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ILLUMINATION FOR CHATTER MARK DETECTION USING MACHINE VISION

Authors of this research present a new method for image acquisition using special illumination for milled surfaces. The presented method uses special light and camera setup to reveal chatter marks on processed surfaces. After the acquisition the images are digitally processed using a method based on Continuous Wavelet Transform. A milling experiment has been preformed for validation of the methods. The biggest advantage of this method is that it doesn't have to be manually set like other image processing methods used in chatter detection.

1. INTRODUCTION

Modern inspection systems depend on process automation, especially in high volume production environments. Still there are some inspection tasks difficult to automate. Those tasks are a bottleneck for the whole production process. One of such needed but difficult to automate tasks is chatter detection in machining. Chatter can be described as a self-exited valiant dynamic motion between the cutting tool and the workpiece. The unwanted vibration is a problem that increases tool wear, worsens machining accuracy. One of the most important issues is that chatter marks worsen the surface quality. Preventing and online monitoring is not a complete solution. Tool wear, bad workpiece fixing and other factors can cause chatter too. If the unwanted vibration was present in the process, how to determine if the machined parts are still acceptable? Manufacturers and researchers have made effort to incorporate different kinds of inspection methods for chatter detection.

Khalifa et al. [1] presented research where a gray-level co-occurrence matrix (GLCM) method was introduced. The GLCM was calculated form surface images. However in the research, only two samples with extremely different surfaces were analysed. The GLCM method is prone to light conditions. Another method was introduced by Szydłowski et al. [2] using an edge detection approach. This method was also sensitive to non-uniform

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illumination of the acquired surface image. Lee et al. [3] proposed a method using polynomial networks and a G_a parameter calculated form images to asses roughness in turning operations. This method also implies some image preparation and test runs to initialize the method. Another method proposed by Szydłowski et al. [4] normalizes the images to avoid changing light conditions, and uses local gradient based processing to extract ridges and valley directions, later creating an error map of the surface. The method needs information about the milling process to set up parameters for the gradient estimation procedure correctly. Bamberger et al. [5] used radial edge detection and GLCM for valve seat inspection. Image separation and valve seat unwrapping needs to be done for every new type of inspected valve seat. The shown methods use different attempts at chatter mark detection and surface quality inspection. This method is proven to be efficient only for valve seats machining, it is not usable for typical milling operations.

The novel method presented in this article has a capability of fully autonomous performance without human intervention. The author's approach is focused on milled surfaces chatter mark detection. The method has three key elements, one is the special illumination setup presented in the paper. Second is the image processing using two-dimensional continuous wavelet transform (2D CWT). The last element is an innovative laboratory vision based inspection setup designed and constructed by the authors.

2. THE SPECKLE PATTERN METHOD

The proposed method is based on light placement that exaggerates the machined surface topography. The pattern of ridges and valleys created by the cutting inserts of a mill is very consistent in vibration free conditions. If the chatter is present, the pattern is distorted. Due to the unwanted vibration the cutting edges slightly divert form their normal motion given by the systems kinematics, and therefore a new pattern is created. The local orientation of valleys and ridges on the milled surface is changed and is more random as shown in an article by Szydlowski and Powalka [4]. This new pattern can be observed by human eyes and classified depending on the severity of the chatter. Trained inspectors look at the workpiece form different angles, or pitch and roll it to see the surface topography. The inspector can see reflection patterns on the surface while changing the inspected surface's orientation. The patterns are results of self shadowing, light reflections and scattering. Inspection methods found in literature used different light sources to illuminate the surface equally. The purpose was to avoid light spills and light flooding, under and over exposure in some regions of the inspected area. The method proposed by the authors has an approach based on speckle patterns acquisition. Figure 1 illustrates the lighting concept used in the described method. A high but narrow light source is placed in front of the workpiece centrally aligned to the inspected area. The bottom of the light emitter is aligned with the examined surface. A tilt angle $\varphi < 90$ [deg] is introduced between the light sources vertical axis and the inspected surface so that the incident angle $\boldsymbol{\alpha}$ is small (approximately 1-5 [deg]).

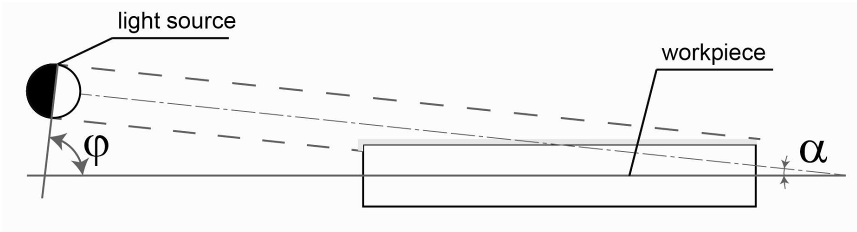

Fig. 1. Light source placement and light beam incident angle

It is important to place the source so that it emits light in the feed direction or its opposite. The light rays hit the ridges and valleys incised on the surface creating a speckle pattern. The speckle pattern can be seen clearly when the imaging plane is perpendicular to the inspected surface, and no other light sources are present. Figure 2 illustrates how speckle patterns are crated on the surface. The top one is of a chatter free surface, while the bottom illustration is of a surface created in unstable conditions. In the bottom image the light pattern has a more jagged edge near the light speckle falloff, while the top images shows a more smooth line near falloff. On the chatter free surface the light speckle has high intensively in the centre and creates a straight line. The chatter marked surface has a less narrow and more saw like speckle shape.

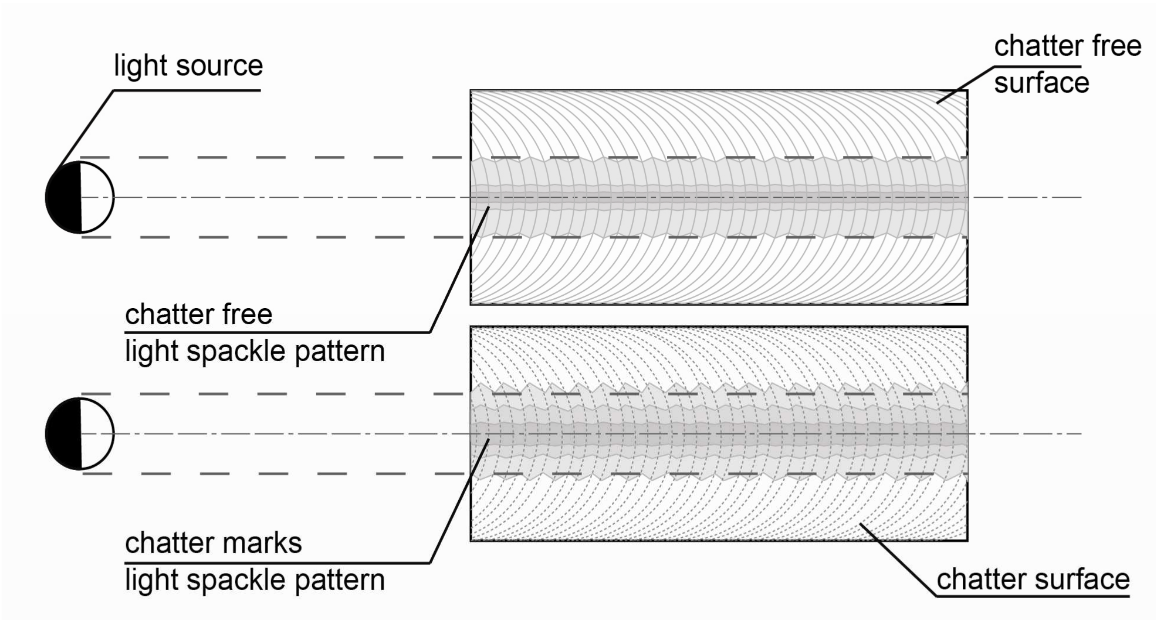

Fig. 2. Speckle patterns for chatter free surfaces and chatter surfaces

Figure 3 shows two experimentally acquired images of speckle patterns for two surfaces. The bottom pattern is found on chatter marked surface. A speckle pattern of a non-chatter surface is found on top of Fig. 3.

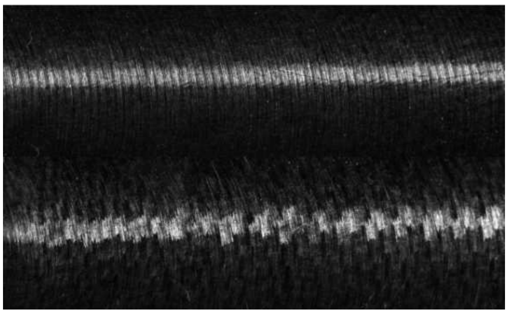

Fig. 3. Speckle patterns acquired during the experiment. Top image for chatter free surface, bottom image for chatter present during milling

3. IMAGE ACQUSISTION AND PROCESSING

It is crucial for the methods' performance to acquire the images correctly. The speckle patterns must be visible and clear so that processing analysis can be preformed. The acquisition must take place in an environment where only the needed source is emitting light. The light position is shown on the schematic in Fig. 4. The light source should produce a narrow beam of light with quick falloff. LED bar light mounted vertically are preferred. No other light sources, strong reflected lights or ambient light can hit the inspected surface. All images should be acquired in the same conditions and with the same parameters so that results can be compared. The sensors gain and exposure time, as well as the light source intensity should be set so that the speckle pattern is clear on a particular inspection surface. The sensors gain may increase image noise so it is reasonable to keep the gain on a low setting. It is also needed to acquire an calibration image (noise level image). It can be done by acquiring a image of darkness (no light in the frame), or by simply putting on a lens cap. The acquisition parameter should not be adjusted when taking the calibration image.

The image processing proposed by the authors is based on 2D CWT (2D Continuous Wavelet Transform). Before the main processing is done two preparation steps can be needed. First the image can be cropped to smaller size, leaving the speckle pattern and its falloff in the centre of the frame. Then a simple normalisation as proposed by Szydlowski and Powalka [4] can be made. After those steps, the 2D CWT can be calculated. Wavelet transformations can be categorized as discrete wavelet transform (DWT) or CWT. Whereas the DWT operates over scales and positions based on the power of two, the CWT have no such limitation. The CWT translates at any point and at any given scale, and any wavelet that satisfies the minimum criteria can be used. A one dimensional CWT can be represented mathematically as *C(a,b)* using equation (1) as Daubechies [6] proposed.

$$C(a,b) = \int_R s(t)\psi_{a,b}(t)dt,$$
$$\psi_{a,b}(t) = \frac{1}{\sqrt{a}}\psi\left(\frac{t-b}{a}\right), \tag{1}$$

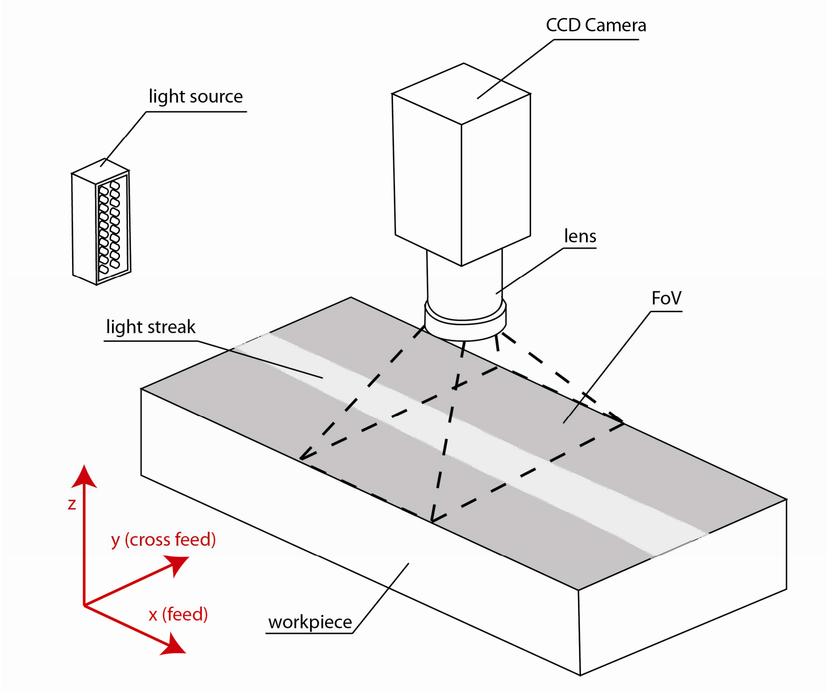

Fig. 4. Experimental setup for chatter mark detection

The transformed signal is $s(t)$, ψ is the mother wavelet and $\psi_{(a,b)}$ is the scaled and translated wavelet, using $a \in R^{+} - \{0\}$ as the scale parameter and $b \in R$ as the translation. With $\psi^*_{(a,B,\theta)}$ being a complex conjugate of ψ as shown in equation (2), and introducing a rotation parameter $\theta \in (0, 2\pi)$ for $X = (x,y)$ given in equation (3) one can introduce equation (4) as a 2D CWT [7].

$$\psi^{*}_{a,B,\theta}(X) = \frac{1}{\sqrt{a}} \psi\left(\frac{r_\theta (X - B)}{a}\right) \tag{2}$$

$$r_\theta = (x\cos\theta - y\sin\theta, x\sin\theta + y\cos\theta) \tag{3}$$

$$C(a,B,\theta) = \int_{R^2} s(X)\psi^{*}_{a,B,\theta}(X) d^2 X \tag{4}$$

The authors chose the Mexican Hat wavelet given by equation (5). The chosen wavelet is known for good performance in peak detection [8].

$$\psi(x,y) = (x^2 + y^2 - 2)e^{-\frac{1}{2}(x^2+y^2)} \tag{5}$$

The processing procedure using 2D CWT can be divided in to following steps. First a 2D CWT of the image is calculated, for scale value 1 and 2. Using the scale parameter in a 2D CWT image decomposition is similar to using band pass filters in the frequency domain. A small value of the scale parameter is to be affects low frequency, and higher values of *a* affect high frequencies in the image. When 2D CWT is calculated, normalised and computed to a binary image, the objects within the image are labelled using a common flood-fill algorithm. Next all objects' pixel areas are calculated. The largest object on the image is considered the light speckle on the surface. The labelled speckle object on the CWT image is isolated from other objects. For the first two scale values $a=1$ and $a=2$ edge detection using Canny algorithm is preformed. The detected edges are the borders of the speckle. If the edges (borders of the light speckle falloff) are strait, there was no chatter in the process. If the edges are wave-like, the chatter has occurred during the milling process. Using a minimum axis aligned bounding box approach we estimate the smallest rectangle that fits all the edge points inside (individually for both edges). The height h_{bb} of the box determines the line straightness. If the boxes' height was 1px the edge would be a perfect straight line. For the detected edges two other parameters are calculated the edges y coordinate standard deviation s_y and the average peak height h_{peak}.

4. EXPERIMENTAL SETUP

An experimental opto-mechatronic system shown in Fig. 5 was used for image acquisition. The machine has a set of linear travelling axis (z and x). The z-axis is responsible for the cameras working distance changes, while the x-axis is a stage for the workpieces. The interior of the machine is sealed from ambient light. The source of light was a small two row LED bar light mounted as mentioned in the article. The light, linear axis and camera was controlled using dedicated software. The system ensured light control, acquisition parameters stability and automation. The CCD camera used in the system was a 5 Mpx Basler Pilot, with bi-telecentric lens TC 24-16 from OptoEngineering.

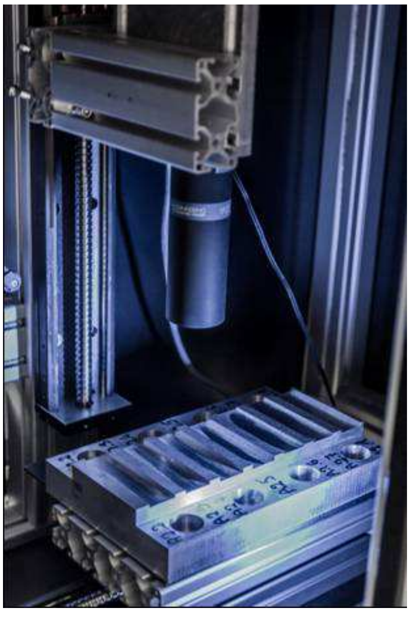

Fig. 5. A photo of the inspection space inside the experimental system

A set of PA6 aluminium surfaces were machined. The used tool was a 21mm mill with two inserts. Seven grooves where made on the test samples using full immersion scenario. While milling data was recorded using a SCADAS transducer, Kistler dynamometer, and a set of PCB accelerometers mounted on the wokpiece, as well as on the spindle of the machine. The purpose of that setup was to monitor the vibration, and chatter frequencies. The milling parameters were chosen specifically to introduce chatter on 5 of the seven surfaces. This was achieved by increasing the depth of cut. The last step was the image acquisition using the setup described in the article.

5. RESULTS

The experiment delivered interesting results presented in Table 1. One can see that the chatter free surface have significantly lower values for all of the proposed parameters h_{bb}, h_{peak}, s_y. This proves that the applied processing is able of isolating the light speckle and

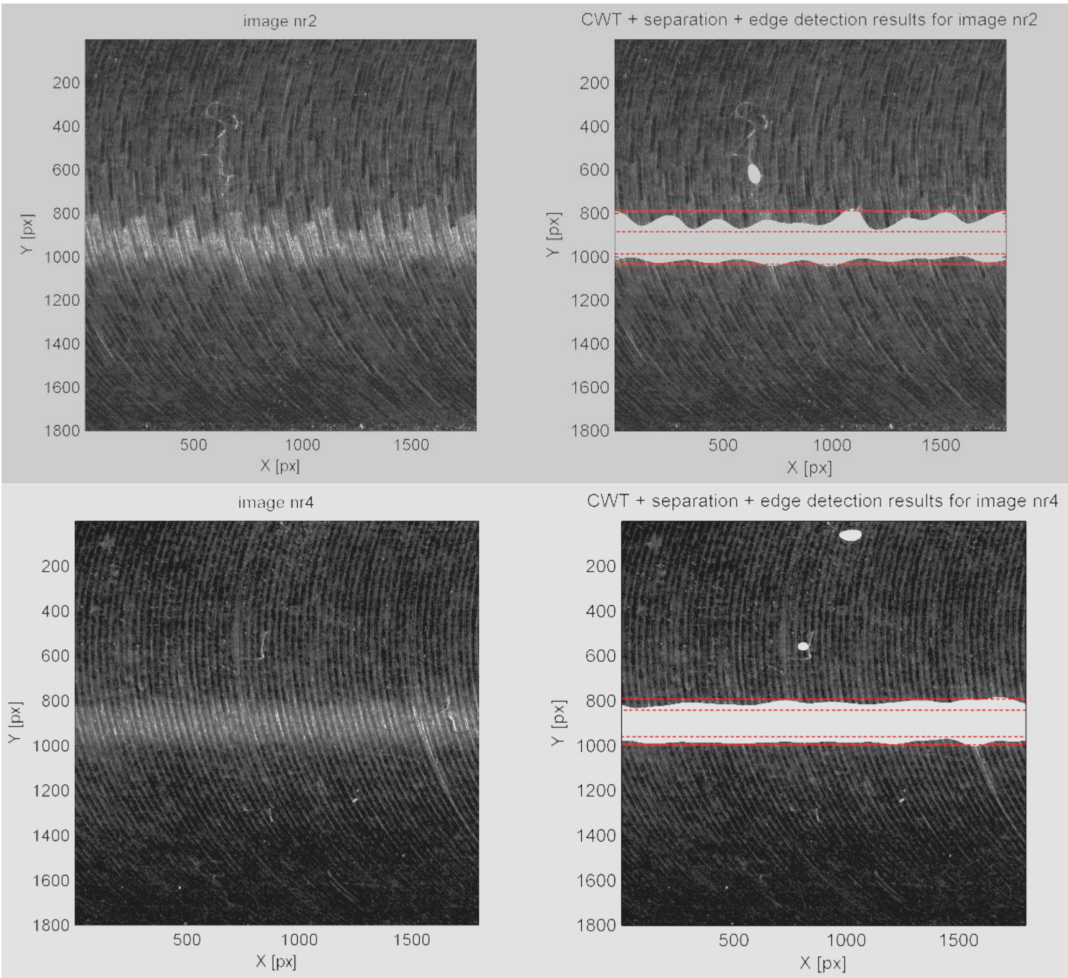

Fig. 6. Two samples speckle images; on the left side without processing and on the right side processed. The top surface with chatter marks

extracting information about the surface finish form the speckles' shape. Figure 6 presents two surface images. The top surface was milled in unstable conditions, while the bottom one was milled without chatter. On the left side unprocessed images are presented. On the right side of the figure results of the processing are presented. The top surface has a modulated, wavelike shape of the edges. The dotted lines represent a bounding box for those edges. The bounding box is clearly bigger than the one on the bottom surface. Also the bottom surface has more straight edges of the light falloff, with smaller modulation amplitude.

Table. 1. Experimental results; Surfaces 3 and 4 are for chatter free and have significantly lower values for all calculated parameters

Image nr	**Average peek height**	**Bounding box height**	**Edge std**	**Rotation speed**	**Feed per insert**	**Depth of cut**	**Traditional inspection**
	h_{peak} [px]	h [px]	s_y [px]	n [obr/min]	f_z [mm/ins.]	a_p [mm]	
1	50.25	88.00	24.70	7957	0.1	2	chatter
2	22.17	47.00	10.72	7957	0.2	4	chatter
3	8.50	22.00	4.73	7957	0.1	4	ok.
4	11.33	34.00	5.71	7957	0.2	3	ok.
5	24.83	65.00	13.38	7957	0.1	3	chatter
6	49.13	96.00	21.45	7957	0.1	2	chatter

6. CONCLUSION

An interesting property of the milled surface has been observed - the surface light speckle. The presented algorithm has been tested with satisfying results, but it was possible because of the acquisition process. The light configuration and experimental opto-mechatronic system were the key elements in delivering the result. The connection between chatter presence and the speckle shape has been proven.

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