming book-edges with a disc knife. The theoretical model is based on our own experimental data.

Problem Description

Various authors studied cutting of various materials with disk knives. Two main hypotheses regarding to the direction of the cutting force were considered [1]: the total cutting force is directed against the speed, or the cutting force has two components: the normal force, directed normally to the knife blade, and the sawing force, directed tangentially to the blade. According to the results of our experiments, the first hypothesis is not confirmed. In previous papers, the authors have dealt with theoretical studies of the kinematics of the process of cutting book blocks with a circular knife mounted centrally and eccentrically, and published some results of experimental studies of cutting forces [2, 4, 6] and others. This paper attempts to relate the results of theory and experiment and to establish some mathematical relationships between the kinematic parameters of the process and the cutting forces.

Methods

Our testing equipment allowed us to register the longitudinal force *Fx*, transverse force *Fz* and vertical force *Fy*. Our studies showed that the value of the vertical component *Fy* is relatively small [2], so it can be ignored. Fig.1 shows the relationship of the recorded forces *Fx* and *Fz* with the normal cutting force *Fn* and the tangential force, or sawing force, *Ft*. Knowing the values of the registered components of the total force F, it is easy to calculate the appropriate values of the normal force and the sawing force (Fig. 1):

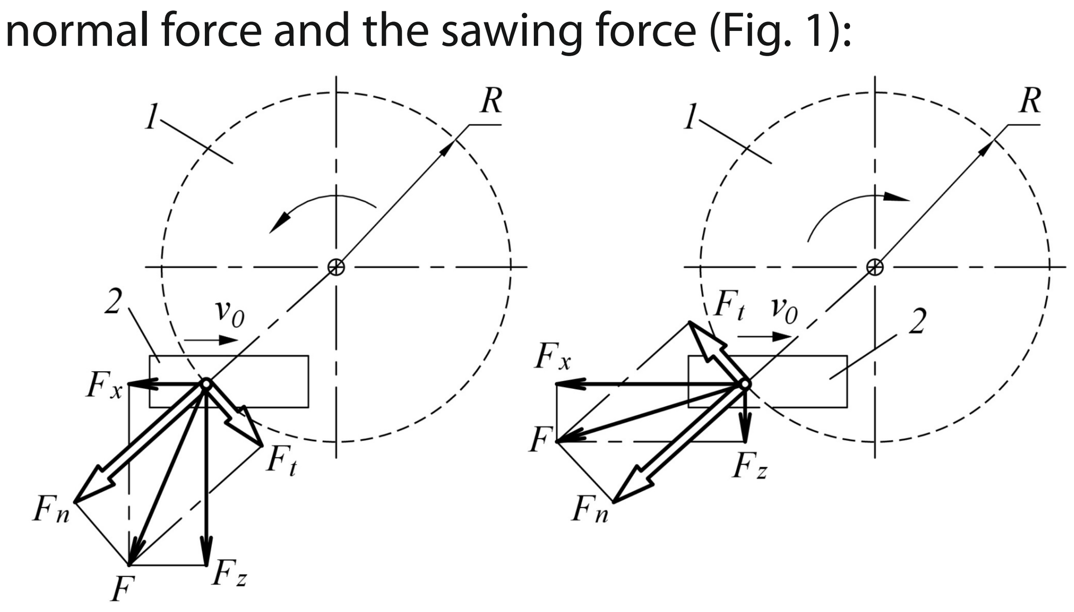

Figure 1

Different representation of the components of the force acting on the block from the side of the knife during the forward (left) and reverse cutting (right).
F - total cutting force, 1 - circular knife, 2 - book block.

During the testing, the dependence of cutting forces on different parameters of trimming process were established. Fig.2 shows typical graphs of dependence of the measured cutting forces Fx and Fz on the distance to the knife rotation axis. Graphs of normal Fn and tangential force Ft in the right chart are obtained by means of recalculations according to Fig.1:

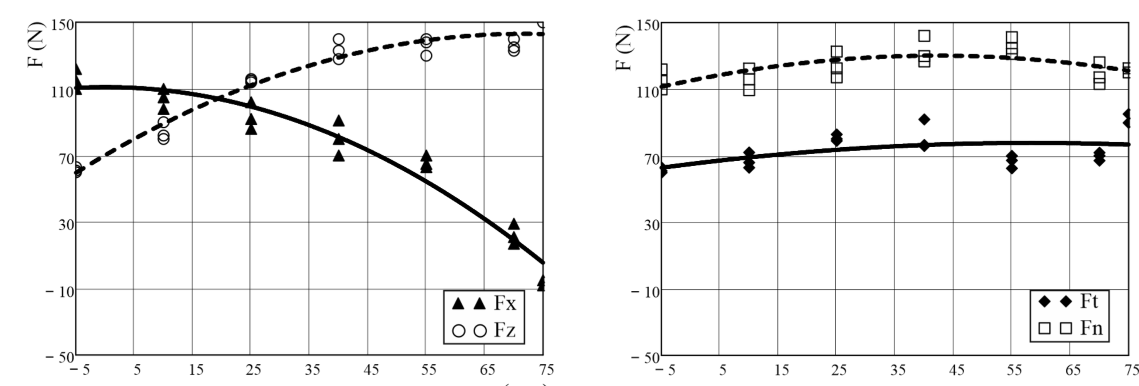

Figure 2

Dependence of cutting forces on the distance of a book block to the axis of rotation of the knife. Left – measured forces, right – recalculated nomal and tangential forces.

The result showed that the ratio between the tangential force and the normal force is an almost constant value for certain conditions. Hence, it is sufficient to determine what the normal cutting force depends on. To do this, it is convenient to represent it in the form of unit cutting force. Unlike a flat knife, the total cutting length of a book block with a circular knife depends on the height of the book block and on its position relative to the knife rotation axis (Fig.3):

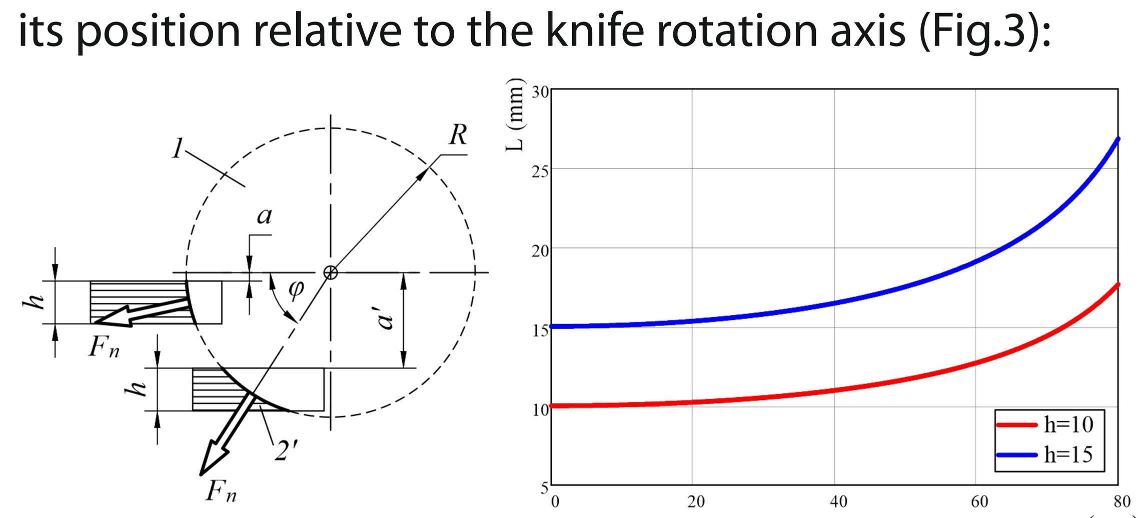

Figure 3

Dependence of the cut length L on the distance a.
1 - knife, 2 - book block. h - block thickness, R - knife radius. Calculated by R=98 mm, h= 10 mm and 15 mm.

The main factor influencing the value of the unit normal force of cutting is the value of the transformed angle of blade sharpening [5]. For a circular knife, this angle was studied in [6]. According to the research of some authors [3] the normal force of cutting with a flat knife can be approximated with a formula:

$$F = K_0 \cdot L \cdot \alpha_T^{\gamma} \quad (1)$$

where α_T - transformed sharpening angle, L – cut length, K_0 and γ – empiric coefficients. Regression analysis and approximation by the formula were performed in Mathcad. In our estimation, they are of the values: K_0=19.3...22.6, γ=1.6... 2.2 for offset paper 80 gsm. According to our experiments, the ratio between the tangential force and the normal force remains close to constant and equals about 0.55...0.65.

Results

Based on the above, we make the following assumptions when deriving formulas:

- The total cutting force consists of a normal component, and a tangential component, acting in the direction of the linear velocity of a blade point. The normal component raises due to the destruction of the sheets of paper as the blade plunges in, and the tangential component is equal to the sum of the sawing force and the frictional force.
- The value of the unit normal component of the cutting force depends on the value of the transformed angle of the knife blade sharpening at the cutting point and the empirical coefficients.
- The sliding cutting coefficient is equal to the ratio of the tangential component to the normal component of the cutting force, and is constant for certain cutting conditions.

Let us imagine a disk knife blade as a set of elementary straight prismatic knives of infinitely small length *dl* with the sharpening angle corresponding to the transformed angle at the current position on the blade. Each elementary knife moves along its own trajectory (Fig.4.):

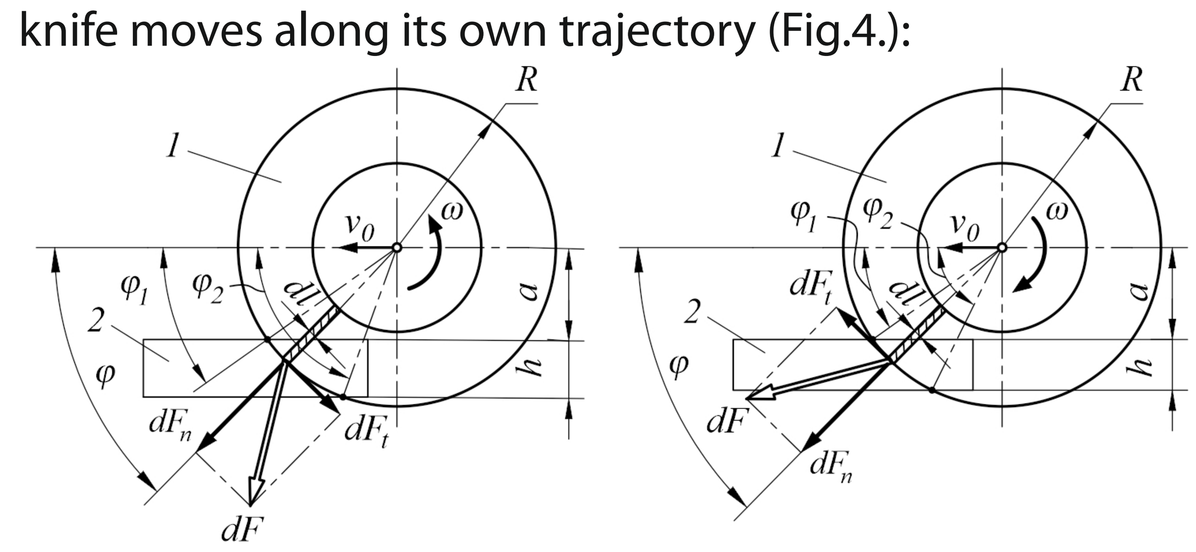

Figure 4

Diagrams for calculating the cutting forces.

We calculate the elementary cutting forces taking into account the formula(1) and the sliding cutting coefficient *f*. Then we project the normal and tangential components onto the axes and integrate the obtained expressions:

$$F_x = \int_{\arcsin\left(\frac{a}{R}\right)}^{\arcsin\left(\frac{a+h}{R}\right)} K_0 \left\{ \arctan\left[\tan(\alpha_0) \frac{v_0 \cos(\varphi)}{\sqrt{[\omega R \sin(\varphi) \pm v_0]^2 + [\omega R \cos(\varphi)]^2}} \right] \right\}^{\gamma} R[\cos(\varphi) \pm f \cdot \sin(\varphi)] d\varphi \quad (2)$$

$$F_z = \int_{\arcsin\left(\frac{a}{R}\right)}^{\arcsin\left(\frac{a+h}{R}\right)} K_0 \left\{ \arctan\left[\tan(\alpha_0) \frac{v_0 \cos(\varphi)}{\sqrt{[\omega R \sin(\varphi) \pm v_0]^2 + [\omega R \cos(\varphi)]^2}} \right] \right\}^{\gamma} R[\sin(\varphi) \mp f \cdot \cos(\varphi)] d\varphi$$

The upper signs are taken for reverse cutting, the lower signs - for the forward cutting. To calculate the integrals, we used numerical methods in Mathcad. Fig. 5 is a comparison of some experimental data and calculations by formulas (2):

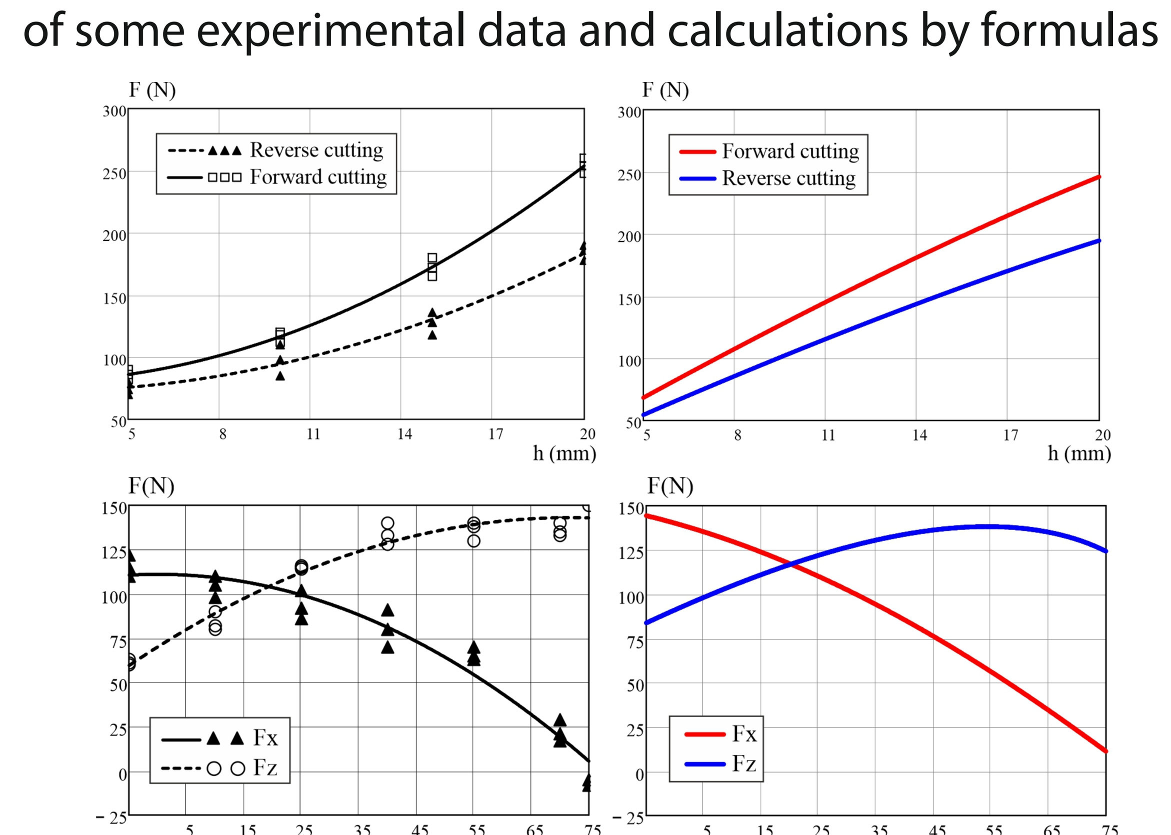

Figure 5

Dependence of the total cutting force and its components on different parameters of cutting process.
Left - experimental data, Right - calculations by formulas (2)

Conclusion

Comparison of the calculated values with the experimental ones shows a good match of the results in a certain range of parameters. With the help of these formulas, it is possible to study the influence of various parameters of the process on the cutting forces. There is no need to perform time-consuming and expensive experimental studies in full.

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