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Nanfeng Zhu · Chiaki Tanaka · Tadashi Ohtani
Hiroshi Usuki

Automatic detection of washboarding in bandsaws

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Abstract This paper presents an on-line method for detecting washboarding generated in bandsaws. It uses a parameter based on the shape of sawing force amplitude distributions. The curve of the probability density function of the parallel sawing force amplitude obeyed a normal distribution for the normal sawn surface, but it changed to an M-shaped distribution when washboarding appeared on the sawn surface of the workpiece. The curve of probability density function of the normal sawing force amplitude obeyed the normal distribution for any sawn surface investigated. The workpiece including a knot did not influence use of the parameter for detecting the appearance of washboarding.

Key words Bandsaw · Washboarding · Probability density function · Sawing force

Introduction

Full automation of the wood cutting process requires fast, automatic detection of abnormal cutting. During bandsaw operation, one of the signs of abnormal sawing is the appearance of washboarding on the sawn surface of the workpiece. The term "washboarding" is used to describe a regular sinusoidal-like pattern that sometimes occurs on the sawn surface. Washboarding is a common problem in the sawmilling industry. Almost all sawmills produce lumber having a corrugated surface similar to that of a washboard at some time.[1] This sawn surface is undesirable because it must be removed at a deeper level than the normal sawn surface to produce a smooth surface; moreover, sawing an excessive amount leads to wasting a large volume of material.

N. Zhu · C. Tanaka (✉) · T. Ohtani · H. Usuki
Faculty of Science and Engineering, Shimane University, Matsue 690-8504, Japan
Tel. +81-852-32-6562; Fax +81-852-32-6598
e-mail: chiaki@riko.shimane-u.ac.jp

Some researchers[2–5] have studied the washboarding generated by bandsaws. Most of these studies investigated the causes and mechanisms of washboarding by considering the tooth-passing frequencies, natural frequencies, and the lateral cutting forces; and they have reported methods to predict the appearance of washboarding using natural frequencies. However, the problem is complicated because changing the wood species and the saw blade tension affects the appearance of washboarding.[1] The purpose of this study was to find a parameter for detecting washboarding using sawing force amplitude distributions suitable for various sawing conditions.

Experiment

Materials

The workpiece for the experiment was Japanese cedar, or sugi (*Cryptomeria japonica*, D. Don). It had a moisture content of 11%–13%, specific gravity 0.43, thickness 60 mm, and length 300 mm.

Sawing conditions

The sawing was conducted using a woodworking bandsaw machine with 700 mm diameter wheels and a distance between the wheel axles of 1250 mm. The saw blade used in the experiment had a length of 4700 mm, width 50 mm, thickness 0.65 mm, gullet depth 5 mm, kerf width 1.3 mm, tooth pitch 20 mm, and number of teeth 235. The rake and clearance angles of each tooth were 20° and 23°, respectively. In the experiment, the rotation speed was kept at 200 rpm, and the feed speed was kept at 3.6 m/min.

Sawing force measurement

Two components of the sawing force, normal and parallel forces, were measured by load cells installed in the workpiece feed table. "Normal force" is a component of the

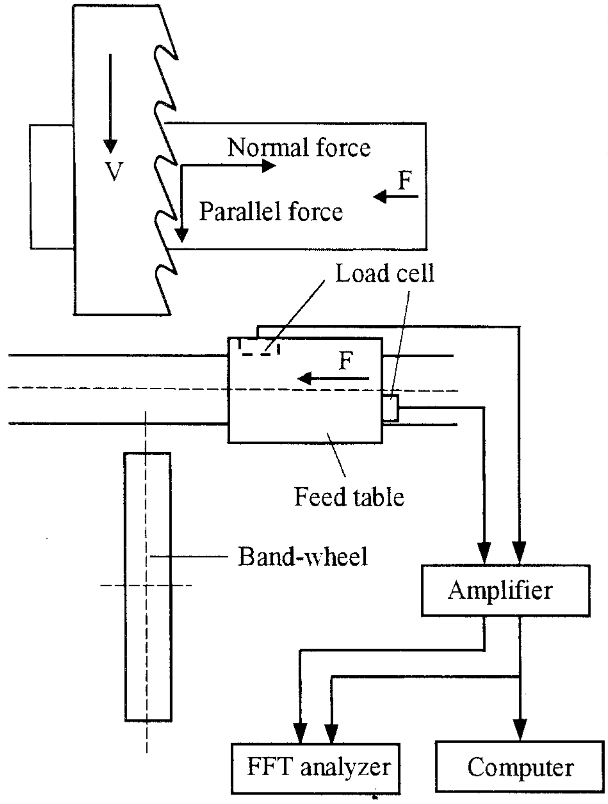

Fig. 1. Experiment setup. *V*, sawing direction; *F*, feed direction; *FFT*, fast Fourier transform

Fig. 2. Sawn surface of a workpiece divided into four parts. Parts *I* and *IV* show normal sawn surfaces. Part *II* has the appearance of a washboard. Part *III* has a washboard pattern

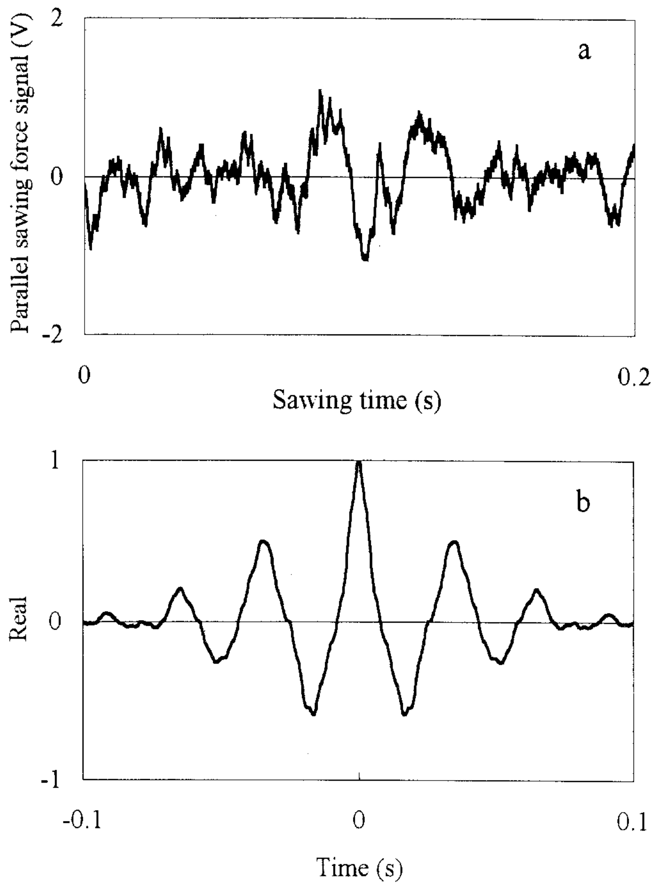

Fig. 3. Parallel sawing force signal (**a**) and its autocorrelation function (**b**) for part I in Fig. 2

sawing force parallel to the feed direction, and "parallel force" is a component of the sawing force parallel to the sawing direction. The signals from the load cells were amplified and transferred to two channels of a fast Fourier transform (FFT) analyzer and a personal computer, as shown in Fig. 1. The load cell responded up to 2kHz with uniform sensitivity. The amplitudes of the sawing force signal were recorded at a rate of 512 sample points per 0.1s on the FFT analyzer. The FFT analyzer was used to calculate the probability density of the sawing force signal, and the computer was used to analyze the frequency value of sawing force at various amplitude intervals.

Results and discussion

Figure 2 shows the sawn surface of a workpiece. It was found that washboarding appeared on part of the sawn surface. The whole sawn surface was divided into four parts. On part I the washboarding pattern did not occur, and the sawing process was stable. On part II the washboarding began to appear. On part III the sawing process was unstable; that is, washboarding was always present on the sawn surface. On part IV the sawing process returned to a stable state, and washboarding disappeared from the sawn surface.

Figure 3 shows the parallel sawing force signal (Fig. 3a) and its autocorrelation function (Fig. 3b) for part I, shown in Fig. 2. The autocorrelation function indicated that the autocorrelation of the waveform decreased with increasing time delay. Therefore, the chief component of the signal can be considered a random signal.[6] Figure 4 shows the parallel sawing force signal (Fig. 4a) and its autocorrelation function (Fig. 4b) for part III, shown in Fig. 2. The autocorrelation was maximum at zero time, and the autocorrelation function exhibited a peak with the same period. Therefore, the signal can be considered a sine wave plus a random signal.[6]

As described above, the parallel sawing force signal $F(t)$ can be considered a compound process of a random signal plus sine wave during the whole sawing process. That is

$$F(t) = F_n(t) + F_s(t) \tag{1}$$

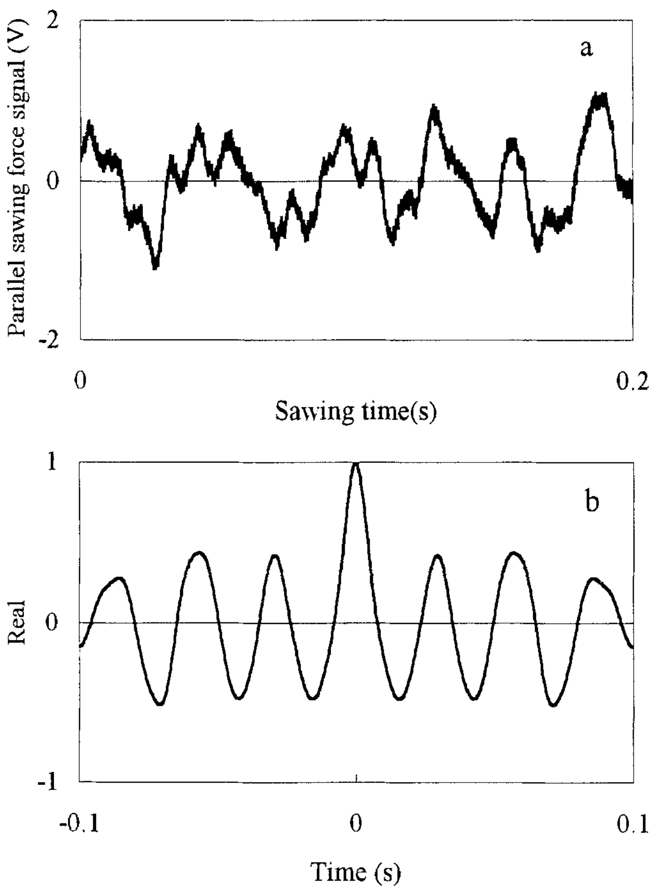

Fig. 4. Parallel sawing force signal (**a**) and its autocorrelation function (**b**) for part III in Fig. 2

where $F_n(t)$ is a random signal, $F_s(t)$ is a sine wave, and t is time.

To analyze the random signal $F_n(t)$, the central limit theorem of statistical analysis[7] is effective. The probability density function $p_n(F)$ of signal $F_n(t)$ obeys the normal distribution and is determined by the mean value and standard deviation. For convenient calculation, assuming a zero mean value for $F_n(t)$, $p_n(F)$ is given as:

$$P_n(F) = \frac{1}{\sigma_n\sqrt{2\pi}}\exp\left[-F^2/2\sigma_n^2\right] \tag{2}$$

where σ_n is the standard deviation, and F is the amplitude of the sawing force.

The sine wave $F_s(t)$ can be represented as:

$$F_s(t) = F_a\sin(2\pi tf + \theta) \tag{3}$$

where F_a is the amplitude of the sawing force, f is the circular frequency of the sawing force, and θ is the phase of the sawing force.

The probability density function $p_s(F)$ of signal $F_s(t)$ obeys the sine distribution.[6]

$$P_s(F) = \left[\pi\sqrt{F_a^2 - F^2}\right]^{-1} \qquad (-F_a < F < F_a) \tag{4}$$

The standard deviation of this sine wave is $\sigma_s^2 = F_a^2/2$.

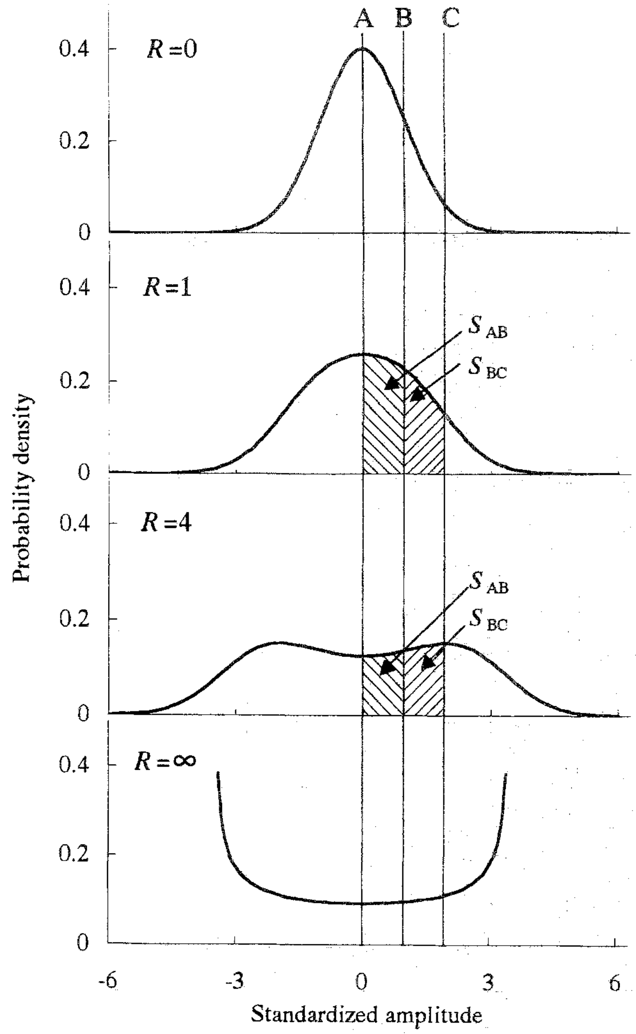

Fig. 5. Standardized probability density curves of the normal distribution plus sine distribution. $R = \sigma_s^2/\sigma_n^2$, σ_s is the standard deviation of the sine wave, σ_n is the standard deviation of the normal distribution function. Zero mean value is assumed for the normal distribution and sine wave. *AB*, *BC*, amplitude domain intervals

The probability density function of $F(t)$ is the convolution of the individual density functions in Eqs. (2) and (4). Assuming zero mean values for both $F_n(t)$ and $F_s(t)$, the probability density function $p(F)$ can be shown to be[6,8]:

$$P(F) = \frac{1}{\sigma_n\pi\sqrt{2\pi}}\int_0^{\pi}\exp\left[-\frac{\left(F-\sqrt{2}\sigma_s\cos\theta\right)^2}{2\sigma_n^2}\right]d\theta \tag{5}$$

According to Eq. (5), some curves of probability density function can be plotted as shown in Fig. 5. The shapes of the probability density function curve are changed with the variation of R ($R = \sigma_s^2/\sigma_n^2$), which indicates the ratio of the sine wave variance to the normal variance. When $R = 0$ the curve shows a normal distribution, which means that the signal of the parallel sawing force contains random components only, and that the sawing is stable. With an increase in R (e.g., $R = 1$), although the sine component begins to contain the parallel sawing force signal the curve still shows a normal distribution. With a large increase in R (e.g., $R = 4$), the sine component increases the parallel sawing force signal. This means that the sine component becomes dominant in the signal, and that washboarding occurs on the sawn surface. When R increases indefinitely, the curve of probability density presents in a U-shaped distribution.

Some amplitude domain intervals of the sawing force signal, such as AB and BC (interval AB is equal to interval BC, and A is kept at zero), can be established in Fig. 5. S_{AB} and S_{BC} are the areas under the curve of $p(F)$ between A and B and between B and C, respectively. When the curve of probability density function obeys a normal distribution, the value of the curve (e.g., $R = 1$) increases with a decrease in the absolute value of amplitude, that is, $S_{AB} > S_{BC}$. When the sine component becomes dominant in the sawing force signal, the value of the curve (e.g., $R = 4$) decreases with a decrease in the absolute value of amplitude, that is, $S_{AB} < S_{BC}$. Based on the above analysis, a parameter K_s, based on the shape of the sawing force amplitude distribution, can be used to investigate the appearance of washboarding, as in the following equation:

$$K_s = S_{AB} - S_{BC} = \frac{P_{AB}}{P} - \frac{P_{BC}}{P} = \frac{1}{P}(P_{AB} - P_{BC}) \qquad (6)$$

where P is the total frequency value of the sawing force in the amplitude domain, P_{AB} is the frequency value of the sawing force in the amplitude interval AB, and P_{BC} is the frequency value of the sawing force in the amplitude interval BC. Because the total frequency P is a constant value, the appearance of washboarding can be investigated by comparing P_{AB} and P_{BC} of different sizes. For convenient calculation, Eq. (6) becomes:

$$K = P_{AB} - P_{BC} \qquad (7)$$

Considering the changes in the sawing force amplitude distributions, when the value of K is always larger than zero in any amplitude interval AB and BC, it is thought that the random component is dominant in the sawing force signal, and the sawn surface is normal. If one or more of the K values is less than zero in any amplitude interval AB and BC, it is thought that the sine component is dominant in the sawing force signal, and that washboarding occurs on the sawn surface.

In the experiments, the computer changed the data of the sawing force signal to be zero for the mean value, and the value of K was calculated by Eq. (7) for each 0.1 s of sawing time. Five amplitude domains for calculating K were set up in the program: 0–0.20–0.40 V, 0–0.25–0.50 V, 0–0.30–0.60 V, 0–0.35–0.70 V, and 0–0.40–0.80 V.

Figure 6 shows the curves of probability density function of the parallel sawing force signal for parts I–IV, shown in Fig. 2. For part I the curve showed a normal distribution, and the maximum value of the probability density function corresponded to the mean of the amplitude. The frequency P_{AB} was larger than the frequency P_{BC} in any of the five amplitude domains. For example, P_{AB} was 145 for interval 0–0.25 V, and P_{BC} was 76 for interval 0.25–0.50 V. Therefore, K was 69. For part II the curve changed to a W-shaped distribution. The maximum value of the curve decreased somewhat, and the variation range of the amplitude scattered slightly compared to that for part I. In this case, K was 54 for P_{AB} and P_{BC} at intervals 0–0.25 V and 0.25–0.50 V. For part III the curve showed an M-shaped distribution. P_{AB} for interval 0–0.25 V was less than P_{BC} for interval 0.25–0.50 V. In this case, K was -65. For part IV the curve returned to a normal distribution, and K was more than zero again in the five amplitude domains.

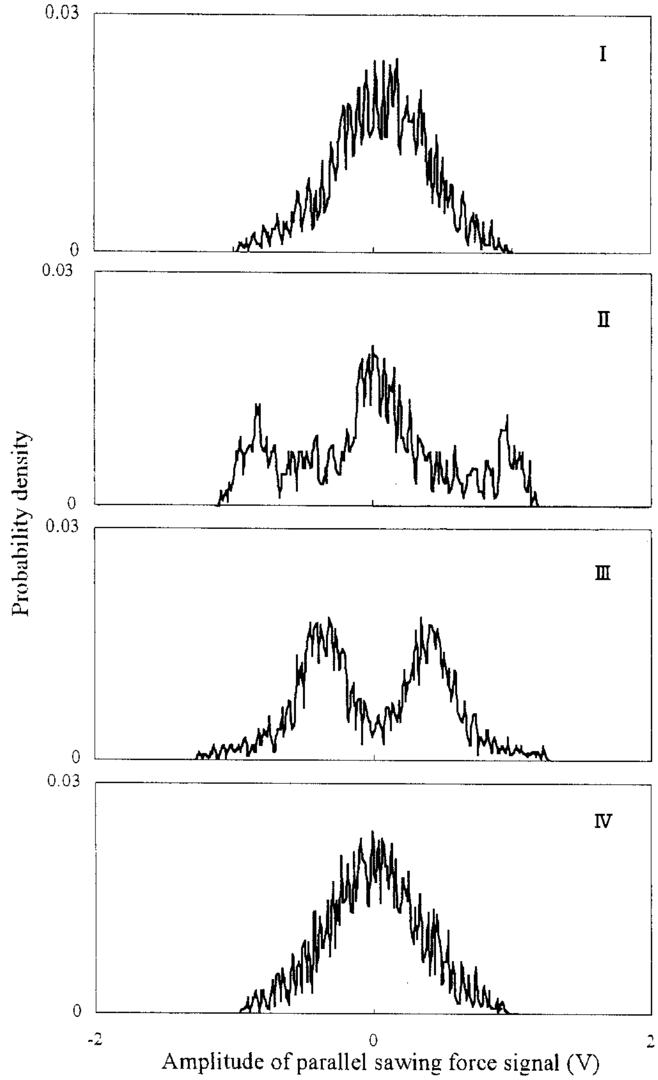

Fig. 6. Curves of probability density function of the parallel sawing force for four parts of the sawn surface, I to IV, shown in Fig. 2

Figure 7 shows the curves of probability density function of the normal sawing force signal for parts I–IV, shown in Fig. 2. They were of normal distribution. The standard deviations of the curves were 0.18, 0.21, 0.24, and 0.20, respectively. This phenomenon demonstrated that the appearance of washboarding had not greatly influenced the curve of probability density function of the normal sawing force. Therefore, the normal sawing force can be ignored when using the parameter K for detecting the appearance of washboarding.

Figure 8 shows the behavior of K corresponding to the sawn surface shown in Fig. 2. The intervals for calculating K

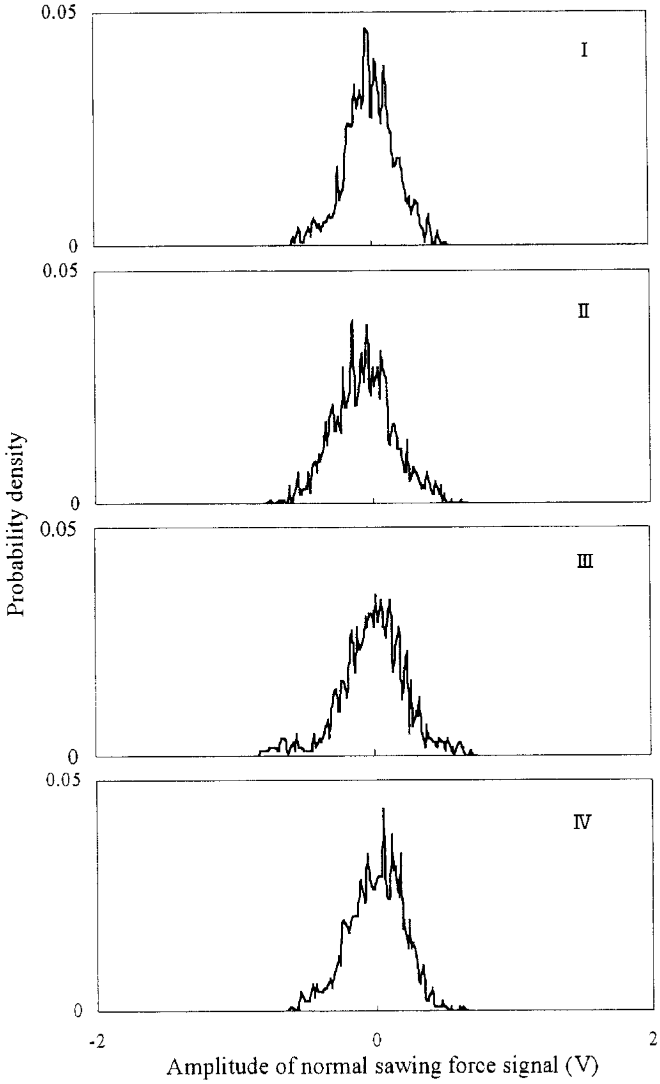

Fig. 7. Curves of probability density function of the normal sawing force for four parts of the sawn surface. I to IV, shown in Fig. 2

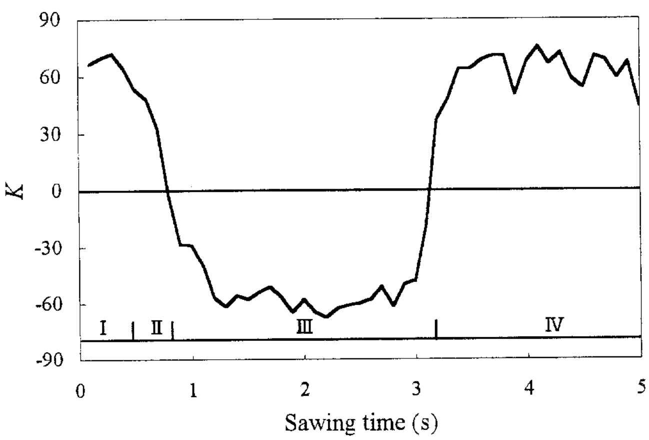

Fig. 8. Behavior of K, corresponding to the sawn surface in Fig. 2

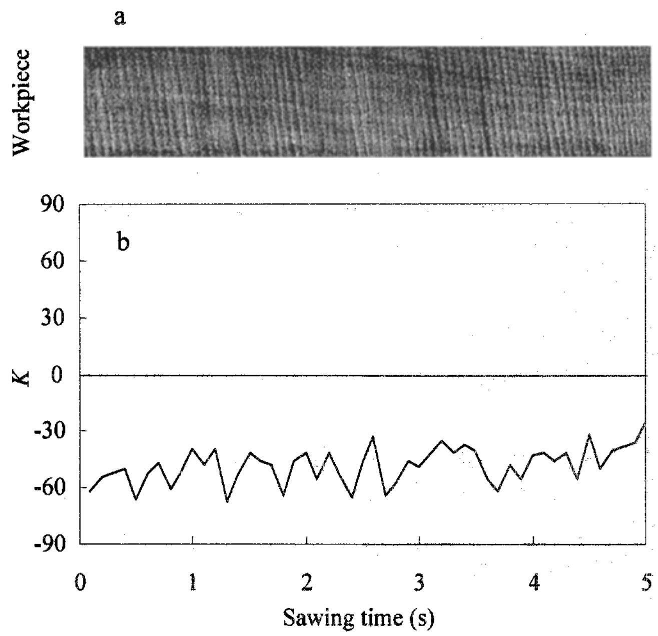

Fig. 9. Situation of sawn surface of the workpiece (**a**) and the behavior of K corresponding to the sawn surface (**b**). Washboard appeared on whole sawn surface

were 0–0.25 V and 0.25–0.50 V. For parts I and IV the K values were larger than zero and had not greatly changed. For part II K decreased continuously until it was less than zero, and for part III K was less than zero. In this experiment, the threshold of K was set at zero, which corresponded to the transitional sawing process. When K was below zero, washboarding was observed on the sawn surface. Figure 9 shows the behavior of K corresponding to the sawn surface; the washboarding appeared on the whole sawn surface. K was always below zero when P_{AB} and P_{BC} were at the intervals 0–0.25 V and 0.25–0.50 V. Based on these results, it was believed that the parameter K was effective for detecting the appearance of washboarding.

Knots are known to affect the sawing force because of their high density and the disorder of their fiber direction compared with that of normal wood. Therefore, application of parameter K was investigated in a workpiece containing a knot. Figure 10 shows the curve of probability density function of the parallel sawing force to the knot part (Fig. 10a), the situation of the sawn surface of the workpiece including the knot (Fig. 10b), and the behavior of K corresponding to the sawn surface of the workpiece (Fig. 10c). Washboarding did not appear on the knot portion, though it appeared on the another part of the sawn surface. For the knot portion, the curve showed a normal distribution, and P_{AB} was larger than P_{BC} in all of the five amplitude domains. When the intervals for calculating K were 0–0.25 V and 0.25–0.50 V, K was 69 compared to the normal sawn surface. However, P_{AB} and P_{BC} were 77 and 59, and K was 18 compared to the knot portion. That is, although K was lower while sawing the knot part, it was still more than zero; but K was less than zero compared to the washboarding part.

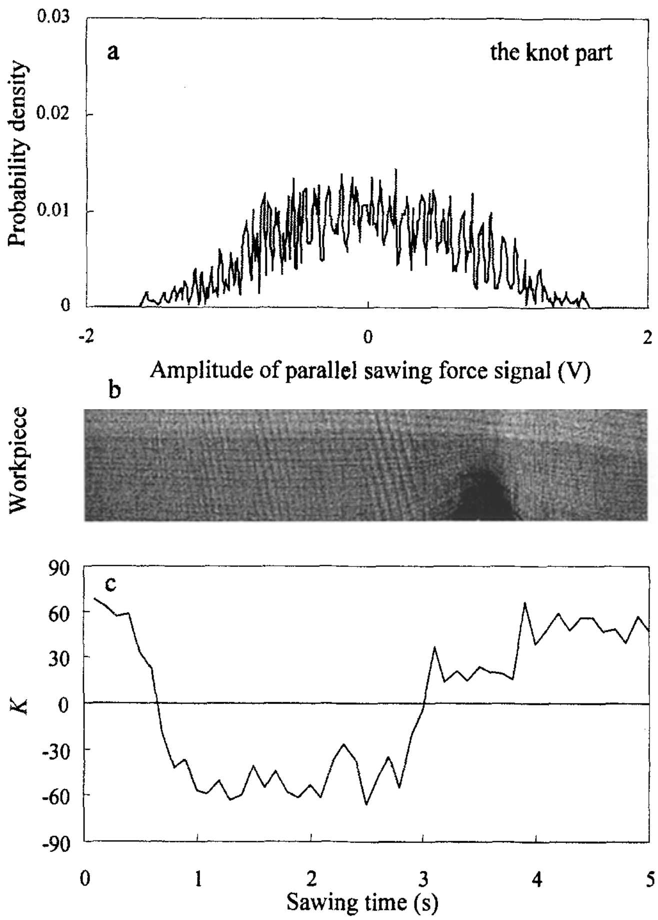

Fig. 10. **a** Curve of probability density distribution of the parallel sawing force to the knot part. **b** Situation of the sawn surface of the workpiece including the knot. **c** Behavior of *K* corresponding to the sawn surface. Washboarding did not appear on the knot part of the sawn surface

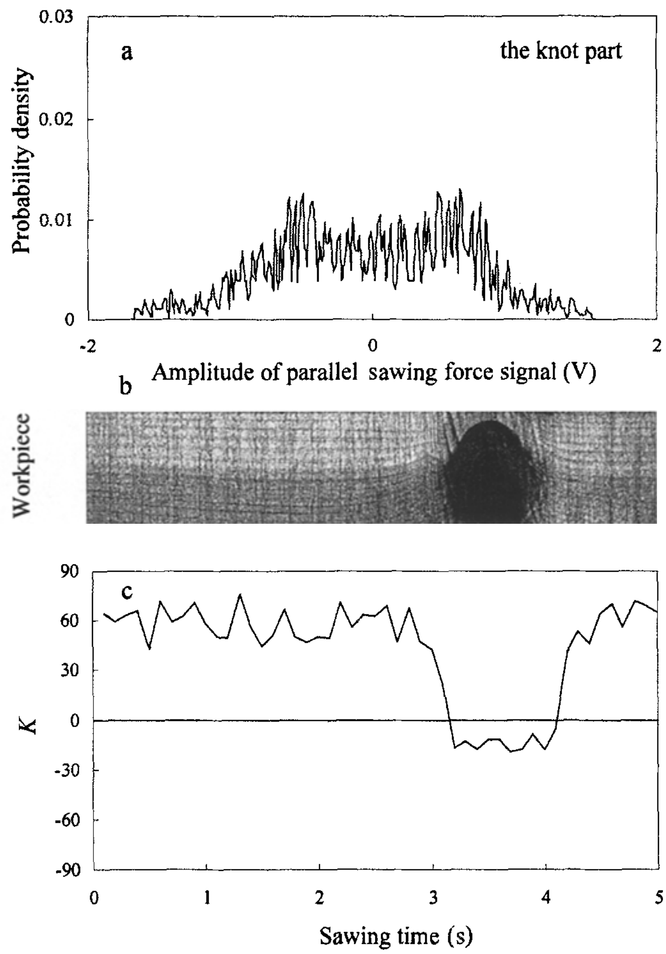

Fig. 11. **a** Curve of probability density distribution of the parallel sawing force to the knot part. **b** Situation of the sawn surface of the workpiece including the knot. **c** Behavior of *K* corresponding to the sawn surface. Washboarding appeared only on the knot part of the sawn surface

Figure 11 shows the curve of probability density function of the parallel sawing force to the knot portion (Fig. 11a), the situation of the sawn surface of the workpiece including the knot (Fig. 11b), and the behavior of *K* corresponding to the sawn surface of the workpiece (Fig. 11c). Washboarding appeared only on the knot portion of the sawn surface. *K* was less than zero corresponding to the washboarding part when the intervals for calculating *K* were 0–0.25 V and 0.25–0.50 V. These results indicate that whether *K* was above or below zero did not depend on the knot but on the washboarding on the sawn surface. It was thus proved that changes of wood structure, such as a knot, do not influence the use of parameter *K* for detecting the appearance of washboarding.

Conclusions

The conclusions obtained in this study can be summarized as follows.

1. The curve of probability density of the parallel sawing force obeyed a normal distribution for the normal sawn surface, but it changed to an M-shaped distribution when a washboarding pattern was induced on the sawn surface of the workpiece.

2. The appearance of washboarding on the sawn surface did not greatly influence the curve of probability density function of the normal sawing force. It showed a normal distribution for any sawn surface investigated.

3. It is possible to detect the appearance of washboarding automatically using a parameter based on the shape of the parallel sawing force amplitude distribution.

4. The knot did not influence use of the parameter for detecting the appearance of washboarding during the sawing process investigated.

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