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MACHINE VISION DETECTION OF THE CIRCULAR SAW VIBRATIONS

Dynamical properties of rotating circular saw blades are crucial for both production quality and personnel safety. This paper presents a novel method for monitoring circular saw vibrations and deviations. A machine vision system uses a camera and a laser line projected on the saw's surface to estimate vibration range. Changes of the dynamic behaviour of the saw were measured as a function of the rotational speed. The critical rotational speed of the circular saw blade as well as the optimal rotational speed of the saw were detected.

1. INTRODUCTION

Circular saws are one of the most widely used tools in the wood industry. The proper preparation of saw blades, machine maintenance and selection of cutting conditions among other factors are the critical to assure faultless and safe operation. The physics of the rotating circular saw blade has been studied worldwide and several related scientific publications can be found in literature.

The effect of a solid saw blade's geometry (such as its diameter, clamping ratio and blade thickness) on the saw dynamic behaviour was described by Schajer [1], Stakhiev [2], Droba et al. [3], Kaczmarek et al. [4], and Li et al. [5]. Optimization of saw blade tensioning by rolling [6-10], the potential for the use of internal pressure in the saw blade as an alternative tensioning method [11] and application of a laser beam for straightening and tensioning circular saws [12] were also researched. Furthermore, Münz [13] revealed that there is a correlation between the critical speeds and residual stresses in the saw blade caused by technological process (grinding). Limitations of the circular saw rotational speed such as material strength, welding seam, vibration properties and the construction of the blade structure were analysed by Li et al. [14]. The effect of slots on the lateral

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vibration of the circular saw blade was also studied [15-18]. Chabrier and Martin [19] as well as Ingielewicz [20] published a review of methods for monitoring circular saw blade preparation.

Recent works by Mohammadpanah and Hutton [21, 22] reported that instability of guided splined circular saw blades rotated with speeds higher than their critical rotational speeds, was caused by flutter (a phenomenon of self-excited vibration). A novel approach to identification of cutting force dynamics in metal cutting processes that highlighted cutting force variations were correlated with the bandsaw geometry [23]. Albrecht and Stehle [24] investigated the twisting behaviour of saw blades in the kerf zone with a contactless measuring system.

Understanding circular saw vibrations is important because saw blade vibrations affect product quality in terms of both surface smoothness and dimensional accuracy. The amplitude of saw blade vibrations has an effect on production economics as well. Greater amplitudes increase kerf width and, consequently, production yields. Personnel safety is another very important issue related to circular sawblade dynamics.

The dynamical behaviour of a rotating saw is a very complex subject to be expressed theoretically or modelled numerically. In addition, novel circular saw blade geometries with compensation slots and compound construction makes theoretical estimation even more difficult. It has been stated by Orlowski et al. [25] that instead of the numerical evaluation of the dynamical behaviour of the circular saw it is more convenient to develop experimental tools for the determination of the saw/sawing machine characteristics, e.g., optimal rotational speed or critical rotational speed. Optimal rotational speeds of circular saw blades may be defined empirically on a dedicated laboratory stand according to methodology proposed by Orlowski and Hyvärinen [26]. In their approach, the behaviour of circular saw blade is examined and the ranges of the minimal values of the blade's lateral displacements (corresponding to the highest value of the dynamic stiffness) are considered as the optimum. It ought to be emphasised that the majority of the scientific works published on this topic are usually more oriented to the formal aspects than to real-world implications. For that reason, state-of-the-art knowledge is not readily accepted by the industry, being considered difficult to implement and comprehend. A simple tool for visualizing the saw vibration could provide highly useful information and therefore improve the knowledge regarding the cutting process itself. The aim of this work was to develop a simple, camera-based system to monitor saw vibrations and to estimate the dynamical properties of the rotating tool coupled with the sawing machine. A system appreciated by the industry should be simple to build while the results provided should be easily interpretable. Such a system could be suitable for educational purposes as well, allowing operators to "*see vibrations*" and to learn adapting the machine's set-up depending upon the varying conditions.

2. CIRCULAR SAW BLADE'S VIBRATIONS / DEVIATIONS

The rotating circular saw can vibrate in diverse modes and with different amplitudes according to the rotational velocity. Stakhiev [17] distinguished a number of characteristic rotational speeds and their general classification is presented in Fig. 1. By increasing the rotational speed/velocity, the vibrations of the saw blade are reduced from high to low amplitudes (according to the out-of-flatness level of the saw blade as well as to the run-out of the spindle) until reaching at first an universal rotational speed n_u. The optimal rotational speed n_o corresponds to the speed when sawing is safe and the saw vibrations are low, while the permissible rotational speed n_p determines the highest rotational speed that still ensures safe processing. The amplitude of saw vibrations is reduced to the point when the backward wave approaches zero (or very low frequency) [15, 17]. At this rotational speed, called the critical rotational speed $n_{cr}^{\min}$ [1, 2, 15], the saw has a tendency to dramatically increase its vibration amplitude. Processing with the critical speed is very dangerous and may result in poor surface quality production, not to mention a highly increased kerf width. An additional increment of the rotational speed leads to the self-excited vibrations of the saw blade at the lowest self-excited rotational speed $n_{\mathrm{out}}^{\min}$ and finally to the destruction of the saw's blade at the destructive rotational speed $n_{\mathrm{des}}^{\min}$. It is important to know the characteristic rotational speeds and to monitor the circular saw's vibration continuously in order to assure high operation efficiency. The real-time information regarding the saw vibration can be an input value for the adaptive control system of the circular sawing machine as well.

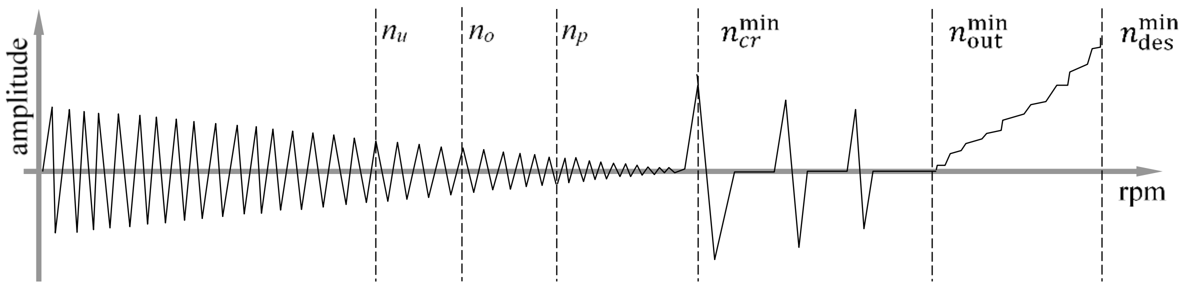


Fig. 1. Characteristic rotational speeds of the circular saw blade according to Stakhiev [17]: n_u – universal; n_o – optimal; n_p – permissible; $n_{cr}^{\min}$ – the lowest critical; $n_{\mathrm{out}}^{\min}$ – the lowest self-excited; $n_{\mathrm{des}}^{\min}$ – destructive

3. MEASURING CIRCULAR SAW DEVIATIONS WITH A LASER LINE

A number of techniques are suitable for measuring circular saw vibrations. The most frequently and widely used is an eddy-current displacement sensor installed close to the saw blade surface [3, 4, 13]. Alternatively, other sensors (e.g., laser displacement sensors [26]) could provide similar data. The results are in general satisfactory. Nevertheless, some limitations still exist, such as positioning of the sensor close to the cutting zone, vibration and dirt sensitivity, restricted area of the measurement usually limited to the single point, etc. Moreover, from the operator's point of view, these sensors are a kind of a "black box" providing limited information, in most cases requiring sophisticated methods for interpretation of readings (such as power spectra, impulse response, etc.). An alternative method for an intuitive visualization of saw vibrations is presented in this paper. The idea bases on the well-known triangulation principle, where the structured light (laser line for example) illuminates the measured plane with a high incidence angle. The shape of the line section depends on the three-dimensional geometrical configuration, including position of the light source and illuminated plane. The laser line shape changes when the distance to the plane alters. The laser line rotates however in a case when the measured plane twists. The laser line image is a simple thin line when the shutter time is short. In contrast, the shape and thickness of the line image changes when extend the shutter time. It is especially advantageous for monitoring the position of the vibrating elements, such as band or circular saws. Figure 2 presents an example of the laser line shape when projected on the vibrating plane. The camera captures a thin line image if the amplitude of vibrations is minimal, or the object is motionless (Fig. 2a). The thickness of the laser line increases proportionally with increasing the amplitude of vibration (Fig. 2b) and imitates a “butterfly” shape when reflecting on twisting planes (Fig. 2c).

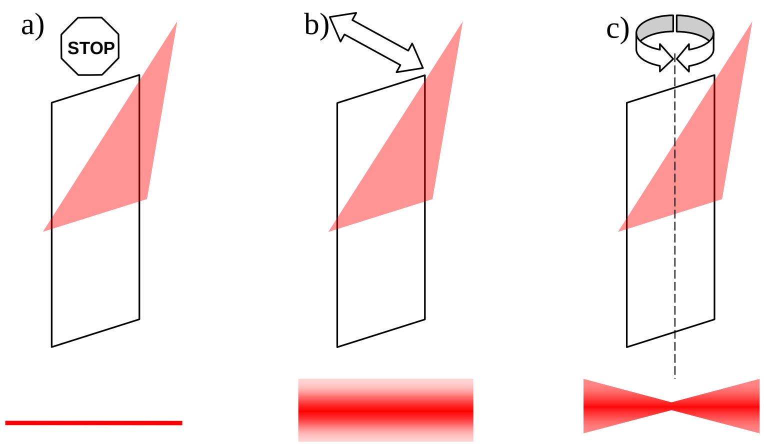


Fig. 2. Shapes of the laser line illuminated on the vibrating surface: a) static mode, b) oscillating linearly c) oscillating rotationally

An ordinary video camera could be used for the detection of the laser line shape. In that case the area covering the laser illuminated zone on the measured surface could be photographed and processed further. Though, different forms of the laser line image may be acquired by the camera when varying the shutter time.

4. MATERIALS AND METHODS

A prototype of the machine vision detection system, usable to realize the concept presented above, was implemented for the purpose of visualizing circular saw vibrations. The experimental set-up installed on a sliding table circular sawing machine is presented in Fig. 3a. The overview of the hardware assembly is shown in Fig. 3b. All components of the system are relatively low-cost and processing the results is straightforward by means of open software image analysing tools. Some of most important performance-affecting issues are listed below.

The captured image can vary in size depending on the optics, the video camera and the computer's performance. The images captured in this experiment had 936×3000 pixels (horizontally×vertically, respectively). The highest scanning speed attainable with the hardware components used was 10 frames per second. However, after considering the optimal shutter time of 1 second, the effective sampling frequency was 1 Hz. An important limitation of the experimental set-up was the stiffness of the measurement system. The mechanical support was not entirely rigid, and therefore it contributed a source of possible measurement errors.

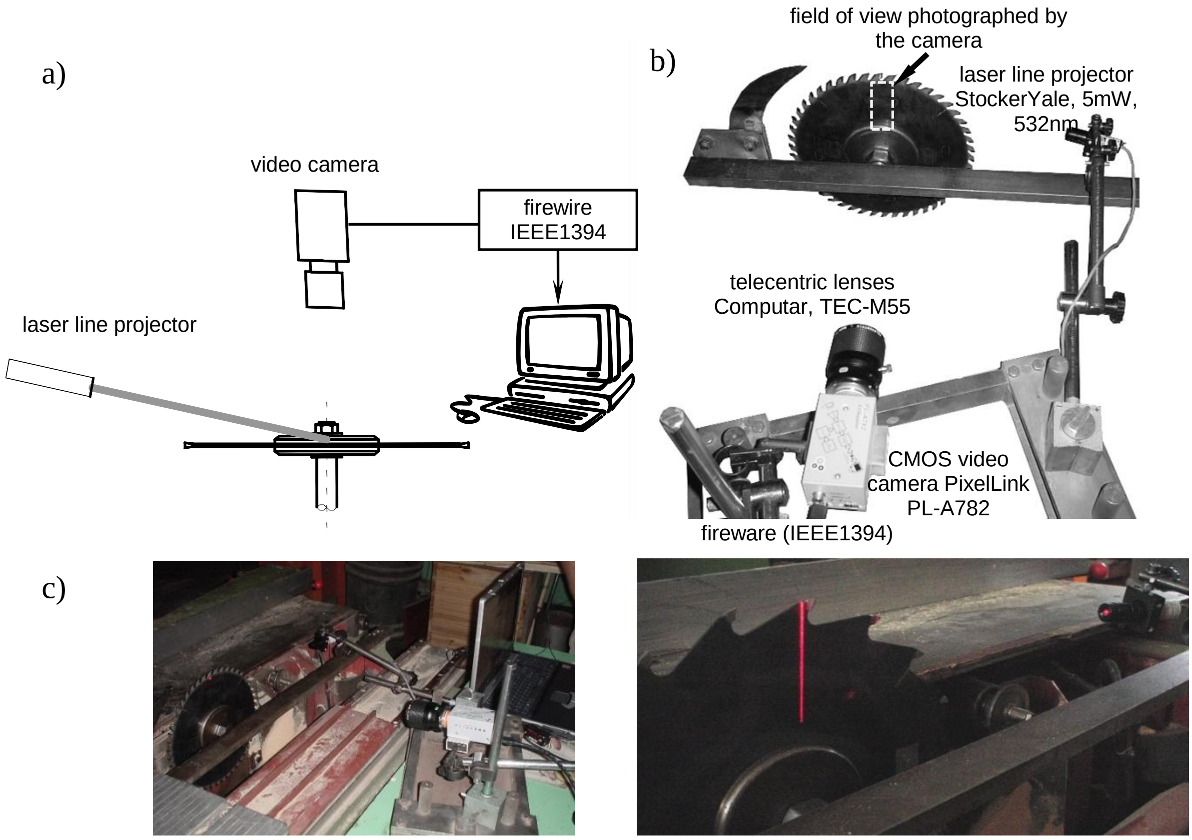


Fig. 3. Experimental set-up: a) conception, b) hardware configuration, c) practical implementation

The raw data provided by the vision system is the colour image of the laser line focused on the surface of the rotating saw blade. An example of the output image is shown in Fig. 4. A variety of important information can be extracted from such image, including centre of the laser line (corresponding to the deviation of the saw blade) and thickness of the laser line (corresponding to the vibration amplitude of the saw blade) along the sawblade radius. Custom software was developed in LabView (National Instruments, USA) in order to obtain results from each investigated image. The stream data from the camera was stored on the hard disk as a series of BMP files ready for the further processing. Supplementary software was used for pre-processing images. The procedure included extraction of the proper source frame/image, extraction of the Green channel from the RGB colour image, and manual thresholding. The post processing included filtration of the noise, detection of edges along the laser line and finally computation the centre of the line and the line width. The results were stored as text files for supplementary analyses.

A commercially available circular saw was tested in this experiment. The saw has outside diameter D = 350 mm, hole diameter d = 30 mm, saw blade thickness s = 2.5 mm, teeth count z = 18, collar diameter A = 125 mm and clamping ratio A/D = 0.35. The saw blade was carefully measured in additional experiment determining experimentally values of the critical speeds [25]. It was found that the 1st critical speed was equal $n_{cr}^{\min}(f_{n=2}(0))$ = 5133 rpm and 2nd critical speed was $n_{cr}^{\min}(f_{n=3}(0))$ = 6015 rpm. The circular saw blade image and its natural frequencies identified on the power spectrum of the impact test are shown in Fig. 5.

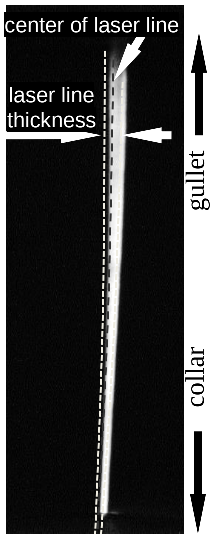


Fig. 4. Processing of the laser line image

a) b)

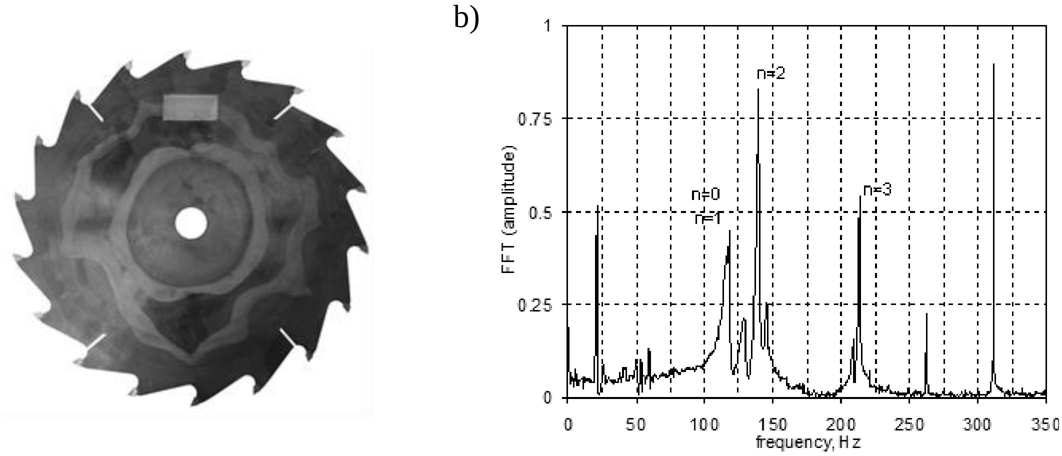


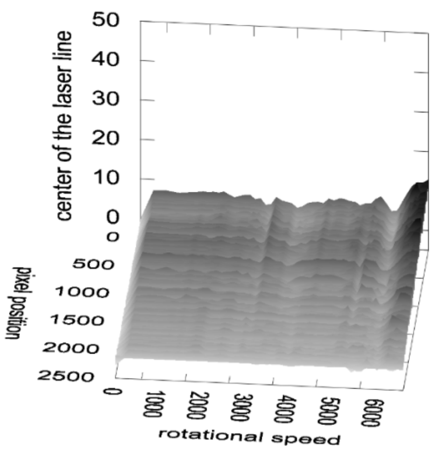
Fig. 5. Examined circular saw blade (a) and power spectrum of its flexural displacements with characteristic mode frequencies n (b) [25]

The vibrations of the rotating saw blade were measured during idling on the sliding table circular sawing machine DMMA-40 (REMA SA, PL). The spindle rotational speed was controlled with a conventional frequency inverter, by supplying the current frequency of 0 Hz to 20 Hz with a step of 5 Hz, and between 22 Hz and 110 Hz with an increment of 2 Hz. These settings corresponded to 0 rpm to 1200 rpm with a step of 300 rpm and 1320 rpm to 6600 rpm with a step of 120 rpm respectively. Consequently, 50 laser line images corresponding to varying levels of rotational speeds were recorded during the experiment.

5. RESULTS AND DISCUSSION

As it described earlier, changes in the laser line thickness illuminating the rotating saw blade corresponds to changes in the saw blade deviation and vibration level. The saw blade rotational speed changed following the described parameters, and corresponding images of the laser line were captured by the camera. Contours of the laser line were extracted for each level of the rotational speed after image processing. The thickness of the laser line was relatively thin for the non-rotated saw (0 rpm) and varied noticeably for other rotational speeds. In general, the increase of the laser line thickness near the collar was negligible (this variations where mostly related to the vibration of the spindle/collar). However, the thickness of the laser line in the outer area of the saw differed noticeably as a function of the spindle rotational speed. Variations of the centre of the laser line appeared to be less evident, even that further analyses provided a clear confirmation of the saw blade deviation changes. A summary of the obtained results is presented in Fig. 6. It should be emphasised that spindle vibrations and radial run-out were excluded from analysis. Moreover, “0” for the pixel position axis (Figs. 6a, 6b) corresponded to the line positon just below the gullet, while the maximum value of the axis “2500” corresponds to the position close to the clamping collar.

a)



b)

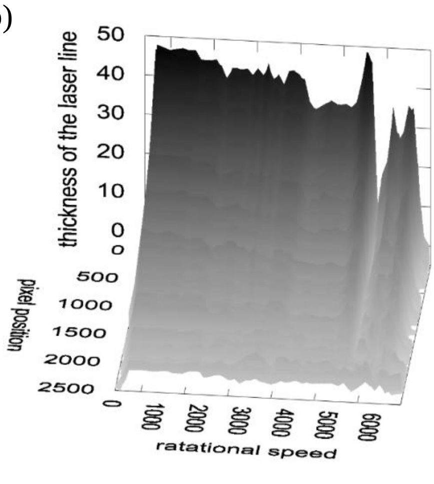


Fig. 6. Variations of the centre laser line in pixels (a) and laser line thickness in pixels (b) in a function of the spindle rotational speed

The trend of the laser line thickness changes (Fig. 6b) was apparently independent from the changes of the laser line centre (Fig. 6a). The vibration level gradually reduced with increase of the rpm up to the level of 5000 rpm. An evident increase in the laser line thickness was observed at 5280 rpm. This value is value very close to the lowest critical speed $n_{cr}^{\min}(f_{n=2}(0))$ = 5133 rpm determined for this circular saw in a different (static) experiment [25]. After a slight increase of the rotational speed (5400 rpm) a vast reduction of the saw blade deviation was noticed. This observed value corresponded to the vibration level of the stationary saw. The only evidence of differences was a significant deviation of the saw blade profile observed as a change of the laser line's centre curve (Fig. 6a). A further increase of the saw vibration level was observed for rotational speed of 6000 rpm. This phenomenon corresponds to the second critical rotational speed $n_{cr}^{\min}(f_{n=3}(0))$ = 6015 rpm. After exceeding the second critical speed, the saw blade again reached a state with nearly zero vibration, but very clear and noticeable bent deflection were present.

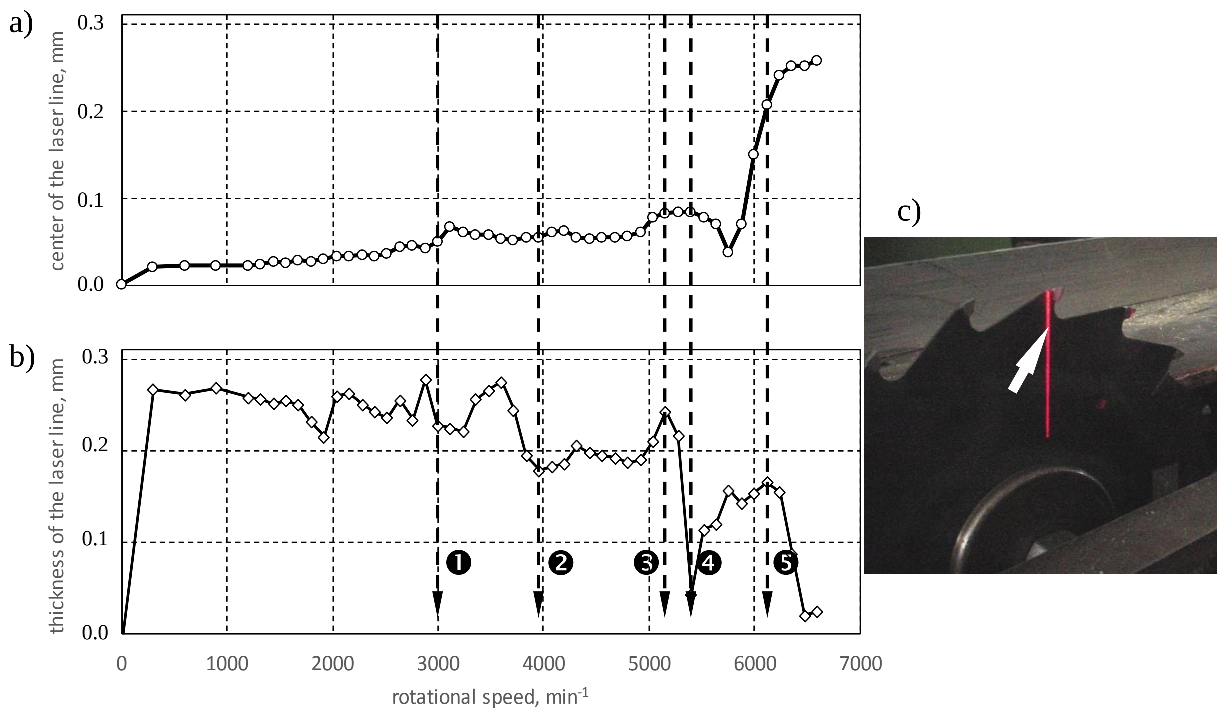


Fig. 7. Change of the saw deviation (a) and axial run-out (b) of the saw blade in the zone close to the gullet (c) versus the spindle rotational speeds; ❶ - typical, ❷ - first optimal, ❸ - first critical, ❹ - second optimal, ❺ - second critical

It was not possible to continue the test with rotational speeds higher than 6600 rpm due to the limitation of the frequency converter. However, the usefulness of this method for detection of the critical speeds for rotating circular saws was clearly demonstrated. Furthermore, deeper analyses of the experimental results revealed a possibility for enhancement of that particular cutting system (tool coupled by collars with the spindle). It was observed that after a slight increase to the commonly used rotational speed (from 3000 to 3960 rpm) the saw vibrations were minimized, still assuring safe operation below the critical rotational speed. It is clearly visible in Fig. 7, where axial run-out of the saw blade, measured at pixel position "0", corresponding to the zone close to the gullet, is related to the rotational speed of the saw. As a consequence, the saw kerf could be reduced by 0.10 mm, improving the production yield. In that case, less material is converted to wooden chips and the target sawing sizes (dimensions) may be reduced. Moreover, the feed speed can increase when the rotation speed of the saw rises, assuring constant feed per tooth value. Any increase in production efficiency is appreciated by the wood industry as global competition and the demand for increased resource efficiency increases.

Other characteristic rotational speeds of the circular saw blade can be clearly identified on the axial run-out chart, including the first and second critical rotational speeds (❸ and ❺ as presented in Fig. 7).

6. CONCLUSIONS

The presented experimental set-up may be efficiently applied for straightforward determination of the circular saw blade's critical rotational speeds in industrial and research settings. The system can be used for identification of optimal processing conditions as well. The machine operator could set the machining process parameters iteratively based on his interpretation of the vibration amplitudes. The same information (circular saw vibration and deflection levels) determined with a machine vision detection system could be used to adaptively and automatically control the optimal machine configuration and to monitor process according to the desired levels of the kerf width.

Producers and users of both circular saw blades and sawing machines could benefit from implementing a simple camera-based system not only from reducing the kerf ("timber rather than sawdust") but also by assuring safe operation and optimal use of available resources. This methodology can be especially useful for identification of the optimal (critical) rotational speeds of rotating circular saws and for determination of the circular sawing machine adjustment with a special focus on the spindle.

Several of the sensor solutions available on the market may provide similar results to these presented here. However, most of those sensors are limited to the single point measurement and requires sophisticated interpretation of the outputs. The great advantage of the proposed system is its simplicity, low cost and straightforward implementation that does not require any modification of the existing machines. In addition, the system as proposed can be simply improved by adding additional laser line projector(s) enabling measurement of several profiles of the vibrating saw blade simultaneously on a single image captured by the camera.

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