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Optimisation of Selected Components of a Roller Carding Machine in the Aspect of Improving their Cooperation Quality

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Abstract
The quality of web produced by a carding machine is largely influenced by the shape and height of the gaps between card clothings of workers and the doffer cooperating with the main cylinder as well as between the doffer clothing and doffing blade. The following paper describes the methodology of selection of a structural form and basic dimensions of the carding machine shafts and cylinders taking into account the gap shape in the zones of card clothing cooperation. For the study to be complete, optimisation of the blade and comb shaft cross-sections was also performed. The benefit from optimisation of the carding machine components is the improvement in the quality of the web – the final product of carding.

Key words: *carding machine, working cylinders and rollers, doffing comb, optimisation.*

Introduction

The technological process of producing yarn from wool and wool-like fibres requires preparing a web made of loose, straightened and impurity-free fibres of suitable length, arranged in a parallel way. This operation is carried out on carding machine units, in which the pre-opened web is intensely combed with the teeth or needles of card clothings reeled on the surfaces of the cylinders and working rollers. The differences in tangential velocities in the cooperation zones (***Figure 1***) of feeding rollers and the main cylinder (A), workers and the main cylinder (B), and the doffer and main cylinder (C) are large. The proper carding process requires that the fibres should remain in card clothing for some time and be repeatedly exposed to the clothing operation during one rotation of the main cylinder. Therefore carding can be treated as a continuous process of fibre transport by the carding machine, during which there must be adequate conditions in cooperation zones (A), (B) and (C). When the conditions are fulfilled, fibres held by the previous clothing are transmitted to the next one.

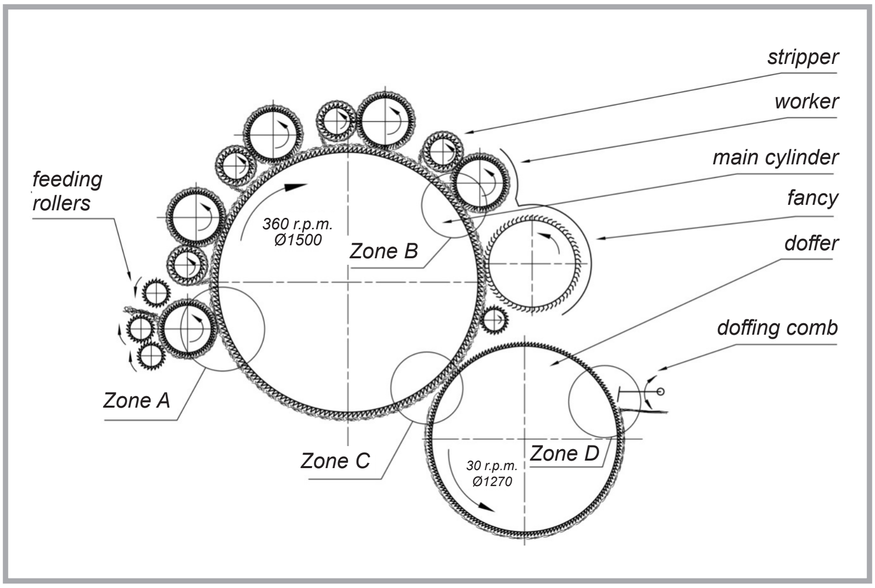

Figure 1. *Roller carding machine scheme.*

A mathematical model of fibre transport in the carding machine seen as a flow of fibre suspension in incompressible fluid - air was given by Lee and Ockedndon [1]. According to this model, transferring fibres between the teeth/needles of card clothing is not only caused by the mechanical impact of card clothing on fibres and resulting friction forces, but also and, perhaps above all, by aerodynamic forces resulting from the impact of the air boundary layer kept by the main cylinder surface moving at a high tangential velocity. Therefore in card clothing cooperation zones there is a fibre suspension flow in the air through the gap between the rollers and the cylinder (A), (B) and between the cylinders (C). The authors [1] described mathematically and distinguished between two fibre transport mechanisms: strong, in which the following card clothing has a much larger tangential velocity than the previous one and the fibres are transferred (A and B), and weak, in which the following card clothing has a much lower tangential velocity than the previous one and the fibres are taken off (C). The mathematical model of fibre transport in a carding machine mentioned is two dimensional, and in order for the model to be applied to a real machine, the gaps between the cooperating working rollers and the cylinder and between the cylinder and the doffer should have the same height along the entire width of the carding

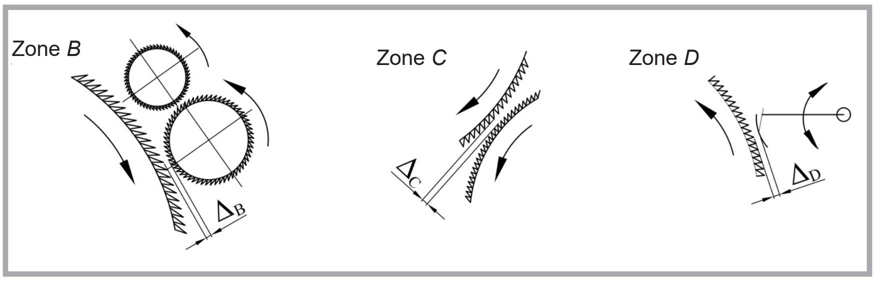

***Figure 2.** Cooperation zones of the key carding machine components.*

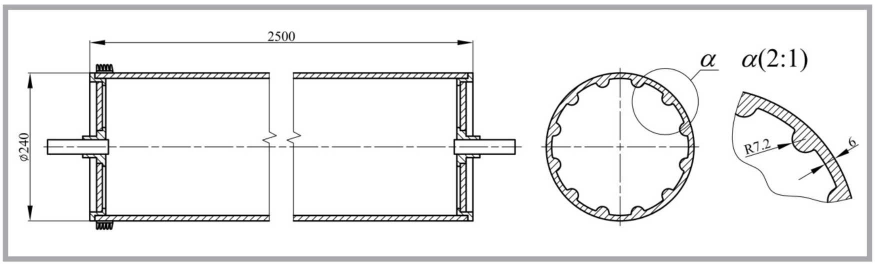

***Figure 3.** Worker with a pipe with an optimal cross-sectional shape and dimensions [3].*

machine. In other words, they should be rectangular. Failure to fulfil these conditions will cause the transport of fibres in card clothing in the direction of the cylinder and the working roller axes, which will impair web uniformity after carding, cause the tearing of fibres and disrupt fibre transport in card clothing cooperation zones.

The aim of the analysis

The quality of the final carding product - the web is influenced by a number of factors: settings of the process, rotational speed, the quality of the raw material fed to the carding machine, and many others. A broad description of the influence of the above-mentioned factors is presented in, among others, [2]. Construction (stiffness) and manufacturing technology of the carding machine components is also of significant importance.

In a real carding machine, when the gap shape between the cooperating rollers and working cylinders is not rectangular, it is caused by their deformations; that is, their designing and engineering tolerances (manufacturing process). The following paper describes the methodology of selection of a structural form and basic dimensions of carding rollers and cylinders with the use of optimisation methods, taking into account the height and uniformity of the gap between them in the zones of card clothing cooperation. Since the velocity circumferential component of the flow through the gap decreases with the square of its height [1], this problem is of particular concern where the height of the gap is the smallest. Each change in the height significantly influences the flow and thus the transport of fibres. Therefore this article analyses cooperating pairs (***Figure 2***): the last worker - the main cylinder (zone B), and the main cylinder - the doffer (Zone C). For the study to be complete, the doffing comb blade and doffer cooperation was also considered – zone D. In the latter case, deformations of the doffing comb blade are caused by its vibration. However, the cooperation quality criterion is similar - the height and shape of the gap between the doffing blade and the doffer.

The aim of optimisation described further in the article is to improve cooperation between the carding machine components. The priority is to obtain a uniform rectangular-shaped gap between the components. In the case of a carding machine, the settings required Δ_B, Δ_C, Δ_D (***Figure 2***) in a static state are obtained by adjusting the distance between the closest points of the cooperating components. As a result of deformations caused by the reeling of the card clothing, rotary motion or bending of the doffing blade caused by induced vibrations, the real gap shape differs from that of a rectangle. In a dynamic state (movement), setting values change. Therefore, if, as a result of optimisation of selected constructional parameters of carding machine components, there is an improvement in gap shape uniformity, it is possible to lower the setting values in a static state, if required by textile technology.

All the analyses were carried out for a roller carding machine with a sheet working width of 2500 mm (the actual width of the cylinder and the doffing comb is 2540 mm) used in the worsted, wool spinning system. Metallic (saw tooth) wire was accepted as card clothing which, when reeled at the tension and pressure of consecutive coils against each other, causes larger cylinder deformations than elastic card clothing.

Optimisation of rollers and working cylinders - a summary of the results of previous work

Worker

Deflection analyses were performed with the use of the worker calculation model, which is the superposition of a beam whose deflection was caused by the dead weight of a worker and a shell whose deflection resulted from surface pressure caused by the reeling of the metallic wire at an appropriate tension [3]. In order to solve the optimisation task, a program based on *Powell's gradient free method of conjugate directions* was applied [4]. In order to reduce the worker's dead weight, while maintaining permissible deflection, it was advised to make an aluminium alloy pipe stiffened with longitudinal ribs on the inside. Several shapes of rib cross-sections were considered and the shape and dimensions of the cross-section were selected ensuring a weight reduction of nearly 60% and with no noticeable change in the value of deflection in relation to the roller made of a steel tube (***Figure 3***).

The main cylinder

Paper [5], taking into account the conclusions and observations included in [6], describes the way of searching for an optimal shape and dimensions for the carding machine's main cylinder according to the criterion of the minimum deflection amplitude of the cylinder shell. Calculations used a discrete parameterised model of the cylinder prepared with the use of the *Finite **E**lement **M**ethod* - FEM. The model was developed based on the author's experience described in [7], where a non-parametrised version of the cylinder model was presented which took into account inaccuracies resulting from manufacturing technology. Moreover the paper included the way of calculating cylinder loads coming from the reeling of clothing saw wire and other loads which result from working conditions. Experimental verification of the assumptions was also performed eliminating loads which are less significant with reference to the cylinder shell deflection. The possibilities of introducing simplifications in the FEM model were mentioned as well.

Detailed analysis described in [5] and [6] proved that for a significant reduction in the deflection amplitude of the cylinder, it is necessary to introduce a structural modification by using internal ring reinforcements and special bottoms with a conical ring with suitable flexibility in the radial and axial directions. The best position of the bottoms relative to the cylinder was determined in a series of numerical tests. Optimal dimensions of the bottom and shell were found by solving an appropriate optimisation problem with the use of the *Polak-Riberie conjugate gradient method* [4]. ***Figure 4*** shows a comparison of the deflection line of the cylinders without reinforcement (i), optimal with flat bottoms (ii), and optimal with bottoms with a conical ring (iii). Optimal dimensions of the cylinder with bottoms with a conical ring (***Figure 5***) give the deflection amplitudes of the shell of a few µm, being significantly smaller than the amplitude of deflection for the construction without reinforcement and that with flat bottoms (***Figure 4***).

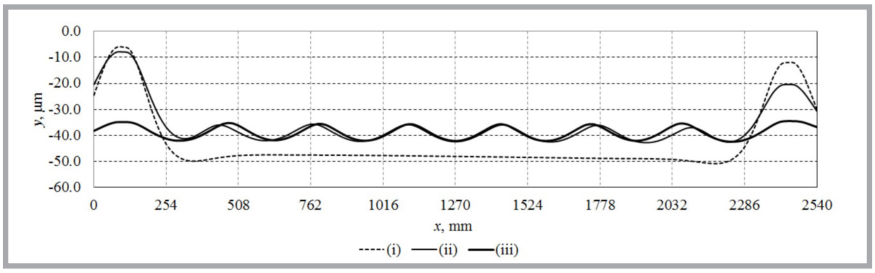

Figure 4. *Comparison of the main cylinder's deflection: without reinforcement (i), with reinforcement and flat bottoms (ii), with reinforcements and bottoms with a conical ring (iii).*

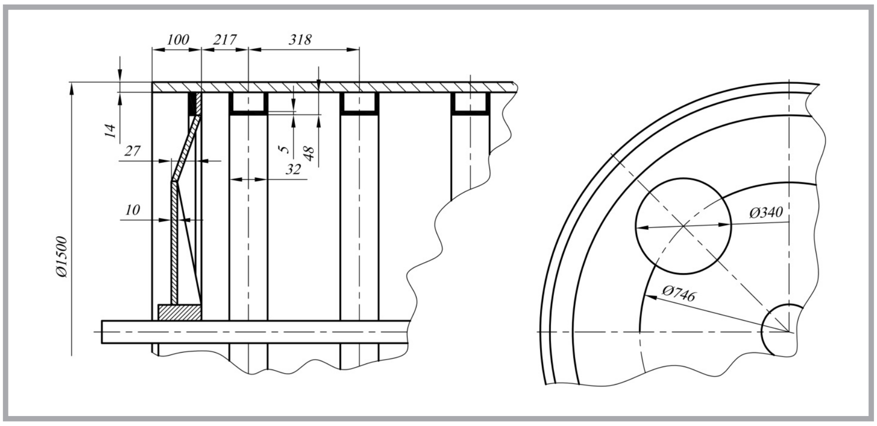

Figure 5. *Dimensions of an optimal main cylinder with the bottom possessing a conical ring.*

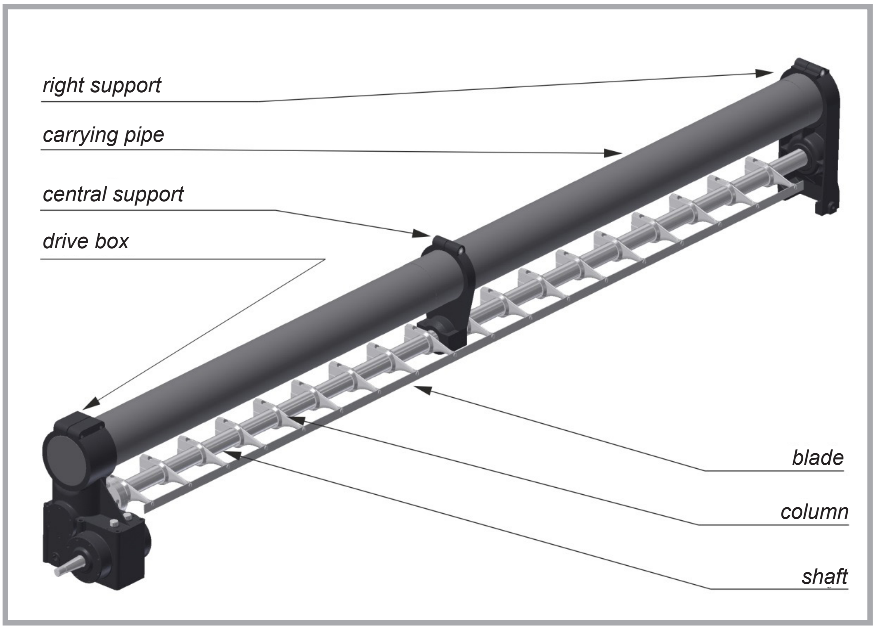

Figure 6. *Doffing comb with a blade and shaft made as one part.*

Optimisation of the shape and dimensions of the doffer

The construction of the doffer is similar to the main cylinder construction [5], the only difference being the diameter. Therefore the methodology for researching optimal dimensions is similar in both cases. The scheme of loads acting on the shell of the doffer and main cylinder is the same, and the most important load is the surface pressure coming from reeling the metallic wire at an appropriate tension and residual pressing of the coils against each other. It is possible to make a parametric FEM model of the doffer and solve the optimisation problem in a similar way as for the main cylinder. Therefore only the results of the analysis will be presented.

Optimisation of the doffing comb blade

The doffing comb, taking off fibres from the doffer, is a device whose output also has an impact on that of the whole carding unit and the quality of the product – the web. Problems with obtaining a sufficiently fast and effective process of taking off the web concern primarily removing woollen and wool-like fibres from the doffer clothing. Due to their length and physicochemical properties, these fibres show high adhesion to the clothing and to one another, which is why the solution to this problem is much more difficult than, for example, for cotton or synthetic fibres. On the basis of the available offers of machine manufacturers, one can conclude that wool carding machines use doffing comb devices almost exclusively. A classic drive system with the crank-and-rocker drive mechanism is

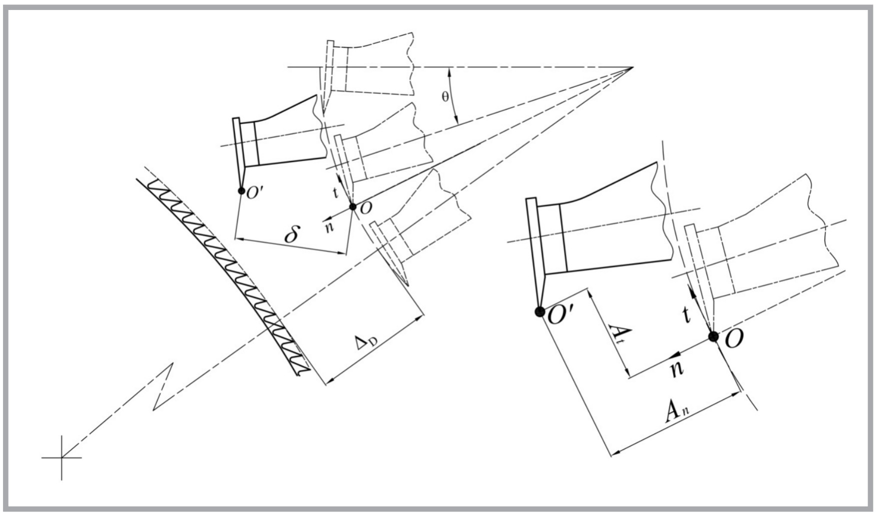

Figure 7. Doffing comb blade and doffer cooperation.

sometimes replaced with a device with a torsional shaft and electromagnetic exciter performing an oscillating-rotational motion, whose parameters were chosen so that the system could work in the range of mechanical resonance.

The object of this analysis is a device with a comb blade and shaft made as one part (***Figure 6***) and with a working width of 2500 mm. The right and central (two parts) supports together with a carrying pipe and drive box make up the suspended construction. A series of columns which link the shaft to the blade were mounted on the shaft. The crank-and-rocker mechanism built in the drive box converts the rotary motion of the drive motor to the oscillating rotary motion of the shaft.

The oscillating rotational motion of the shaft is accompanied by harmful vibrations affecting the shape and size of the gap between the blade and the doffer. As in the case of clothing cooperation zones (B) and (C) (see ***Figure 2***), taking off fibres from the doffer occurs not only as a result of the mechanical operation of the blade, but also due to aerodynamic forces caused by the rapid movement of the blade. Ensuring proper taking off of the web by the blade causes similar problems as the transport of fibres in the air stream through the gaps in zones (B) and (C). It is expected that at a frequency of oscillations of 2000 – 2500 per minute, it will be possible to keep the settings between the blade edge and the doffer (***Figure*** *7*) within Δ_D = 0.25 - 0.4 mm and the gap shape as close as possible to a rectangle.

In addition, the amplitude of the blade vibration cannot be excessive because in extreme cases it can lead to the blade catching on the teeth of the doffer's metallic wire and thus leading to the machine failure.

During the taking off of the web, there appear reaction forces (tangential to the surface of the doffer) which are the result of fibres being removed from the doffer by the blade. Values of these forces, however, are small compared to the forces of inertia resulting from the rotating-oscillating motion of the shaft. Measurements of power demand for the doffing comb drive carried out on the manufacturer's test stand showed that the difference in power consumption of the device working with and without the raw material is within the measurement error. Therefore the influence of the raw material is omitted in the analysis.

Calculation model

In order to determine the optimal dimensions of the doffing comb taking off the web in the carding machine, it is necessary to solve the problem of dynamic analysis. A few previous works devoted to the analysis of mechanical vibrations of doffing comb devices [8], [9] show

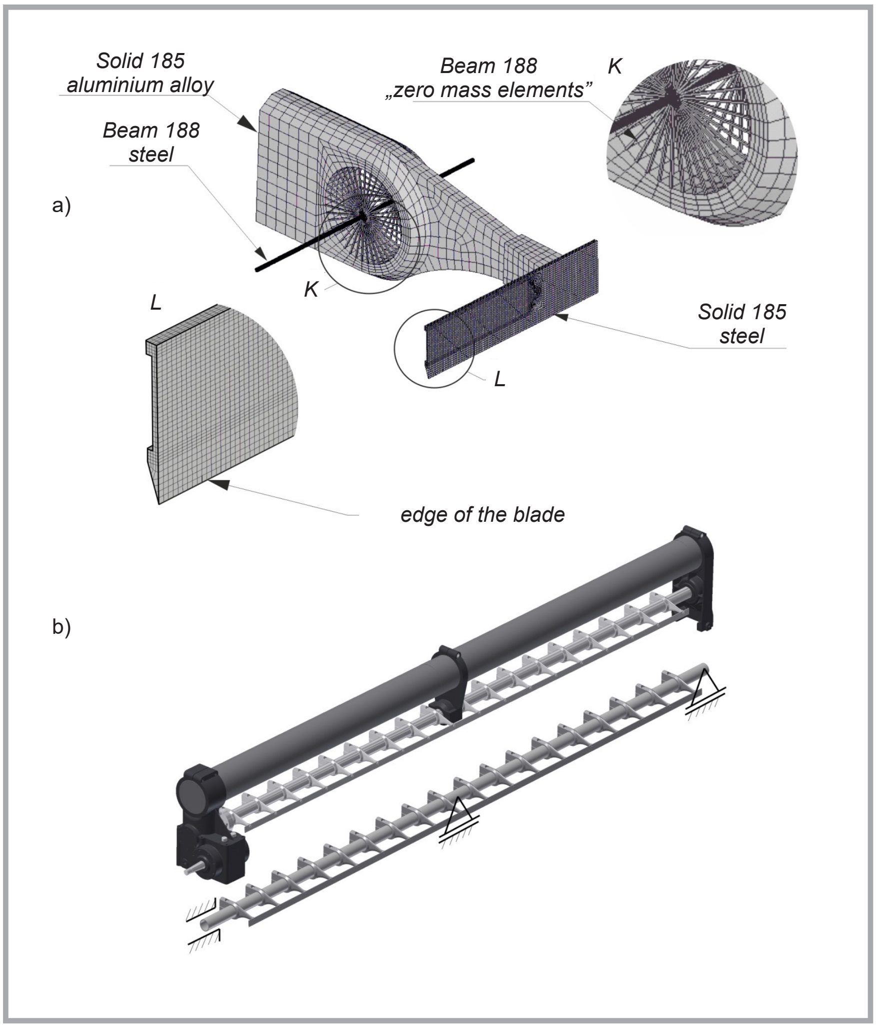

Figure 8. Discrete model of the shaft with columns and blade: a) discretization method - fragment, b) supports.

discrete computational models built with beam elements with cross-sectional parameters determined from the analysis of an auxiliary model. This allowed to determine areas of safe work for the existing doffing comb devices [8] as well as the impact of technological and structural factors [9] on the amplitude of the blade vibration. Paper [9] also describes experimental verification of the doffing device's FEM model. These computational models were not parametric,therefore they were not suitable for solving an optimisation problem. For this reason, a calculation model was developed which enabled the solution of the optimisation problem of the blade and the shaft cross-section. The model was prepared (***Figure 8***) using the Finite Element Method and ANSYS package [10] based on APDL (ANSYS Parametric Design Language). The following was assumed:

- only shaft deformations were taken into account and the suspended structure was treated as rigid;
  The suspended structure (carrying pipe and ribbed iron casts of the supports and drive box) is nearly 80 times more rigid for bending than the shaft.
- insignificant fillets were omitted and screw joints were treated as non-deformable;
  When adjusting the dimensions of the column, special attention was given to preventing these simplifications from changing the mass distribution and mass moments of inertia of the statically balanced shaft with columns and blade.
- in accordance with the principles of good practice of FEM modelling, the shaft was modelled with *Beam188* elements;
  It is a two-node beam element meeting the demands of Timoshenko's beam theory [10].
- the column and doffing blade was modelled with *Solid185* elements;
  It is a 10-node solid element with 3 degrees of freedom in each node. The blade shape was precisely modelled due to the significant influence of its mass moment of inertia and stiffness on vibration amplitudes.
- *Beam188* elements were used to link the shaft to the columns; Their cross-sectional parameters provided a rigid connection of the shaft and columns (*zero mass elements*).
- a frequency of comb oscillations of 2500 1/min was assumed,

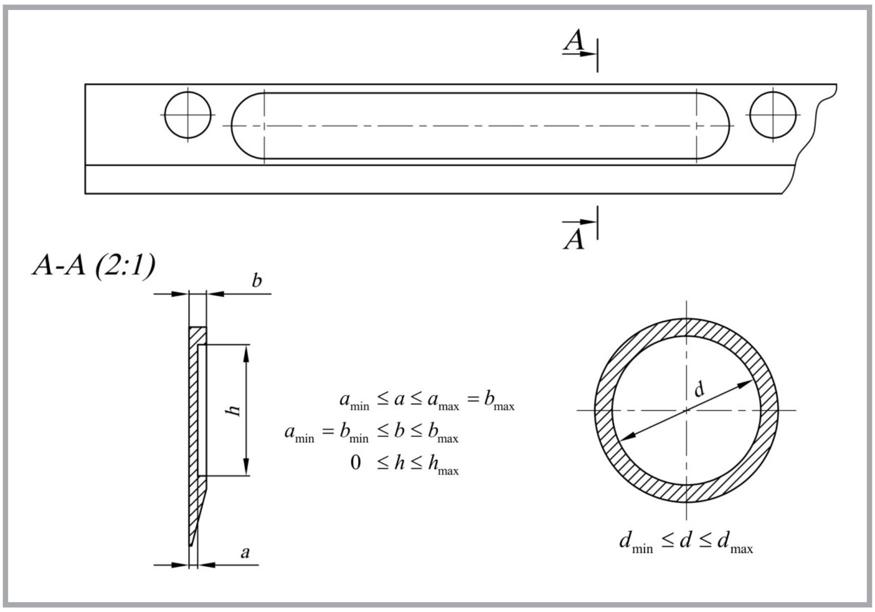

Figure 9. *Decision variables in tg optimization problem.*

- the conditions of the comb shaft support result directly from the method of its bearing (***Figure 8.b***).

Due to a large excess of engine driving torque over its demand to drive the unit, kinematic excitation was assumed in calculations. Oscillating rotary movement was obtained by setting the rotation of the last finite element of the comb shaft (***Figure 8***) at consecutive points in time, according to the function resulting from the kinematic analysis of the drive mechanism. The Newmark method with the automatic integration step size [11] implemented in ANSYS was used for the direct integration of equations of motion.

Optimization task

When formulating the optimisation problem, it was assumed that any deviation from the set (theoretical) trajectories of points of the system should be regarded as undesirable (requiring elimination or at least reduction). In view of this, for each of the N discrete model nodes lying on the blade edge (see ***Figure 8.a***), the distance δ (***Figure 7***) was determined at any given time τ. The distance is a measure of the deviation from the assumed trajectory of motion. The objective function was written as follows:

$$\max\{\delta(t)\} \to \min, \quad \text{for } i = 1, ..., N,\ \tau \in \langle 0, \tau_k \rangle \qquad (1)$$

where, N - node number on the blade edge, τ_k - time of the end of the analysis. Criterion (1) may be explained in the following way. The shaft with columns and blade has no axis of symmetry. Therefore coupled bending-torsional vibrations are performed. It is thus advisable to limit both of them. The deviation of the trajectory of the nodes lying on the edge of the blade in a mobile, local coordinate system ($O\ n\ t$) is the geometric sum of the normal component with amplitude A_n caused by bending vibrations and the tangent with amplitude A_t caused by torsional vibrations (***Figure 7***).

However, to assess comb blade cooperation with the doffer, one should consider the amplitude of the normal component A_n. Its value makes it possible to conclude about the shape and height of the gap between the blade and the doffer and find a potential collision.

Decision variables in the optimisation problem are dimensions characterising the shape of the blade cross-section: a, b, h and the inner diameter of the shaft (***Figure 9***). The parameterization method of the blade cross-section and the ranges of decision variables suggested enable analysis of the impact of both the shape and dimensions of the blade cross-section on the amplitude of vibrations.

Due to the size of the FEM model (over 370,000 nodes) and the type of the analysis (*transient analysis*), in order to solve the optimization problem, the *subproblem approximation* method, recommended for problems with high computational complexity, was used [10]. It is a zero-order method, with the problem with constraints being an implementation of the method of the internal penalty

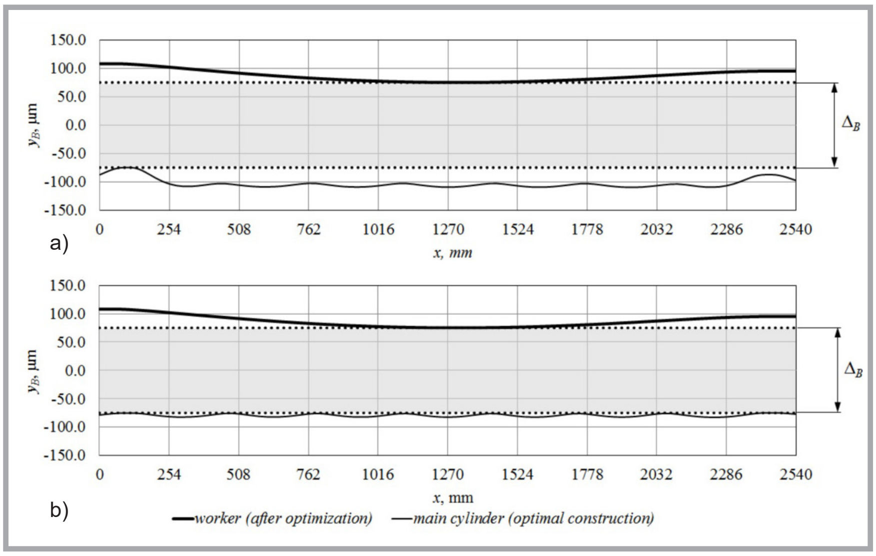

Figure 10. *Cooperation in zone (B): (a) before optimization, (b) after optimization.*

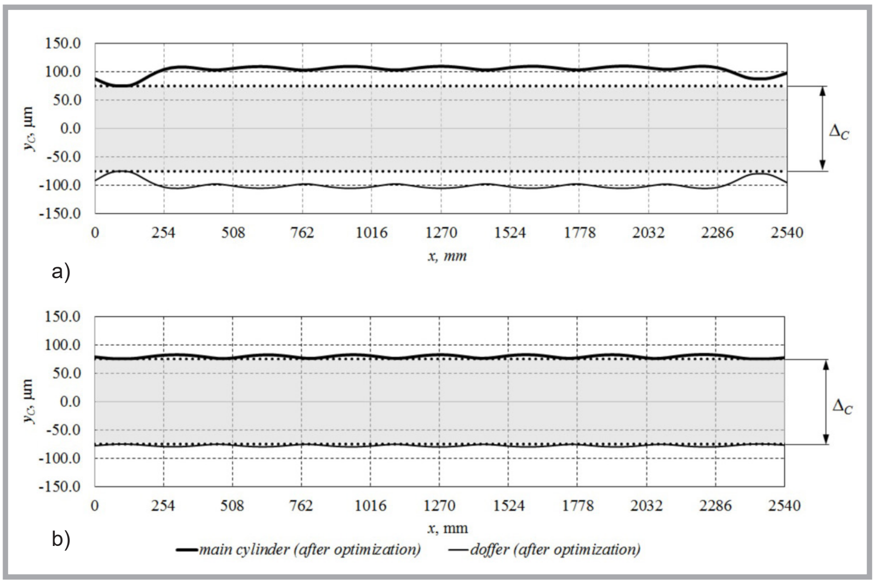

Figure 11. *Cooperation in zone (C): (a) before optimization, (b) after optimization.*

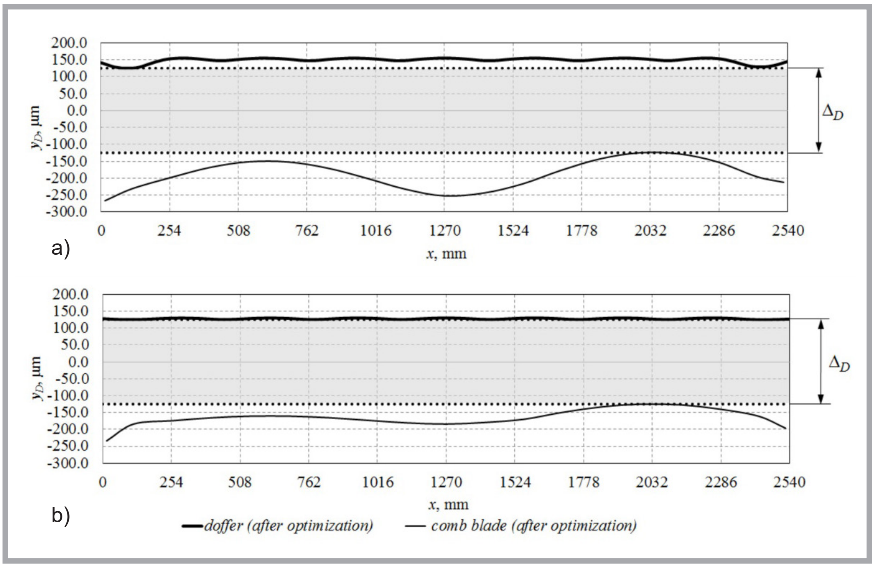

Figure 12. *Cooperation in zone (D): (a) before optimization, (b) after optimization.*

function. The initial values of decision variables were the dimensions consistent with technical documentation of the doffing comb.

Quality evaluation of carding machine components in cooperation areas (B), (C) and (D)

To assess the quality of cooperation of carding machine components, it was assumed, according to the carding machine manufacturer's recommendation, that the set settings are, correspondingly (***Figure 2***): $\Delta_B = \Delta_C = 150$ µm, $\Delta_D = 250$ µm.

The graphs (***Figures 10*** to ***12***) summarise the results of analyses for the construction before and after optimiation. In zones (B) and (C), curves mapping static deflections of the pairs: last worker - the main cylinder, and the main cylinder - doffer are compared. In zone (D), the static deflection of the doffer was compared with the envelope of vibration amplitudes of the doffing comb blade determined in the normal direction *n* to the assumed trajectory (envelope of consecutive positions of the nodes lying on the edge of the blade, see ***Figure 7***). An ideal expected shape of the gap between the cooperating components was marked grey.

Since the previously mentioned fibre transport model in the carding machine is a 2D model, the average height of the real gap with the upper and lower deviations was assumed as a criterion to assess the quality of the results. The height was determined before and after solving the optimisation problem (***Table 1***), allowing to assess the height of the gap with respect to the carding machine settings Δ_B, Δ_C, Δ_D (see ***Figure 2***) and, based on the width of the tolerance range, conclude the uniformity of web.

The percentage change (decrease) in the gap's average height and narrowing of the tolerance range for optimal constructions were calculated for each zone in relation to the initial construction (***Table 1***).

Conclusions

Nowadays progress in the field of carding machine quality and efficiency concentrates mainly on improvement in the controlling, automation and monitoring of the semi-finished product parameters, achievements in textile technology, and the method of fibre processing. There

Table 1. *Quantitative assessment of cooperation in particular zones.*

Cooperation zone	Average height of the gap with deviations, μm		Change, %	
	before optimization	after optimization	gap height	width of tolerance zone
B	191^{+27}_{-41}	167^{+24}_{-17}	-12.6	-39.7
C	203^{+13}_{-53}	157^{+6}_{-7}	-22.7	-80.3
D	344^{+78}_{-94}	297^{+68}_{-47}	-13.7	-33.1

is still, however, room for improvement in the quality of constructions of machines traditionally used in textile technology. Only after all reserves for the improvement of the quality of the construction itself are used, is it justifiable to raise the accuracy of manufacturing of components and machine automation.

For many years, the development of carding machine construction has been based on engineering intuition and designer experience as well as on observations during operation. In recent years, the use of computer aided design tools and optimisation methods has enabled significant improvement in existing construction. Examples of such design methodology applied to selected components of a carding machine in terms of the improvement in the quality of their cooperation has been presented in the article. The authors' experience shows that the starting point for the design methodology proposed should be a verified parametric computational model that takes into account important characteristics of the component analysed. A useful method of analysis in such cases is the FEM. However, given the fact that improvement in the construction will be the result of solving an appropriate optimisation problem which, due to its iterative nature, requires a lot of computational cost, FEM models should take into account the structural features that significantly influence the optimization criterion. On the other hand, computational models must maintain an acceptable compliance of simulation results with the reality.

Taking into consideration the examples described in the article, it can be concluded that the major benefit coming from the solution of optimisation problems of the carding machine components chosen was the improvement of the shape (mainly uniformity) of the gap in cooperation zones B, C and D (***Figure 2***). This, in turn, will improve the quality of the web – the final product of the carding process. ***Table 1*** shows that the average height of the gap, taking into account the deflection of the components, decreased correspondingly by 13% (B), 23% (C) and 14% (D). At the same time, the uniformity of the gap improved significantly by 40% (B), 80% (C) and 33% (D).

The above-mentioned problem of numerical efficiency of discrete computational models for the optimization of textile machine construction requires further studies. In order to improve the construction, it is necessary to use more complex computational models for their description or to formulate and solve multi-criteria optimization problems. Further studies are being carried out on the improvement of the efficiency of numerical computational models.

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