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ORIGINAL ARTICLE

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Evaluation of surface smoothness by a laser displacement sensor II: comparison of lateral effect photodiode and multielement array

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Abstract Development of accurate surface assessment technology is of vital interest to modern wood industries. In this experiment we investigated new and fast noncontacting sensors to determine their usefulness for wood surface evaluation and to verify their accuracy. Two types of laser displacement sensors [equipped with a position sensitive detector (PSD) and a charge coupled device (CCD) detector] are compared with a conventional stylus and with theoretical profiles. Hornbeam workpieces with triangular profiles of differing slope and height were used for the evaluation. The results show that resolution of both sensors decreases as the height of the profile decreases. The error ratio of the laser-scanned profiles changes as a function of profile height, in the range 5%–33%. The CCD method is superior for accurate surface roughness evaluation, although the PSD approach can still be used for monitoring the error of form in most applications.

Key words Wood surface roughness · Laser displacement sensor · Position sensitive detector (PSD) · Charge coupled device (CCD)

Introduction

Interest in the production of desirable surface quality products has increased considerably in recent years. Although a number of methods may be used to evaluate surface quality automatically, the best method for that purpose is noncontacting and capable of precise reproduction of the profile method.[1] The best technique must also be able to make measurements at high production speeds.[2] Laser displacement sensor (LDS) techniques belong to the noncontacting group of methods[3] and hence have considerable potential in surface quality control.

Properties unusual to wood, such as anatomical structure, porosity (density), and color variations, make the measurement of wood surface smoothness problematic.[3,4] Previous experiments have shown that the accuracy of the position sensitive detector (PSD) LDS depends not only on the above properties but also on the profile shape and even on the installation position of the sensor.[5] These experimental results suggest that the weakest features of LDS surface measurement might be the poor conditions of the laser light on the measured surface (e.g., reflectance changes, flooding of the laser light on the wood surface, or diffusion of the light into wood) and the performance of the laser light position detector. Therefore, LDS methods reported to date cannot yet be fully utilized for on-line surface smoothness measurements in industrial applications. Hence, more accurate sensing techniques are required.

It is thus advisable to compare PSD LDSs with novel charge coupled device (CCD) LDSs that have been introduced to the market. In previous research we compared LDSs with stylus profilometer measurements. We aimed here to determine the usefulness of both LDSs for evaluating wood surface geometry, and we wanted to verify their accuracy.

Materials and methods

The two LDSs examined here are based on triangulation measurement methodology. Laser light emitted by a semiconductor laser diode passes through a transmitter lens and is focused on the target. Part of the light energy is reflected from the target and is focused on a detector after passing through a receiver lens. Two types of detector are commonly used.[6]

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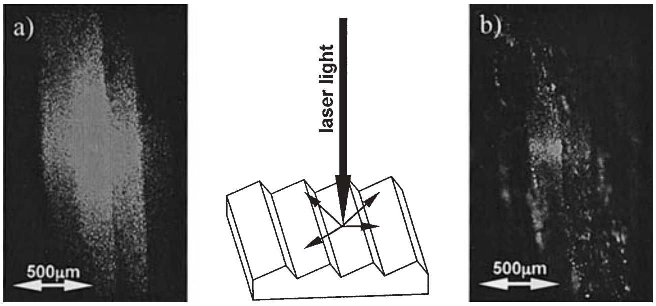

Fig. 1. Image of a laser light spot on the triangular profile surface projected by two laser displacement sensors. **a** Position sensitive detector (PSD). **b** Charge coupled device (CCD)

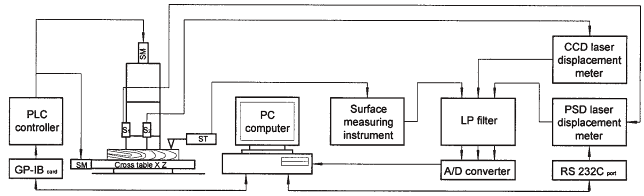

Fig. 2. Experimental setup. *S1*, PSD laser displacement sensor; *S2*, CCD laser displacement sensor; *ST*, stylus; *SM*, stepper motor; *PC*, personal computer; *LP*, low pass filter; *A/D*, analog/digital; *GPIB*, general purpose interface bus

1. Lateral effect photodiode: a PSD that uses the distribution of the entire beam spot entering the light-receiving element to determine the beam spot center of gravity and identifies it as the target position
2. Multielement array: a CCD that detects the peak value of the light quantity distribution of the beam spot for each pixel and identifies it as the target position

In a previous study, Rhemrev et al.[7] were critical of CCD sensors because of their poor positional resolution and the requirement that the light spot be smaller than the pixel. However, recent advances in electronic technology (e.g., faster microchips and miniaturization) coupled with improved signal processing algorithms now make multielement array sensors attractive alternatives to lateral effect photodiodes.

It should be noted that the LDSs investigated here have different systems for projecting light onto the target surface. The power of the PSD sensor's light is constant at all times. In contrast, the CCD sensor uses laser flash time control circuitry, which automatically controls laser emission time based on target surface conditions. If a dark surface is scanned, the time of laser light emission increases. The time of emission becomes shorter in the opposite situation – when a bright surface is scanned. The effect of these approaches on the laser spot shape on a wood surface can be observed in Fig. 1, where the size of the laser spot emitted by the CCD sensor is significantly smaller than that emitted by the PSD. Nevertheless, that "nominal" laser spot's size of both sensors in certain conditions is similar (according to producer specifications: PSD spot's dimension is 45μm/20μm and CCD's diameter is 30μm). This was confirmed by authors in a supplementary experiment, where the surface color of the workpiece was dark.

Setup

Figure 2 shows the experimental setup. A computer with a general purpose interface bus (GPIB) interface and programmable logical controller (PLC) module controls the position and speed of a numerically controlled x-z cross-table. Two laser displacement sensors (Keyence LC-2450 and Keyence LK-030) and a stylus (Tokyo Seimitsu Surfcom) were sequentially installed on the vertical support of the cross-table. The angle between the light triangle and movement direction was 90 degrees (perpendicular position) for both laser sensors. The laser wavelength was 670 nm, the incidence angle of laser light was 0 degrees, and the reflectance angles were 22 and 40 degrees, respectively, for PSD and CCD sensors. The stylus sensor's geometry was the same as reported in our previous study[5] (steel tip with an angle of 29 degrees and tip radius of 10μm). The installation positions of all sensors were carefully controlled to minimize total experimental error.

The experimental data generated by the sensors were acquired by a 12-bit analog/digital (A/D) converter card (Quatech DAQ-1202) and stored in computer memory after preanalysis. Custom software was prepared for the experiment using MS Visual Basic. This custom program was able to supervise the cross-table and laser displacement controllers, as well as to calculate the surface roughness descriptors.

Workpiece

Hornbeam (*Carpinus* sp., 0.72 g/cm^3) was used as an experimental workpiece. The wood samples utilized were without defects and were conditioned to approximately 11% moisture content. Blocks were cut with a computer numerical control (CNC) router machine to produce triangular profiles with differing geometry. The wood fiber direction was parallel to the feed direction. Profiles prepared for the experiment had different steepness (profiles A, B, and C with inclination angles of 45, 30, and 15 degrees, respectively) and different heights (profiles S, M, and L with triangle heights of 75, 250, and 700μm, respectively). The profile contours and their corresponding description codes are illustrated in Fig. 3. After cutting, the profile quality of all samples was verified under a microscope, and properly-formed triangular profiles were selected for evaluation.

Experimental procedure

All profiles were scanned along a straight line three times: first by the PSD laser sensor, then by the CCD laser sensor, and finally by the stylus. The sensor movement speed was 0.3 mm/s, and the sampling length was 8 mm. The profile data were collected at a rate of 128 sample points/mm. Laser-scanned profile lines were compared to both the profile lines scanned by the stylus and the theoretical profiles (ideal imagination of the triangular form). Surface roughness parameters R_a, R_y, R_z, kurtosis (Kt), and skewness (Sk)[8] were calculated and analyzed, along with the average intensity of the laser light reflected from the wood surface, power spectral density, and linear regression coefficients (slope and determination coefficient r^2) between the corresponding values of theoretical, stylus, and laser profile points obtained from the profiles. Additionally, the average error ($\overline{E}$), counted as a main difference between the profile height measured by laser sensor (y_{laser}) and stylus (y_{stylus}), was calculated using Eq. 1. High-frequency signals caused by electrical noise or wood anatomical microroughness were removed from the primary profiles by a low-pass digital filter (cutoff 0.08 mm). Theoretical profiles were processed by the same manner as profiles obtained from sensors.

$$\overline{E} = \frac{1}{N}\sum_{i=0}^{N}\left|y_{\text{stylus}}(i) - y_{\text{laser}}(i)\right| \tag{1}$$

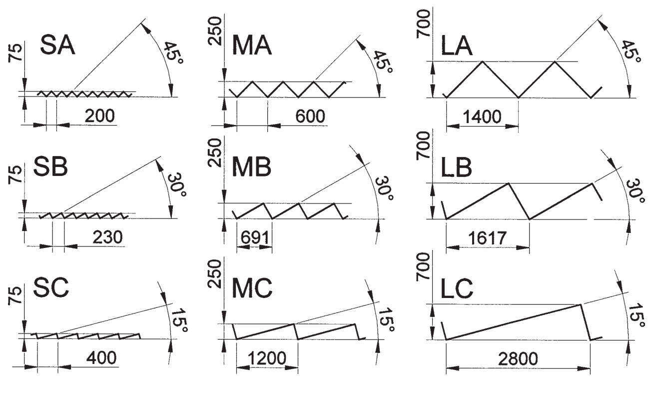

Fig. 3. Sets of triangular profiles investigated in the experiment. Dimensions are in micrometers. *SA*, *SB*, *SC*, *MA*, *MB*, *MC*, *LA*, *LB*, *LC*, see text

Results and discussion

Figure 4 shows the contours obtained by various methods for typical triangle profiles. A visual inspection of the curves proves that both laser sensors reproduced the surface contour correctly, especially when high profiles (LB) were scanned. With lower profiles (SB), the representation from the CCD sensor seems to be closer to the theoretical and stylus profiles than the equivalent representation generated by the PSD sensor. It is also apparent that all laser-scanned lines have more or less rounded profile peaks and valleys. This phenomenon is similar to that discussed previously,[5,9] where rounding of profile peaks and valleys was generated by the differences in light reflection in those areas. Some high-frequency distortions (less smoothness) can also be observed on the PSD profiles. The deformation of other contours was noted mainly in the profiles scanned by PSD LDS, particularly when the profile height was small (75 μm). In contrast, the CCD-scanned profiles were much more comparable to the theoretical profiles. However, some vertical compression of the CCD profiles contours could be observed.

As a consequence of the deformation of the PSD LDS profiles, calculated roughness parameters for the method also differ from the expected values. This phenomenon was most noticeable in the case of the low profiles (SB), where R_a was slightly less than corresponding parameters obtained from the stylus and the theoretical profiles. The "noisy" character of the low profiles scanned by the PSD sensor makes the maximum height of the profile (R_y) significantly greater. When the CCD sensor was used to scan high profiles (LB, MB), the roughness parameters (R_a and R_z) were similar to those calculated from the stylus profiles. Unfortunately, this advantage did not hold when low profiles (SB) were examined, and the calculated roughness parameters were significantly smaller than those from the stylus and from the theoretical values.

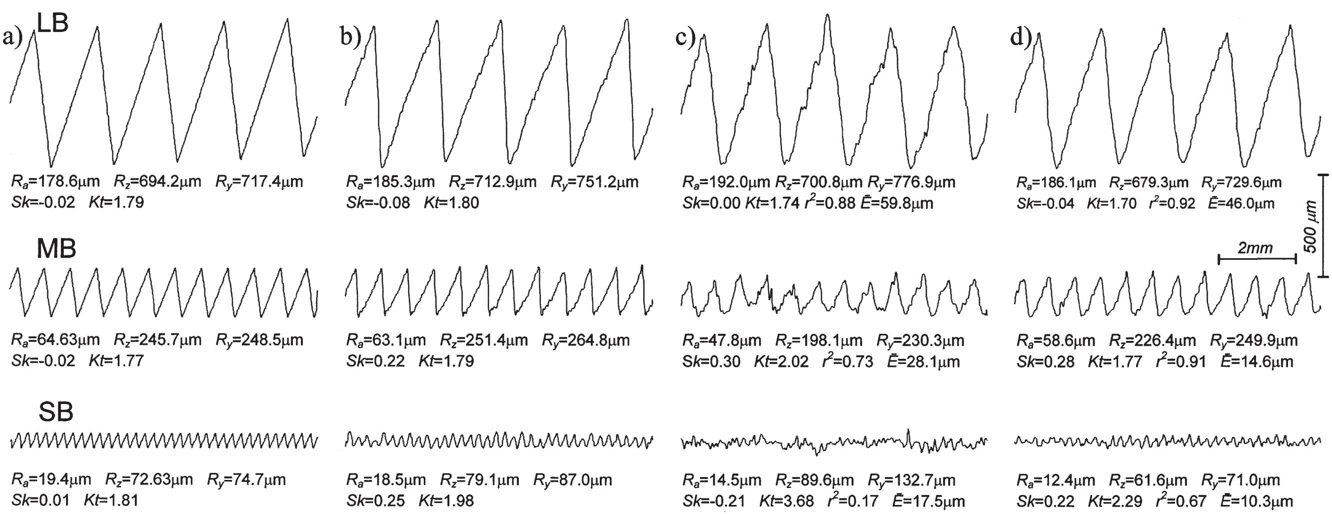

Fig. 4. Typical profiles obtained from scanning triangular profiles (*LB*, *MB*, *SB*). **a** Theoretical profile. **b** Stylus. **c** PSD sensor. **d** CCD sensor

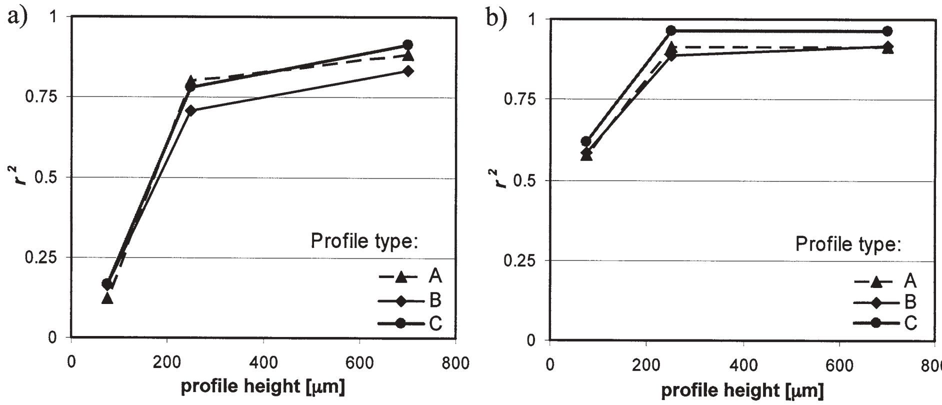

Fig. 5. Determination coefficients (r^2) between the laser and stylus profile points when scanning triangular profiles by PSD (**a**) or CCD (**b**)

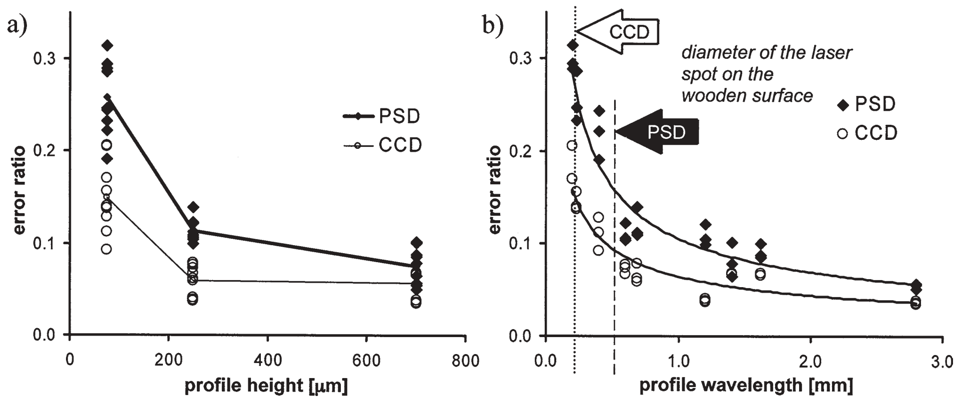

Fig. 6. Error ratio of the laser method when scanning triangle profiles as a function of profile height (**a**) or profile wavelength (**b**)

Correlation diagrams (Fig. 5) confirm that the accuracy of both laser sensors decreased as the height of the profiles tested decreased. However, the determination coefficients (r^2) in all types of CCD-scanned profiles were greater than the equivalent coefficients calculated from PSD profiles. The essential differences appear when low profiles (height of profile 75μm) were examined. The low r^2 of low profiles (SB) scanned by the PSD sensor is a consequence of profile deformation. No distinct influence of the profile's slope on the r^2 between the laser-scanned and stylus profiles was observed; however, r^2 calculated from type C profiles of various heights were always greater than those of type A and B profiles.

Based on the information from Fig. 5, the minimum profile height that can be accurately evaluated by PSD LDS is approximately 250μm. However, for the CCD sensor the minimum profile height can be less than 75μm with the performance of the sensor still accurate.

The scanning error ($\bar{E}$) decreases when the height of the profile decreases. Conversely, the error ratio ($\bar{E}$ divided by the profile height) decreases when the profile height increases (Fig. 6a). The CCD error ratio is about two-thirds that of the PSD ratio and remains constant over 250μm profile height, where its value does not exceed 0.07. This leads to the conclusion that when surfaces are scanned by CCD LDS the calculated surface roughness parameters based on the average profile height (R_a, or RMS) are within $\pm$7% of the profile's real height. The poorest performance was observed in the SA profile scanned by PSD, where the error ratio reached 0.33, meaning that in extreme situations the maximum variation of the surface roughness descriptors could reach one-third of the profile height. Among all types of profile, the level of the average errors and error ratios were smallest for those of type C.

The effect of the profile wavelength on LDS accuracy is illustrated in Fig. 6b. The error ratio generally rises as the profile wavelength decreases. However, the ratio increases dramatically when the surface profile wavelength is less than 0.5 mm. The two laser sensors show similar trends of change in the error ratio; but as with the relation with the profile height, the error ratio of CCD LDS is half that of PSD LDS. This is caused by the tendency to "average" the surface irregularities when the wavelength of the scanned profile is smaller than the radius of the laser spot. Laser light distribution on porous surfaces differs significantly between PSD and CCD sensors owing to their different methods of light emission, as noted above. In addition, specific properties of wood such as anisotropic anatomical structure, existence of microscopic pipe-like elements (vessels or tracheids), uneven density, and other factors enable laser light to "flood" on the wood surface (similarly to flooding on the surface by a drop of liquid). Finally, as shown in Fig. 1, the size of the laser spot emitted by the CCD sensor is significantly smaller than that emitted by PSD, where the size of the light spot nears the length of three profile wavelengths. Theoretically, the accuracy of the LDS does not depend on the size (area) of the laser point focused on the target. However, it is required that the light

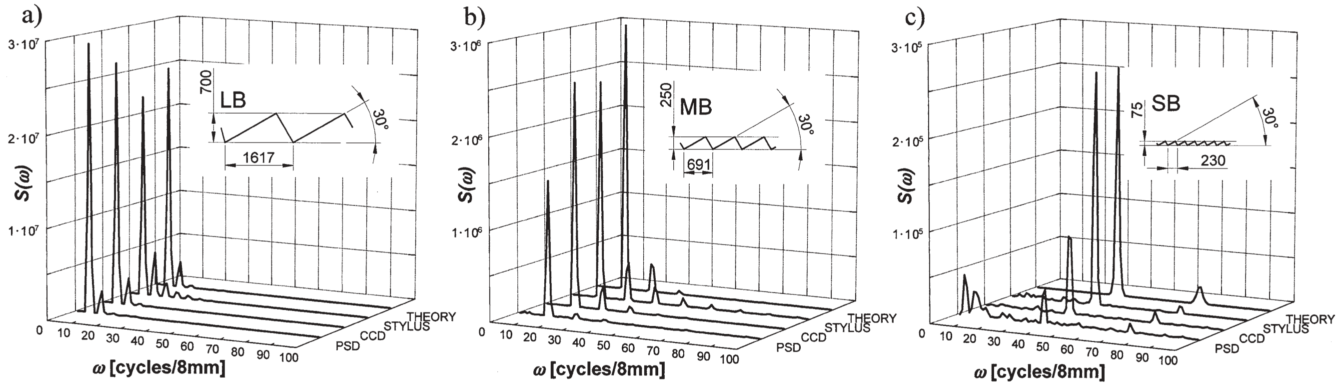

Fig. 7. Power spectral density of investigated profiles. **a** LB. **b** MB. **c** SB

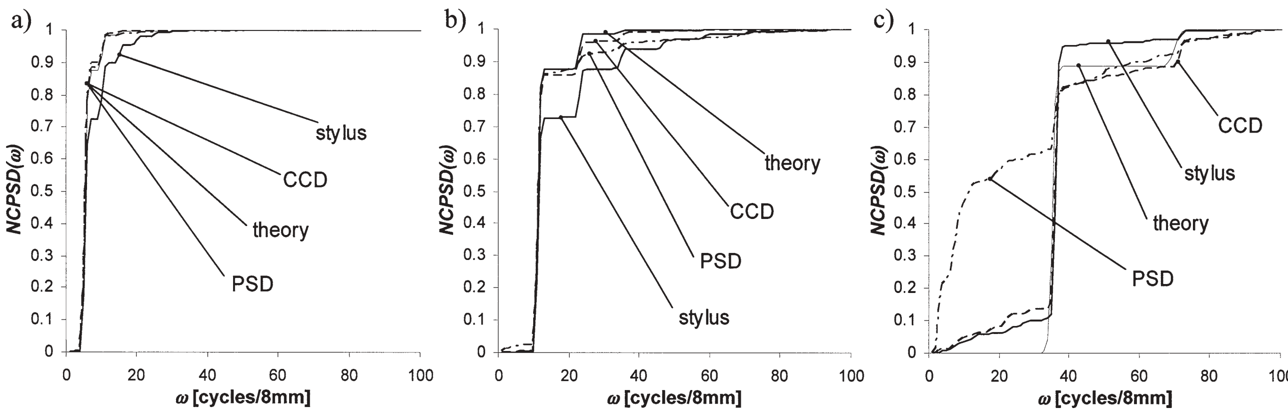

Fig. 8. Normalized cumulative power spectrum density (*NCPSD*) of triangular profiles. **a** LB. **b** MB. **c** SB

distribution must be scattered symmetrically to the center of the gravity point. If that requirement is kept, the sensor should have perfect accuracy. Unfortunately, in reality, the laser spot on a porous wooden surface becomes distorted, and the light distribution on the detector also deforms (e.g., increases the spot size, deforms the circularity, perturbs the uniformity of light distribution). With increasing spot size, the probability of the distortions increases. As a consequence, the gravity center of the spot detected by a lateral effect photodiode might not be the real center of the spot. It is thus natural that the PSD sensor averages the profile height over that area. As a result, the periodic triangle form is distorted when the triangle length exceeds the laser light spot diameter. With CCD sensors those distortions are reduced because array sensor considers the pixel with the highest intensity as the real center of even deformed spots.

Tested triangular contours have a periodical nature. Fourier transform functions have usually been used to evaluate these kinds of profile.[10–14] In this experiment, we calculated the power spectrum density function $S(\omega)$ of spatial frequency ω for all profiles scanned by laser and stylus sensors and for the theoretical profiles. $S(\omega)$ curves for a type B workpiece with triangular profiles of various heights (Fig. 7) shows that all sensors detected the main frequencies peaks at 5, 11, and 34 cycles/8mm for LB, MB, and SB profiles, respectively. The magnitudes of the maximum frequency components calculated from the CCD sensor profile line were closer to the corresponding magnitudes of the stylus line than were those of the PSD sensor. With the PSD sensor, the noise level was also greater than that of the other sensors, especially at long wavelengths when the profile height was low.

Normalized cumulative power spectrum density curves counted with Eq. 2 confirm the above observations. From Fig. 8 it is apparent that when high profiles (LB) were analyzed similar curves are observed for both lasers and the theoretical profiles along all wavelengths. However, when low profiles were analyzed (Fig. 8c), significant differences are evident between PSD and the other paths. This noise corresponds to the distortion of the triangle form obtained in the measurement

$$\mathrm{NCPSD}(\omega) = \frac{\int_0^{\omega} S(\omega)d\omega}{\int_0^{\infty} S(\omega)d\omega} \approx \frac{\sum_0^{i} S_{\omega=i}}{\sum_0^{100} S_{\omega=i}} \qquad (2)$$

$$(i = 0,1,2,\ldots 100 \text{ cycles/8mm})$$

where NCPSD is the normalized cumulative power spectrum density.

It is also evident here that although the stylus profilometer is widely accepted as the most accurate device for surface smoothness evaluation some misrepresentations can be found in the profile curves obtained by that method. The NCPSD path of the stylus curve differs somewhat from the others, especially for high and intermediate profiles. The main reasons for the difference are tilting of the stylus tip and inclination of the stylus holder arm,[15,16] together with profile deformation affected by the radius of the stylus.[17] The effect of the stylus arm inclination was especially amplified here because of the experimental conditions used (e.g., tall profile height and acute slope). Consequently, the power spectral density function was changed compared to the expected (theoretical) function. The negative performance of the stylus diminished when the height of the profiles was reduced to small values in the experiment with height at 75μm.

Based on the above results, a pixel array seems to be more resistant to the effect of changes in light reflection than the lateral effect photodiode. In all investigated profiles, the CCD sensor was able to detect the real spot position more accurately than could the PSD. This is due to the positive effect of the CCD laser light position detector's performance and to minimization of the laser spot size on the wooden surface. We therefore suggest that the CCD LDS can be utilized to evaluate wood surface roughness in laboratory or industrial applications. However, the PSD sensor can also be employed in a wide range of applications for evaluating some long wave surface components (e.g., error of form or waviness) or for evaluating extremely rough surfaces where the height of the irregularities is appreciable.

Conclusions

Based on visual judgment of CCD and PSD profiles, all profiles were generally imitated properly, especially when tall profiles were scanned. With low profiles, results using the CCD sensor were closer to the theoretical profile than to those produced by PSD. All laser-scanned lines have round profile valleys and peaks.

Roughness estimated by laser methods falls in the range $\pm 5\%$ of the real roughness in the best case. In the poorest circumstances the error can be more than one-third the actual value.

Frequency analysis showed that all sensors detected the main frequency, but the magnitude of the maximum frequency components calculated from the CCD sensor profiles lay closer to the corresponding stylus magnitude than did the PSD. With the PSD sensor the noise level was greater than for the other sensors investigated.

The accuracy of the CCD sensor was superior to that of the PSD sensor in all the profiles investigated, and CCD LDS is thus suitable for evaluating wood surface roughness. The PSD sensor could still be used to evaluate low-frequency surface components (e.g., errors of form or waviness), however, in a wide range of industrial applications.

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