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EXPERIMENTAL EVALUATION OF THE TRACTIVE EFFORT OF THE CHAIN CONVEYOR DURING BOOK BLOCK SPINE PROCESSING BY CYLINDRICAL MILLING CUTTER AT PERFECT BINDING

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Abstract: The article reports on a device for book block spines processing that was designed and assembled on a perfect binding machine Trendbinder. The article shows workability of designed device. The authors have developed a methodology for the experimental study of the tractive effort of chain conveyors by technological load, the wireless module for data measurement and software for its processing. Extensive coverage is given to experimental research of the tractive effort of chain conveyors during book block spine processing depending on book block velocity, type of paper from which they are made and setting angle of cylindrical milling cutter relatively to direction of book blocks movement. The authors have examined the change in the tractive effort. The article experimentally confirms that sluggishness of chain drive causes vibration of the tractive effort. This effect can be observed during free-running movement of chain with carriers of perfect binding machine as well as during technological load influence. The article describes that between research parameters the setting angle of cylindrical milling cutter has the main impact relatively on the direction of book blocks movement.

Key words: tractive effort, cylindrical milling cutter, chain conveyor, book block, perfect binding

1. INTRODUCTION

Perfect binding of book block is the most common way of books and magazines binding. This is due to a number of factors amongst which the main is low cost. Along with that, it has characteristic well-known drawback: sufficient strength and durability of binding cannot be achieved always (Kipphan, 2001). Quality improvement of perfect bound book blocks carried out mainly in two directions: improvement of adhesives and the spine preparation before its applying (Knysh et al., 2019).

The spine preparation before applying adhesive provides for spine folds cutting and its processing by the spine microgeometry 'development' and applying additional grooves for better glue ingress. The development.of means of block spine cutting and processing is on use of tools without any electromechanical drive. As an example, multi-blade cutting tools (Vatuljak and Ju, 2018), screw with sided aggravation of helical cutting edge (Poliudov and Knysh, 2014) and cylindrical milling cutter (Viniarskyi and Knysh, 2003) can be considered. It is apparent that in all cases, technological load causes the increase in the tractive effort, which effects on conveyor drive power. In view of the outlined problem, it can be argued the actuality of researches directed on the experimental evaluation of tractive effort during book block spine processing by cylindrical milling cutter.

Analysis of previous research.

Tokarchuk (2014) studied the change in the tractive effort during the use of conveyor for granular materials with horizontal, curved and vertical sections. The author considered the conveyor as a mean of product transportation, thus the influence of technological loads on the tractive effort is absent. Pilipenko and Poluyan (2015) analysed the influence of sprocket and chain material (metal and plastics) on dynamics of chain conveyor. The experimental researches have defined the average value of dynamic chain loads, which gave an opportunity to calculate drive power, chose pitch and number of chain. Udovytskyi and Soltys (2017) have developed recommendations for reducing the negative impact of dynamic phenomena on the work of conveyors. They have proposed to minimise forced oscillations by reducing chain pitch or changing chain structure. This practice makes possible to reduce the negative impact of oscillations on the dynamic processes in the conveyor. The research of oscillation processes in the traction units of the chain conveyors (Lazutkyna, 2013) has shown that in the oscillations spectrum there are a frequency of natural free oscillations of the traction unit. Such effect is caused by periodic impact of conveyor roller on guide rail joint of plate conveyors. Senkus et al. (2015) have proposed changing of leading sprocket drive by using combined cam-lever mechanism for nonuniformity minimisation of conveyor links running. The study by Egorov et al. (2015) has identified a method that allows determining the torque and the efficiency of chain drives. This method does not require additional equipment, is more cost-effective and gives an opportunity to evaluate the chain drive efficiency with high measurement rate. In the works by Pereira et al. (2010a, 2010b), they have proposed the methodology of evaluation of the initial positions and velocities of all components of the chain drive that are consistent with the kinematic. The article by James and Johnson (1996) has shown the results of experimental studies of roller chain drives dynamics. They have studied the chain tension during the change of its velocity by use of strain gauges. According to the research results, it has been established that chain dynamics phenomenon increases by increasing its velocity. In addition, they have studied the change in horizontal and vertical resistance force in bearing depending on chain velocity. The article by Ambrosio et al. (1996) has shown a multibody dynamics methodology for the study of roller chain drives. The chain drive mechanisms are described as a planar multibody system. The contact force model includes the geometric contact detection and the contact force evaluation, which in turn includes energy dissipative features resulting from the friction and restitution coefficients terms used in the model. Niels et al. (2016a) have researched kinematic and dynamic model of chain drive and, as a result, received models that provide a basis for analytical and experimental research of roller chain transmissions. The work by Niels et al. (2016b) presents precise and approximate kinematic analysis of chain drive that has been modelled as a quadro-lever mechanism. They have studied kinematic parameters of sprocket rotation and behaviour pattern of its change. Comparative analysis of kinematic research results has shown their proximity to modelling results. These results have given new conceptions about the kinematic characteristics of the chain drive and the impact of the basic structural parameters. For the purpose of theoretical analysis of chain drive, Junzhou et al. (2013) have proposed and have used mechanical models. They have established that teeth quantity and pitch of sprockets have the most impact on chain vibrations. The article has shown the research of external loads impact on chain tension. These modelling results are well consistent with the theoretical results and illustrate the significant impact of pulsed loads on chain tension. The article by Perawat et al. (2018) has shown the results of experimental research of increase in endurance and hardness of roller chain elements. It has been established that improvement of these parameters increases chain lifetime. This ensures better dynamics of chain conveyor during long-term lifetime. In the article by Troedsson and Vedmar (2001), they have exemplified the results of calculations of loads distribution on sprockets of chain transmission, which work with moderate or high velocity. Chain roller position and their impact on dynamics distribution of loads in chain drive have been considered. The article by Kozar (2014) has given the results of experimental research of book block cutting by flat curvilinear knife. The author studied the components of cutting force and transportation force. However, it is noteworthy that track conveyor has been used as a mean of transportation, which is rarely used in perfect binding equipment. In the article by Xu et al. (2010), they have proposed a model that can well simulate the transverse and longitudinal vibration of the chain spans and the torsional vibration of the sprockets. This study can provide an effective method for the analysis of the dynamic characteristics of all the chain drive systems. The kinematic analysis demonstrates that the total length of the chain wrapped around the sprockets generally varies during one-tooth period. Some researchers proposed new structure of chain and sprockets to avoid problems of existed one. Liu et al. (2012) provided a reference for the optimisation design of the structure of the chain and sprocket wheel, through the analysis on the moving velocity and acceleration curve of the chain.

Because of the analysis, we can conclude that in the recent years, considerable research on the chain drive has been done. There are no results concerning the problem of the study of the technological load impact on the tractive effort in the conveyors of perfect binding machines. Therefore, we assume that the study of experimental research of tractive effort during book block spine processing by cylindrical milling cutter is the topical problem.

The aim of the article is to study the tractive effort of chain conveyor of perfect binding machine during book block spine processing by cylindrical milling cutter.

To achieve the aim of the article, we need to determine the following tasks:

- to design, manufacture and assemble the testing bench in perfect binding machine Trendbinder;
- to develop the experimental research methodology of tractive effort on driving chain of perfect binding machine Trendbinder;
- to design and manufacture wireless module for transferring of experimental data and to develop the processing software;
- to study the changing characteristics of the tractive effort during book block spine processing by cylindrical milling cutter;
- to study the impact of book block velocity, paper type from which blocks are made and setting angle of cylindrical milling cutter on the tractive effort.

2. TECHNIQUE AND EXPERIMENTAL TEST BENCH

We have conducted the experimental research on special designed test bench, which had been assembled on perfect binding machine Trendbinder-18 («Muller Martini», Switzerland). Because of this, it is possible to get accurate value of the tractive effort because of the change in studied parameters. Trendbinder-18 is the conveyor type machine. For book blocks transportation, it has 18 carriers that are connected by roller chain with pitch p = 25.4 mm. The axle spacing of transmission is 5,360 mm. Chain conveyor consists of drive R1 and driven R2 sprockets with a radius of 283 mm (Fig. 1). The machine has consecutive assembled units: (1) feeder and jogging stations, (2) cut-off of the folded sheets station, (3) spine processing station, (4) spine processing station by cylindrical milling cutter, (5) main gluing station, (6) infrared drying station (if polyvinyl acetate dispersions are used), (7) side gluing station, (8) back-stripping unit (lining station), (9) cover bonding station, (10) drying unit for PVAD by high-tension current, (11, 12) pressing stations and (13) delivery of bound book block out of machine. The power of the conveyor drive is 5.5 kW.

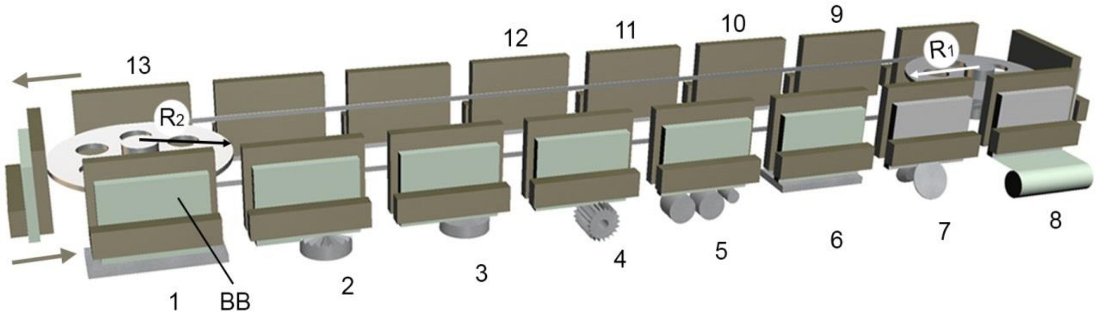

Fig. 1. Principal scheme of perfect binding machine Trendbinder-18

Experimental test bench (Figs. 2 and 3) consists of cylindrical milling cutter 1 with a tooth pitch of 7 mm, a sharpening angle of 20° and an outer diameter of 50 mm. Milling cutter is fixed on the shaft 2, which freely rotates in the support of support-bracket 3 that is inflexible and fixed to frame 4 of the machine. Book block BB is fixed by moving clamp 5 in carriage 6. Carriage connects by bracket 7 to chain 8 of conveyor. Linear translation of carriage is accomplished on guides 9. Guides 10 additionally press the spine part of book block, which bulges out the carriage.

Book block spine processing passes in a sequence given as follows. Book block that is fixed by moving clamp 5 in carriage 6 after cut-off of the folded sheets (not shown) transports to the cylindrical milling cutter 1. Contacting the spine and cogs of the milling cutter 1 during the movement of the blocks gradually makes incisions on block spine surface (Viniarskyi and Knysh, 2003).

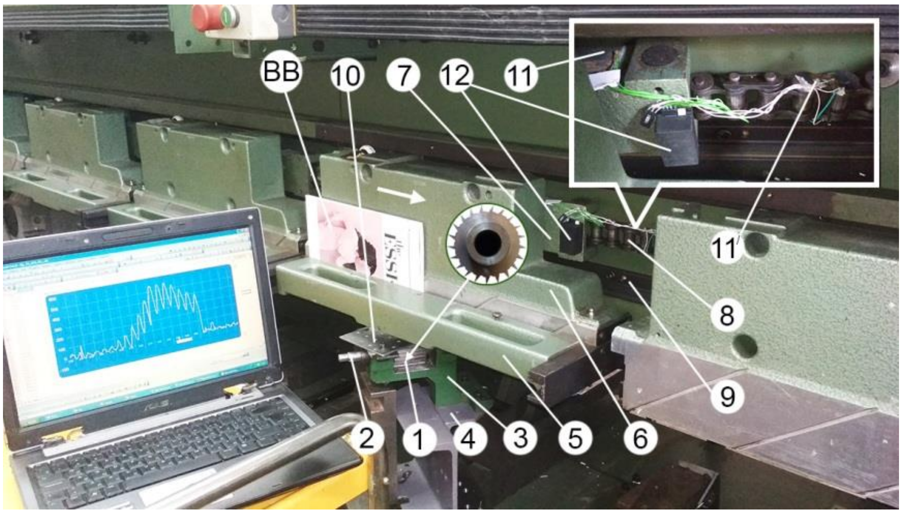

Fig. 2. Photo of the part of perfect binding machine Trendbinder and the experimental test bench

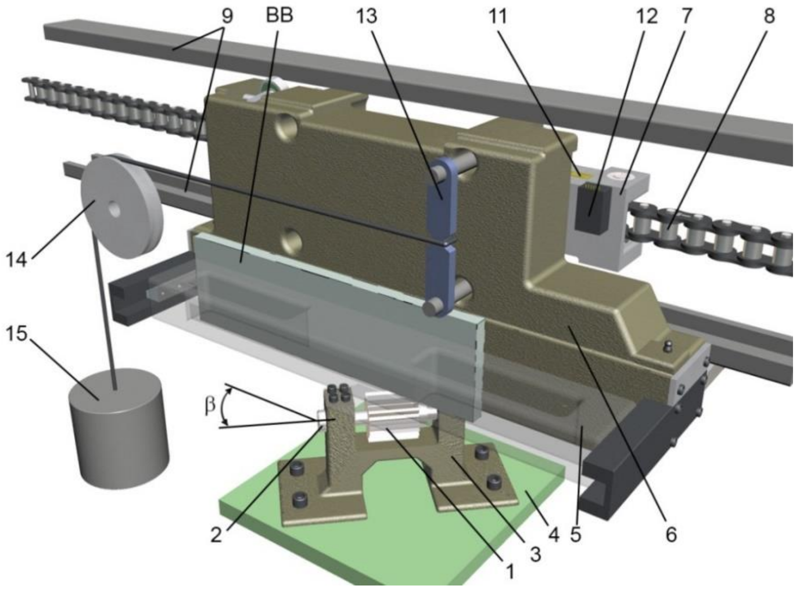

Fig. 3. 3D model of carriage and experimental test bench

For experimental research of tractive effort during book block spine processing by cylindrical milling cutter, we have used the method of strain gauge measurement. For this purpose, four foil resistance strain gauges type N2A-06-T007R-350 with a resistance of 350 Ohm and a base of 150 mm have been used. These strain gauges have been connected into complete bridge connection. We have connected strain gauge bridge to measurement equipment by specially designed module 12 for data processing and its wireless transferring. Such principle of wireless data transferring has been used because of carrier movement by a closed trajectory at a comparatively long distance (about 10 m) that makes data transferring by wire impossible.

Module 12 of wireless data transferring consists of three elements: 24-digit analogue-to-digital converter (ADC) H×711 with integrated amplifier (gain 128 times), microcontroller ATmega 328P and Bluetooth unit HC05. The principle of module 12 works as follows. Microcontroller makes data processing from ADC and its transfer by UART protocol to Bluetooth HC05 unit, which transfers the data by wireless method. For wireless data reception by Bluetooth v2.0 + EDR protocol from module 12, we have used the programme IVT BlueSoleil that receives data and creates virtual COM port and transfers data there.

For data reception and mapping in real time, we have created in spreadsheet MS Excel macros in Visual Basic for applications that get data from microcontroller by virtual COM port, interpret and write data into appropriate cells of spreadsheet without any other software. Final data processing and visualisation were made by inbuilt and own functions of MS Excel.

For matching between indexes of ADC and real values of loads, we have made calibration. For this purpose, we have inflexibly fixed the drive sprocket of chain conveyor and have connected special plate 13 (Fig. 3) to which a reference mass is applied by means of a rope through block 14. For recording of calibration diagram (Fig. 4), loads with different masses 15 were changed.

Due to fact that different masses have been applied, we have used next dependence for data conversion of ADC into effort values:

$$F = n_0 \cdot K, \tag{1}$$

where n_0 is the starting value of ADC, n is the current value of ADC and K is the conversion ratio of ADC values into loads, which is determined by the formulae:

$$K = \frac{(m \cdot g)}{n_t}, \tag{2}$$

where n_t is the quantity of ADC values that corresponds to change of applied mass.

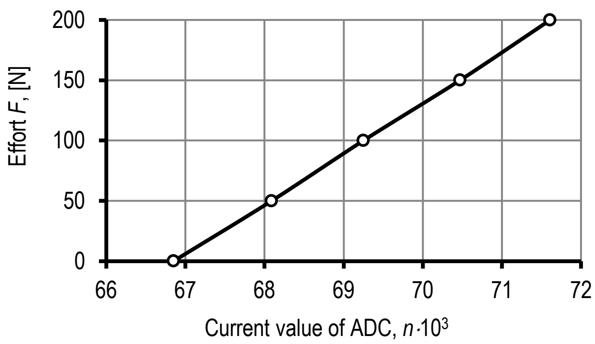

Fig. 4. Calibration diagram

Calibration diagram (Fig. 4) helps to transform values of ADC into indexes of tractive effort values. Here, the load F is laid off along the X-axis, which had been applied to the carriage, and the value n of ADC is laid off along the Y-axis. As seen from the diagram, we have got linear dependence that proves the correctness of strain gauges installation and possibility of getting trustworthy data of experimental research. At the first stage of research, we have used strain gauges 11′ (Fig. 2) on chain link and have connected to module of data processing and transferring. However, this method of tractive effort determination cannot give correct values. It can be explained by the fact that in case of such an arrangement of strain gauges, we have got parametric oscillations that had been raised by resistance effort and carriage mass. At the same time, it was impossible to distinguish tractive effort caused by technological loads. The dependence of tractive effort on time in case of strain gauges arranged on chain link at the book block velocity 0.3 m/s is shown as an example in Figure 5.

As we see (Fig. 5), oscillations peak of tractive effort of chain at idle on intervals t = 0.00–1.38 s and t = 2.02–2.95 s is round 350–400 N. On the interval of working stroke (t = 1.35–2.05 s), we can observe an increase in the tractive effort. However, the character of its change is chaotic and does not reproduce the real value of technological loads on conveyor drive.

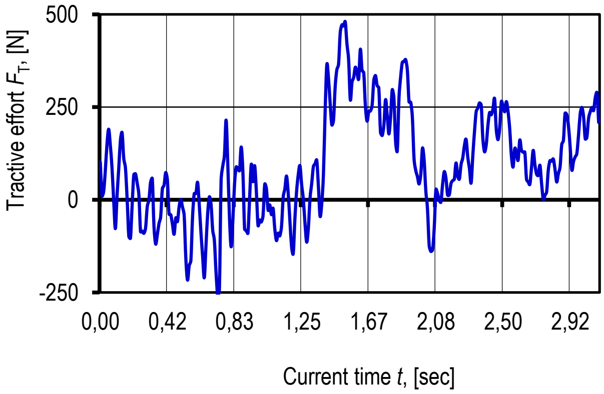

Fig. 5. Diagram of tractive effort dependence on time in case of strain gauges arrangement on connecting chain link

For the aim of avoidance of such a drawback, we have performed new run of experimental research. This time we have arranged strain gauges 11 (Fig. 2) on bracket 7, which connects carriage 6 to chain 8. This has given an opportunity to avoid the impact of inertial loads of conveyor and to determine the tractive effort directly on carriage with book block.

3. RESULTS OF EXPERIMENTAL RESEARCH

For experimental research of tractive effort, we have used book blocks format 60x84/8 with 20mm of thickness made of five types of paper: printing (55 g / m2), offset (70 g / m2), offset (75 g / m2), coated (85 g / m2) and coated (120 g / m2).

The graphical dependence $F_T = f(t)$ of tractive effort on period of spine processing by cylindrical milling cutter with the book block velocity V = 0.3 m/s and the setting angle of cylindrical milling cutter β = 45° is shown in Figure 6. The diagram had been taken when strain gauges were stuck on bracket that connects the carrier and the chain. Comparative analysis of dependencies, which are shown in Figures 5 and 6, shows more accurate character of tractive effort change in second case. There has been minimal impact of vibrations caused by inertia of conveyor on the tractive effort change. The amplitude of tractive effort oscillations at idle without technological loads is minimal and is 50–70 N.

We have conditionally divided the graphical dependence on five segments:

- segment I – carrier idle;
- segment II – smooth increase of tractive effort;
- segment III – maximal value of tractive effort;
- segment IV – tractive effort decrease;
- segment V – carrier idle.

As we can see from segments I and V of carrier at idle oscillations, period of tractive effort for book blocks velocity V = 0.3 m/s is about 0.06 s. Therewith, the constancy of oscillation period can be observed even on segments II–IV but with technological loads superposition.

Segment II shows gradual teeth incision of cylindrical milling cutter into book block spine. At the same time, the resistance to the carriage with the book block movement is created, which causes the gradual decrease in gaps of conveyor and, as a consequence, the increase in the tractive effort to the maximum value. In segment III, tractive effort reaches the maximum value

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and constant character, which can be explained by final decrease in gaps in conveyor. Character of tractive effort change in segment IV, as we think, is caused by the decrease in longitudinal stiffness of book block in the end of cylindrical milling cutter interaction with spine. In addition, the decrease in simultaneously used teeth quantity of milling cutter and contact line between teeth and spine has an influence on such result.

In addition, we studied the impact of book block velocity on tractive effort. Appropriate results are shown in Figure 7. Book block velocity has discretely changed and has been 0.3, 0.6, 0.8 and 1.2 m/s.

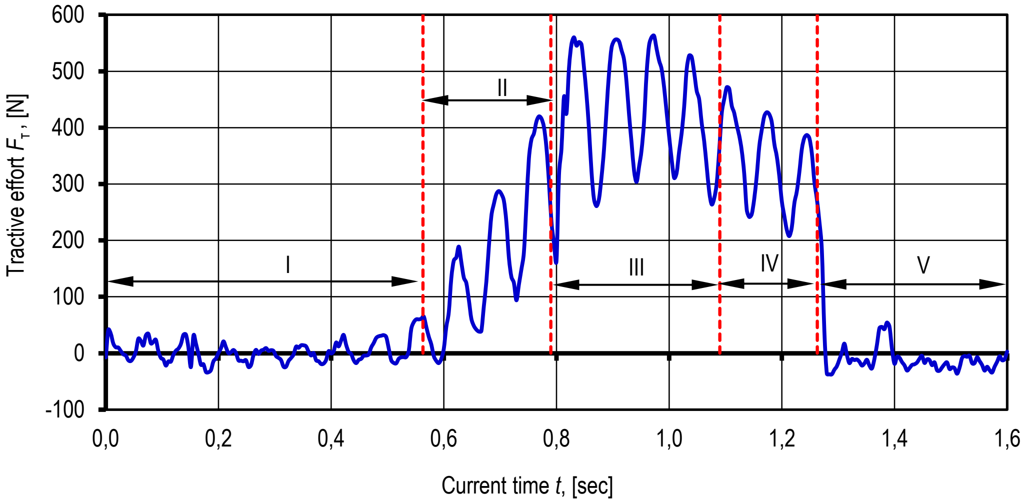

Fig. 6. Diagram of tractive effort dependence on spine processing period

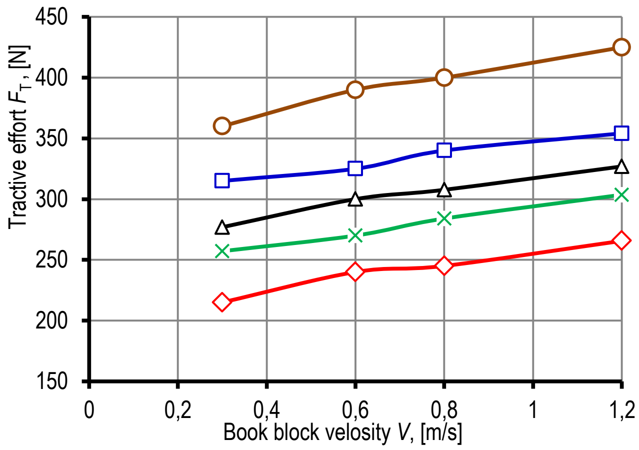

Fig. 7. Diagram of tractive effort dependence on velocity of book block made of paper: ◊ printing (55 g/m²), × offset (70 g/m²), Δ offset (75 g/m²), □ coated (85 g/m²), ○ coated (120 g/m²)

As we can see from the research result, increase in the book block velocity insignificantly increases the tractive effort increase. For example, for coated paper (120 g/m²), the increase in book block velocity by 4 times from 0.3 to 1.2 m/s increases the tractive effort by 1.25 times from 360 to 450 N. We should also note that an increase of 1 m² of paper mass also increases tractive effort because of greater technological loads during processing of 'heavier' type of paper and as consequences higher value of tractive effort.

The results of tractive effort research depend on the setting angle of cylindrical milling cutter, which have been shown in Figure 8. Experimental research has been held for five book blocks made of five paper types. The setting angle of milling cutter has changed discretely and has been 15°, 30°, 45° and 60°. As we can see from the results, increasing the setting angle of milling cutter decreases the tractive effort. Such a tendency is logical and can be explained by the decrease in contact line between milling cutter teeth and book block spine. Because of research, we can state that rational setting angle of cylindrical milling cutter should be 40°–60° because of the decrease in the tractive effort. However, in this case, the defining criteria of book block quality are the stiffness and durability of perfect bound, which was the subject of other studies.

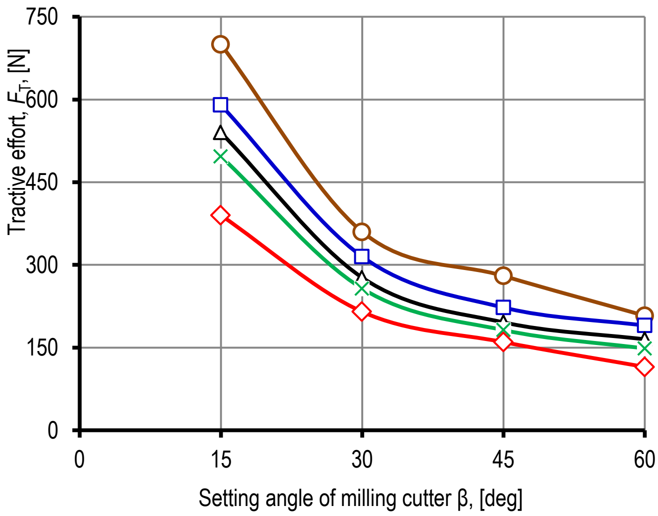

Fig. 8. Diagram of tractive effort dependence on the setting angle of cylindrical milling cutter for paper: ◊ printing (55 g/m²), × offset (70 g/m²), Δ offset (75 g/m²), □ coated (85 g/m²), ○ coated (120 g/m²)

4. CONCLUSION

1. The experimental test bench for research of book blocks spine processing by a cylindrical milling cutter without an electromechanical drive has been designed, manufactured and

mounted on a Trendbinder perfect binding machine. The device's serviceability has been checked in conditions as close as possible to the production.
2. The method of experimental research of tractive effort on a Trendbinder perfect binding machine has been created, which provides the method of strain gauge measurement.
3. The module for wireless data transferring has been designed and manufactured, and special software has been created.
4. The change character of tractive effort of chain conveyor in perfect binding machine has been studied when a machine is idle and during spine processing by cylindrical milling cutter. The tractive effort changes cyclically, which is a consequence of inertia of chain drive and nonuniformity of chain with carrier velocity.
5. Increasing the book blocks transportation velocity by 4 times from 0.3 to 1.2 m/s increases the tractive effort by 1.25 times. The increase in 1 m^2 of paper mass also increases the tractive effort because of the greater resistance to transportation. Increasing the setting angle of milling cutter from 15° to 60° decreases the tractive effort by about 3.5 times. Such a tendency is logical and can be explained by the decrease in contact line between milling cutter teeth and book block spine.

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