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ORIGINAL PAPER

Modelling the Doctor Blade-Roller Tribosystem for Improving the Cleaning Performance During Paper Production

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Abstract Doctor blades are commonly used in paper machines to keep the surface of rollers clean. Due to higher demanding conditions, the requirements for doctor blades have steadily increased. The wear rates must remain low, while simultaneously their cleaning function has to be ensured. For this reason, the paper industry has developed a high degree of empirical knowledge concerning the cleaning of roller surfaces. However, up to now, no systematic approach has been successfully applied to optimize the cleaning performance of the doctor blade-roller tribosystem. This study presents an attempt to model the system based on the force equilibrium conditions at the blade tip between hydrodynamic and contact forces. The change of the blade geometry due to wear is also taken into account. By these means, a non-dimensional group involving the key parameters is obtained. This allows for a systematic improvement of the cleaning efficiency, by targeted changes of the process parameters.

Keywords Paper industry · Doctor blade · Reynolds equation · Hydrodynamic lubrication · Wear

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1 Introduction

Papermaking machines are divided in four different sections. In the forming section, wood fibres are mixed and filtered until a homogeneous paper pulp is obtained. In the press section, the paper pulp is pressed against rolls until its water content is significantly reduced. Afterwards, in the drying section, the paper pulp goes around steam heated cylinders, in order to reduce its final water content to about 5 %. Finally, in the calendar section, the paper is smooth and flattened to its final form.

In the press section, during wet pressing, scraping blades—referred to as *doctor*—are placed in contact with rollers to keep the roller's surface clean [1]. As a consequence of the contact between the cylindrical surface and the blade, the blade wears off and needs to be replaced periodically. The cleaning performance of the blade requires a certain contact force between the blade tip and the cylinder surface. However, a too large contact force increases energy consumption and wear, which shortens the lifetime of the blade and increases the number of stop maintenances of the machine for replacing the blade. The aim of this study is to achieve an optimum cleaning performance, while simultaneously wear of the doctor blade is minimized, thus increasing the blade lifetime and reducing energy consumption. There are different effects influencing the cleaning performance, such as design of the blade bracket, technology and choice of materials of the blade, the presence of rinsing water, type of contaminations, etc. So far, the optimum process conditions have been improved on a trial-and-error basis.

Our hypothesis is that—under the presence of rinsing water and for that study not considering other optimisation measures—optimum conditions occur under "weak" hydrodynamic conditions. Friction force and wear can be substantially reduced, whereas the cleaning efficiency can be maintained as long as the film thickness is kept smaller than the minimum diameter of particles to be removed.

2 Modelling Concept

2.1 Contact at Blade Tip: Hydrodynamic Lubrication

The basic principles of the model are classical hydrodynamic lubrication [2] and elastic-beam theory of conventional Euler–Bernoulli type. This is applied by considering the doctor blade as a pad bearing sliding over the roller surface, so that the induced normal and friction force can be calculated by employing the Reynolds equation. During idealised working conditions, the blade runs with its contact length parallel to the roller surface, where through dynamic or external perturbations like slight deviations from concentricity, surface waviness, vibrations, etc., a small aperture angle δ can be created (Fig. 1). In this case, the lubrication regime of the tribosystem changes from mixed to hydrodynamic lubrication.

The force acting at the blade tip can be decomposed in two components, namely parallel and perpendicular to the blade length. The force component acting in the perpendicular direction causes a bending force F_{Q}, which can be calculated according to the one-dimensional elastic-beam theory:

$$F_{\mathrm{Q}} = \frac{Ed^3\delta}{6l^2}, \tag{1}$$

where E is the Young's Modulus of the blade, l and d are the blade length and thickness and δ is the opening angle. Based on a geometrical relationship depending on the positioning angle β (Fig. 1) there are equilibrium conditions at the blade tip between hydrodynamic and contact forces, which are given by

$$F_{\mathrm{Q}} = F_{\mathrm{N}} \cos\beta. \tag{2}$$

In this context, the friction force can be neglected, because under hydrodynamic lubricating conditions, it is orders of magnitude smaller than the normal load.

For a pad bearing, the Reynolds equation gives the following analytical solution for the normal load F_{N}:

$$F_{\mathrm{N}} = \frac{6U\eta L^2}{h_1^2} So, \tag{3}$$

where U denotes the sliding velocity, η the viscosity, L the contact length and h_1 the minimum film thickness, i.e. the gap height at fluid discharge. So is a non-dimensional parameter named Sommerfeld number. For pad bearings, it is expressed in the form

$$So = \frac{1}{K^2}\left(\ln(K+1) - \frac{2K}{K+2}\right). \tag{4}$$

Here K is known as the so-called convergence ratio or wedge parameter, defined by

$$K = \frac{h_0 - h_1}{h_1}, \tag{5}$$

where h_0 denotes the maximum film thickness, equal to the gap height at fluid intake.

On the other hand, upon substitution of Eqs. (1) and (3) into Eq. (2) a linear relationship between the Sommerfeld number, So, and the convergence ratio is established:

$$So = \frac{h_1^3}{36U\eta L^3}\frac{Ed^3}{l^2\cos\beta}K. \tag{6}$$

Since Eqs. (4) and (6) have to be valid simultaneously, the solution is given by the intersecting point between both graphic lines, whereas the slope of Eq. (6) depends on several process parameters (Fig. 2).

An optimum cleaning performance is achieved for a small gap h_1 and small converging ratios K, i.e. $h_0 \sim h_1$, so that small particle diameters can be successfully removed.

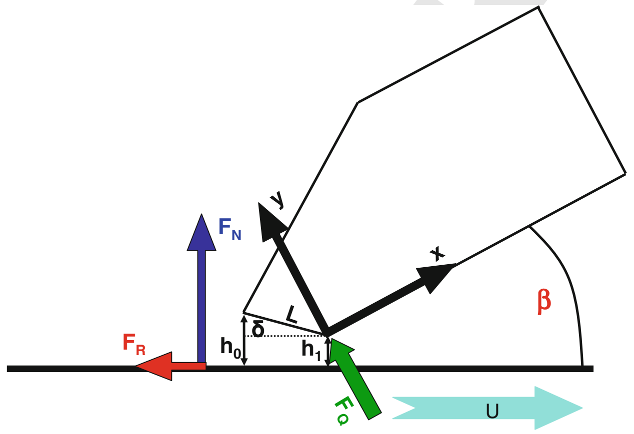

Fig. 1 The doctor blade is modelled as a hydrodynamic bearing with contact length L, inlet and outlet flow h_0 and h_1 and opening angle δ. The sketch shows the geometrical relationship between hydrodynamic forces F_{N}, F_{R} and the bending force F_Q

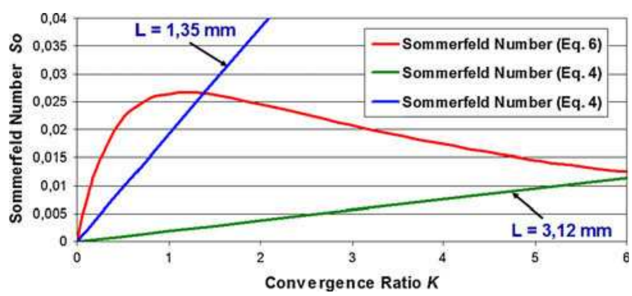

Fig. 2 Graphical solution of Eqs. (4) and (6) for two different contact lengths L; the process parameters for the graphical representation are selected according to Table 1

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However, the tribosystem should be simultaneously in a (weak) hydrodynamic lubrication regime, for minimization of the blade wear and energy consumption. Both boundary conditions are simultaneously fulfilled when the slope *So*/*K* Eq. (6) is as steep as possible, but still cutting the Sommerfeld curve as a function of the converging ratio given by Eq. (4). In this case, the system of equations is still solvable, what it means that the tribosystem can be still under hydrodynamic conditions. The best solution is therefore the tangent of the Sommerfeld number *So*, when the converging ratio *K* goes to zero. The calculation of the derivative at the limit $K \rightarrow 0$ gives as result the value 1/12, so that a condition for a non-dimensional group involving the key parameters is obtained:

$$\frac{h_1^3}{36U\eta L^3}\frac{Ed^3}{l^2\cos\beta} = \frac{1}{12}. \tag{7}$$

The first fraction contains parameters that depend on the hydrodynamic, while the second fraction contains geometrical and process parameters. The parameters from Eq. (7) cannot be freely selected, since the contact length L continuously increases with time as a consequence of wear. In addition, the change of the contact length causes a shortening of the blade free length l and, as a consequence, a change in the positioning angle β. The geometrical relationship between L, l and β as the blade wears off is discussed thorough in the following section.

2.2 Relationship Between the Geometrical Key Quantities at the Blade Tip: A Simple Wear Model

In the paper production, the doctor blade is placed within a holder, which has a constant position. Since the radius of the roller R and the radial distance from the centre of the mill to the rotation axis of the blade-holder system R_{H} are fixed, the positioning angle β increases as the blade wears off and the total length from the blade tip until the rotational axis l_{tot} decreases (Fig. 3). Note that the dimensions of the roller radius are exaggeratedly small for illustration purposes.

Strictly speaking, wear cannot occur as long as the blade is under hydrodynamic lubricating conditions. However, those are partly idealised conditions and wear is observed under almost all operational parameters. Indeed, this is the reason why the doctor blade requires to be periodically replaced. In addition, dynamic effects, not taken into account in the current work, presumably contribute to wear even under the condition of pure hydrodynamic lubrication as the stationary mode, of primary interest here, is rendered invalid within short time intervals [3].

According to Fig. 3, the positioning angle β at a given step n can be calculated as:

$$\beta_n = \arccos\left(\frac{R^2 + l_{\mathrm{tot},n}^2 - R_{\mathrm{H}}^2}{2Rl_{\mathrm{tot},n}}\right) - \frac{\pi}{2}. \tag{8}$$

The value of the R_{H} is constant and can be determined at $n = 0$, since the initial positioning angle β_0, total length $l_{\mathrm{tot},0}$ and radius of the roller R are known.

The changes in blade free length l and in contact length L can be calculated by considering the geometry of the blade tip (Fig. 4).

where α is the tip angle, d the blade thickness, L_n the current contact length, H_n the future contact length at the step $n + 1$ and $L_{\max}$, the maximum possible contact length for a given tip geometry. In general, once H_n is known, the contact length is simply given by

$$L_n = H_{n-1}. \tag{9}$$

The shortening of the blade in one step is denoted by Δl_n. By summing all cumulated shortenings, the blade free length at the step n l_n can be calculated as

$$l_n = l_0 - \sum_{i=1}^{n} \Delta l_{i-1}, \tag{10}$$

where l_0 represents the initial free length. The same expression can be used to calculate the actual total length between the blade tip and the axis of the sample holder by replacing l by l_{tot}.

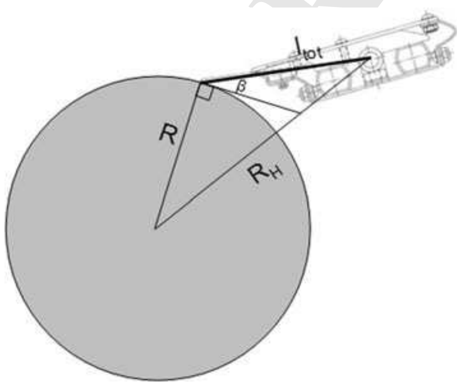

Fig. 3 Schematic representation of the roller-blade tribosystem, highlighting the geometrical relationship between the variables

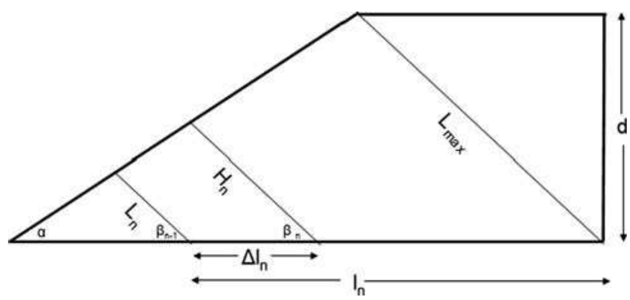

Fig. 4 Schematic representation of the blade tip showing the variables used for the wear model

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Once the current positioning angle β_n and blade length l_n are known, the future contact length H_n and the blade shortening Δl_n can be calculated by assuming a certain removed wear volume ΔV_n. The removed wear volume can be simply assumed to be a constant value, so that a relationship between the geometrical variables as the blade changes its geometry due to wear is known. Alternatively, the removed wear volume can be derived from relevant process parameters by employing a wear law, such as the classical relationship originally put forward by Archard [4]:

$$\Delta V_n = k\frac{F_N U \Delta t_n}{H} = k_D F_N U \Delta t_n, \tag{11}$$

where k_D is a dimension wear coefficient to be fitted to experimental results, F_N is the normal load, U is the sliding speed, H the material hardness, and Δt_n is the time increment. Since the geometry of the blade is stepwise constant and changes discontinuously (see Fig. 5), we deal with (small but) finite increments $\Delta V_n/\Delta t_n$ rather than infinitesimal ones, in accordance with the proposed numerical evaluation of Eq. (11).

For a given incremental wear volume ΔV_n, the value of H_n and, in turn, L_n by Eq. (9) can be calculated by distinguishing two different cases:

- If $H_n < L_{max}$, the contact length, L_n, of the blade has not reached yet its maximum value, L_{max}, and H_n is given by

$$H_n = \sqrt{\frac{2\left(\sum_{i=1}^{n}\Delta V_i\right)\sin\alpha}{W\sin\beta_n\sin(\pi-\alpha-\beta_n)}}, \tag{12}$$

where W is the blade width in the out of plane direction.

- If $H_n \geq L_{max,n}$, it appears that the tip of the blade is completely worn off and H_n simply assumes the value of $L_{max,n}$, which denotes the variation of L_{max} throughout the wear process due to its dependence on the positioning angle:

$$H_n = L_{max,n} = \frac{d}{\sin\beta_n}. \tag{13}$$

The calculation of the removed wear length of the blade Δl_n for a given step n needs the distinction of three different cases.

- First, if $H_n < L_{max,n}$ it means that we are still at the tip of the blade and Δl_n is given by

$$\Delta l_n = \sqrt{\frac{2\left(\sum_{i=1}^{n}\Delta V_i\right)(\cot\alpha+\cot\beta_n)}{W}} - \sum_{i=1}^{n}\Delta l_{i-1}. \tag{14}$$

- If this condition is not fulfilled, we need to check if we have reached the maximum thickness of the blade $L_n = L_{max,n-1}$ and in this case Δl_n takes on the following value

$$\Delta l_n = \frac{\Delta V_n}{W H_n \sin\beta_n} + \frac{H_n\cos\beta_n - L_n\cos\beta_{n-1}}{2}. \tag{15}$$

- Finally, if none of both conditions are fulfilled, then we are just at the transition region between the blade tip and the section of the blade with constant thickness d (Fig. 5). In this case, the change in blade length can be calculated as:

$$\Delta l_n = \sqrt{\left(\sum_{i=1}^{n}V_i + \frac{(H_n - L_{max,n})^2 W\sin\beta_n\sin(\pi-\alpha-\beta_n)}{2\sin\alpha}\right)\frac{2(\cot\alpha+\cot\beta_n)}{W}} - \sum_{i=1}^{n}\Delta l_{i-1} \tag{16}$$

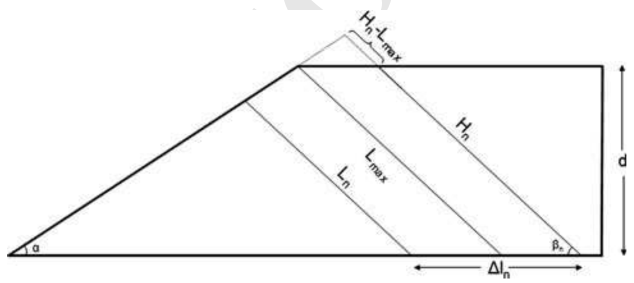

Fig. 5 Schematic representation of the blade tip, showing the particular case $H_n \geq L_{max,n}$ and $L_n < L_{max,n-1}$

Table 1 Selected parameters for the example diagram

Reference case	
Minimum film thickness h_1	5 µm
Initial blade free length l_0	40 mm
Initial positioning angle β_0	32°
Young's modulus E	50 GPa
Roller velocity U	20 m/s
Viscosity of the aqueous medium η	0.001 Pa s
Blade thickness d	1.9 mm

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3 Results

In Eq. (7), the minimum film thickness h_1 is selected as the diameter of the smallest particle contamination to be removed. De facto, its value is limited from below by the sum of the average roughness heights of the blade and the roller, which in practice means an unavoidable leakage. The other parameters are selected according to typical realistic operating conditions (Table 1).

Under these conditions, an unworn blade operates in the mixed lubrication regime. Due to the fact that the contact length L gets longer during operation due to wear, the slope So/K becomes smaller, what causes a transition into the hydrodynamic regime. The changes in positioning angle and free length are also taken into account in Eq. (7), as described in Sect. 2.2, but their effect on the So/K value is not so pronounced.

The most favourable friction conditions occur in the transition between mixed and hydrodynamic lubrication, i.e. for $So/K = 1/12$. In mixed lubrication, the cleaning efficiency is not impaired but a higher wear and friction (i.e. energy consumption) have to be assumed. On the other hand, in the hydrodynamic regime the cleaning performance is negatively influenced by a higher convergence ratio. The transition between both lubrication regimes can be modified by a proper selection of the several geometrical, material and process parameters that appear in Eq. (7). As illustrative result, it is shown that a thicker blade remains longer in the mixed lubrication regime, while setting the remaining parameters to the reference case values (Fig. 6).

Indeed, the transition between mixed and hydrodynamic lubrication can be delayed by selecting a shorter free length and a higher Young's modulus. This is shown in Fig. 7, where the value of the initial free length and Young's modulus are set to $l_0 = 35$ mm and $E = 100$ GPa, respectively.

As a consequence of wear, it is not possible to set all process parameters of Eq. (7) to a value $So/K = 1/12$, mainly because the contact length L is steadily increasing. However, for a given contact length, it is possible to see which value every parameter should have, in order to reach a So/K value of 1/12, while keeping the remaining parameters to the reference case (Fig. 8). For this analysis, the values of the positioning angle β and the free length l all kept constant for all contact lengths, since their value does not change significantly.

In Fig. 8, each column represents the required parameter value for a given contact length to keep a $So/K = 1/12$. A value of 100 % means that the reference case satisfies this condition. For large values of the contact length, a doctor blade would reach the 1/12 condition for longer free lengths, larger thickness, higher rigidities, higher positioning angles, higher velocities and viscosities, and thinner film thickness. The changes of these parameters have basically two main aims: reduce the hydrodynamic normal force and bending, in order to push the system towards the transition between mixed and hydrodynamic lubrication.

During operation, it is observed that sharp blades have a good cleaning performance. As the blade wears off, its cleaning performance starts degrading and eventually, the blade needs to be replaced. If the working conditions are changed according to Fig. 8, it would be possible to extend the lifetime of the blade, by improving its cleaning performance for larger contact lengths.

A set of recommendations based on these results is presented in Table 2. Tmhe recommended actions usually proote a side effect that has to be taken into account before implementation under real operating conditions. For instance, a reduction of the roller velocity will decrease the film thickness and increase the cleaning performance but the output production will be affected. Other parameters are difficult to modify for compatibility issues with the current papermaking production techniques, such as changes in lubricant viscosity, which is mainly water, and it cannot be easily replaced without substantially modifying the actual state of the art. Furthermore, changes of the geometrical and material parameters of the doctor blade, such as free length,

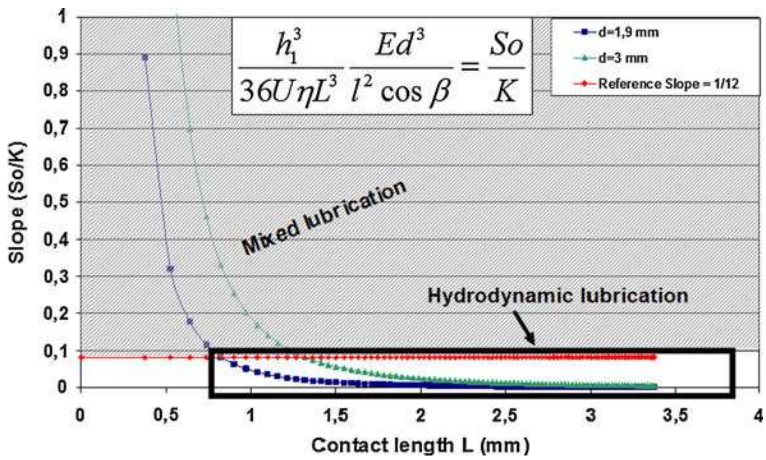

Fig. 6 Slope So/K as function of the contact length L for two different blade thickness d (reference case)

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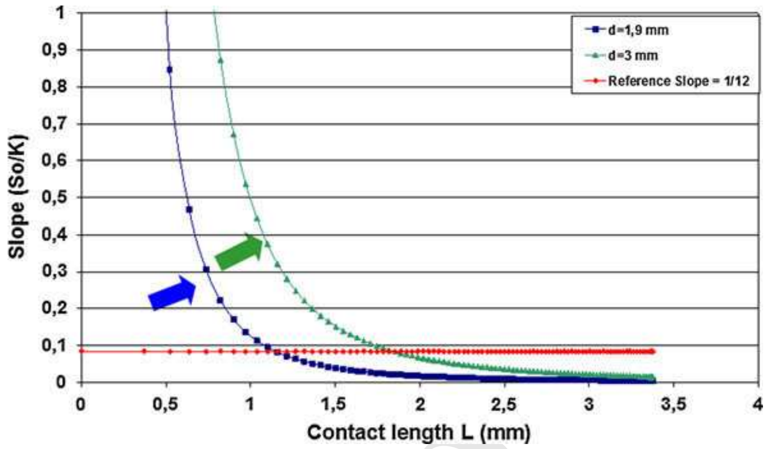

Fig. 7 Slope So/K as function of the contact length L for two different blade thickness d ($l_0 = 35$ mm and $E = 100$ GPa)

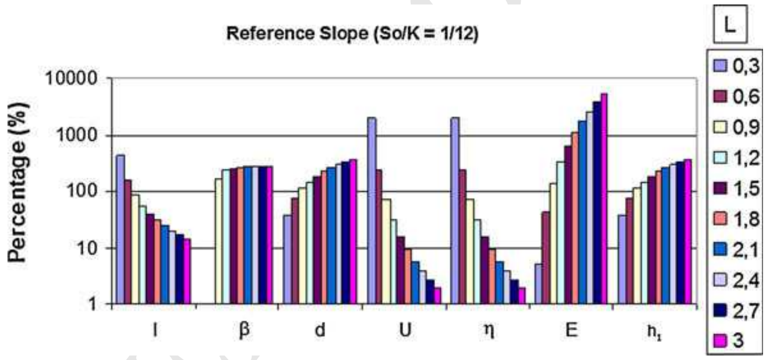

Fig. 8 Parameters required to keep a $So/K = 1/12$ for different contact lengths

Table 2 Summary of actions required for extending the cleaning performance of severely worn doctor blades

Parameter	Action
Blade free length l	↓
Blade thickness d	↑
Positioning angle β	↑
Young's modulus E	↑
Roller velocity U	↓
Viscosity of the aqueous medium η	↓
Minimum film thickness h_1	↑

thickness and Young's Modulus have an influence on its resonance frequencies and eigenmodes, which may hamper the cleaning performance due to vibration-related phenomena. Here we note that both the forced and autonomous oscillatory motions of the blade due to (inevitable) wavy imperfections of the roller surface and the coupling between viscous damping and squeezing of the lubricant film, respectively, are topics of the current research activities.

4 Conclusions and Further Outlook

During the paper production, the tip of the doctor blade is in contact with the roller surface to remove impurities and keep the roller's surface clean. In case of worn blades, the contact length runs parallel to roller surface and hydrodynamic conditions can occur, mainly due to external perturbations, such as vibrations or sticky particles. Under such conditions, the system can be modelled by considering the doctor blade as a pad bearing, which is allowed to bend according to beam theory. The limiting value for occurrence of hydrodynamic effects is determined by the value $So/K = 1/12$. The proposed model allows for a systematic improvement of the cleaning efficiency, by targeted changes of the process parameters. For instance, a blade with a higher thickness remains longer in mixed lubrication, which means that hydrodynamic effects do not occur until a more pronounce wear condition. This is unfavourable for energy consumption and wear, but a better cleaning efficiency is expected.

Future research activities aim at, amongst others, a qualitatively more comprehensive and quantitative parametricoptimisation, either with regard to the cleaning performance or the wear, i.e. lifetime, of the blade and theirbalance. To this end, a more realistic mechanical model of the blade is desirable where it no longer is treatedas a homogeneous and isotropic elastic beam, characterised by its Young's Modulus as the only relevant mechanicalparameter, but the layered construction is taken into account. Also, surface roughness and its targeted

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modificationshould be considered properly in view of the aforementioned aspects of induced vibrations and optimisation, whereone is guided by the more-or-less periodic waviness of the roller surface.

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