NATURAL FREQUENCIES OF ROLL-TENSIONED CIRCULAR SAWBLADES: EFFECTS OF ROLLER LOADS, NUMBER OF GROOVES, AND GROOVE POSITIONS

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Roll-tensioning effects on natural frequencies in circular sawblades for woodcutting were investigated. Adequate knowledge of these effects will enable a more precise and repeatable tuning of natural frequencies, which will ease manufacturing and maintenance of sawblades. With natural frequencies tuned to not create resonance under running conditions, longer running times and more accurate cutting are made easier. The aim of this study was to find the optimum, or most suitable, tensioning parameters for a series of tested circular sawblades and also to draw general conclusions. The effects of the magnitude of the roller load, number of grooves, and groove positions were tested. The magnitude of the roller load was measured by using a universal load cell. The roll-tensioning effects were evaluated by measuring the shift in natural frequencies of several vibration modes. Finite element analysis was performed to model natural frequencies. The magnitude of the roller load, number of grooves, and groove positions all affected the natural frequencies. Natural frequencies obtained with the finite element method were in good agreement with the experimental test results.

Keywords: Roll tensioning; Finite element; Natural frequency; Vibration

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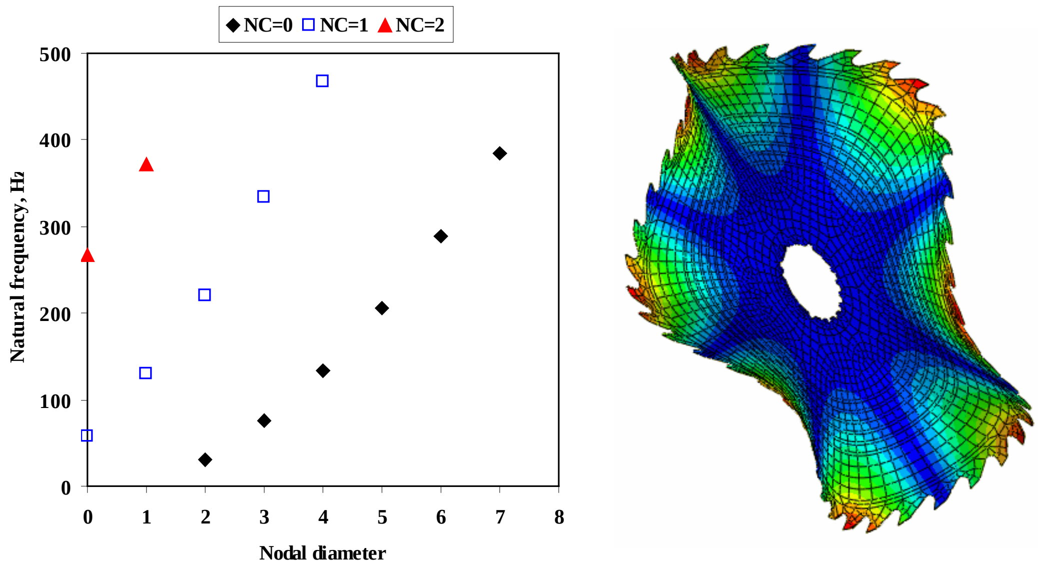
INTRODUCTION

A large amount of low-value sawdust is produced in sawmills during log conversion and lumber production. Much research has been conducted to increase lumber recovery by reducing the kerf width while maintaining productivity (feed speed) and dimensional accuracy. Reducing kerf width means reducing the thickness of the sawblades, which lowers natural frequencies, which, in turn, increases the risk of running into resonances (Lister *et al.* 1997). Running close to resonances causes increased vibration amplitudes, which increases the kerf width and causes poor dimensional accuracy. Tensioning of circular sawblades plays an important role for the performance, especially when using thin and large diameter blades. Its goal is to increase natural frequencies and thus, the gap between exciting frequencies during cutting and natural frequencies. However, excessive tensioning causes the sawblade to buckle (dishing) and unsuitable tensioning may reduce natural frequencies (Schajer and Kishimoto 1996).

Tensioning means introducing a state of residual stress, which affects the stiffness of the sawblade. Residual stresses are hard to measure directly, but since stiffness affects natural frequencies, the natural frequencies are an indirect measure of residual stresses and thus, tensioning (Szymani and Mote 1979). The natural frequencies and mode shapes define the dynamics of any structure. The number of nodal diameters (ND) and the number of nodal circles (NC) characterizes the mode shape for circular saw blades (Fig. 1). Natural frequencies of circular sawblades can be measured acoustically by using a microphone as a vibration sensor. Schajer *et al.* (2011) recently designed and built a prototype system that measures the natural frequencies and also identifies the mode shapes by using two microphones, one fixed and one rotating.



a) b)

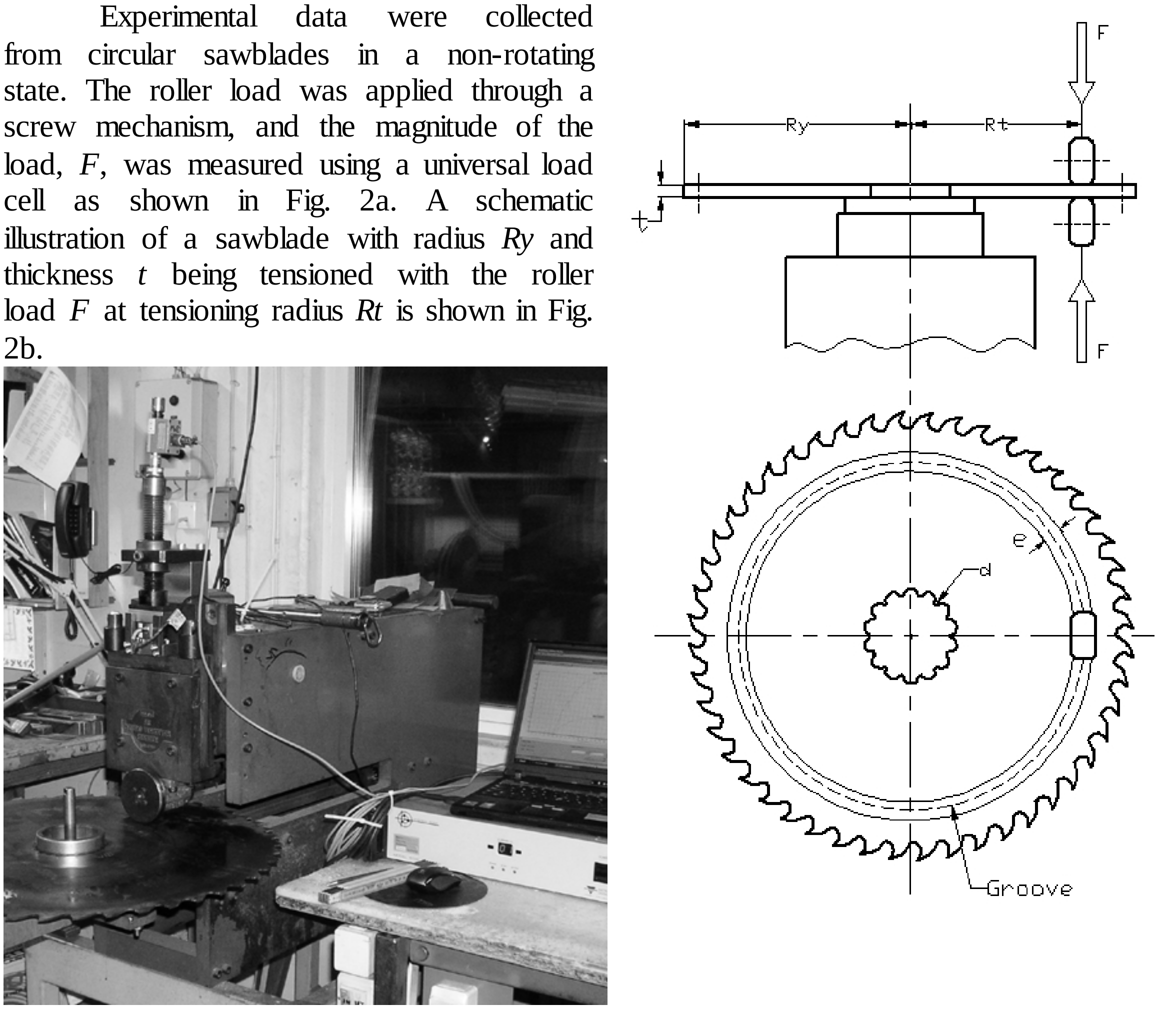
Fig. 1. Vibration mode shapes of sawblade after tensioning one groove: a) branches of nodal circles; b) illustration of ND = 4 and NC = 0

The largest vibration amplitudes appear for modes with a low number of nodal diameters and zero nodal circles. Mote and Szymani (1977) reported that the dominating sawblade vibration modes most often have zero to six nodal diameters and zero nodal circles. There are several ways of tensioning sawblades by either mechanical or thermal means. Roll-tensioning is widely used in sawblade factories and in sawmills. It has been reported by Stakhiev (1999) that the effectiveness of the roll-tensioning process depends on the diameter of the rolled track circle, the profile (cross section) of the rolls, the number of passes in a groove, the number of grooves, and the force of the rolls pressing against the sawblade. Also, a thermal tensioning process is possible, where stresses due to the temperature difference between the central area and outer rim were shown to improve the stability and cutting accuracy of clamped saws (Mote *et al.* 1981).

The purpose of this work was to find the optimum roll-tensioning parameters by varying the magnitudes of the roller load, tensioning radius, number of grooves, and distance between grooves. Here, finding the optimum means finding the right method, the right amount, and the right place to tension the blade in order to increase the margin to resonance as much as possible.

EXPERIMENTAL

Experimental data were collected from circular sawblades in a non-rotating state. The roller load was applied through a screw mechanism, and the magnitude of the load, *F*, was measured using a universal load cell as shown in Fig. 2a. A schematic illustration of a sawblade with radius *Ry* and thickness *t* being tensioned with the roller load *F* at tensioning radius *Rt* is shown in Fig. 2b.



a) b)

Fig. 2. Roll-tensioning of a sawblade: a) tensioning machine; b) schematic illustration

The dimensions of circular sawblades tested were: radius, *Ry*, 350 mm, thickness, *t*, 3 mm, bore diameter, *d*, 126 mm, and rake angle and clearance angle 15°. The tensioning radii, *Rt*, for all tests were set within the range of 117 mm (0.33Ry) to 273 mm (0.78Ry). Seven identical sawblades were tested and denoted A, B, C, D, E, F, and G. The sawblades tested had no inserted carbide tips. Schajer and Mote (1983) showed that saw teeth have negligible influence on the natural frequencies of circular sawblades and thus, the carbide tips must have negligible influence on natural frequency. The roller used for tensioning had a crown radius and a roll radius of 19.5 mm and 48 mm, respectively. The rolling was stopped after each complete revolution, and the blade was removed for examination. Each sawblade was rolled with a constant roll load, making one to five evenly spaced grooves (*Gr*) from inside to outside. Results were collected after each groove was rolled. The roller loads used were 10, 13.5, and 19.5kN.

Two methods of measuring the flatness of the sawblades were considered, namely an indicator gauge and a light-gap technique. The indicator gauge technique entails measuring the vertical displacement around the circumference when rolling the blade on a fixed plane near the center hole, as shown in Fig. 3. The light-gap technique entails measuring the flatness around the diameter with a ruler and manually looking at the light gap between the ruler and the blade. The indentation depth and groove width (*e*) left after tensioning of each sawblade was measured.

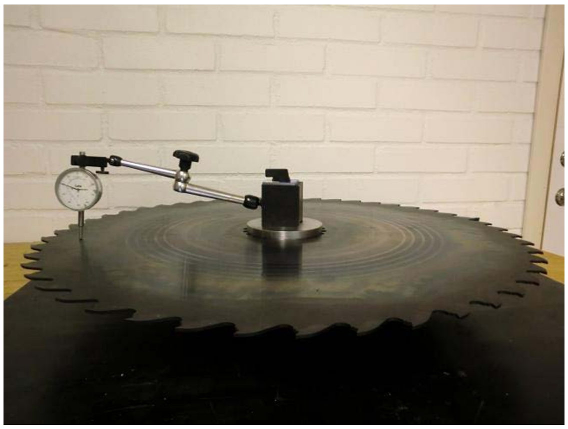


Fig. 3. Measurement of sawblade flatness

Fig. 4. Experimental installation for natural frequency measurement

In this study, the amount of tensioning was determined by measuring the natural frequencies of the free blades, as shown in Fig. 4, before and after tensioning. The non-rotating sawblade was excited by moderately hitting it with a wooden stick, and then the sound was recorded with a microphone, sampling rate 22050 Hz, 16 bit resolution. Finally a FFT (fast Fourier transform) analysis was conducted (16384 points, resolution 1.35 Hz) which showed the natural frequencies as amplitude peaks in the amplitude versus frequency diagram (Fig. 5).

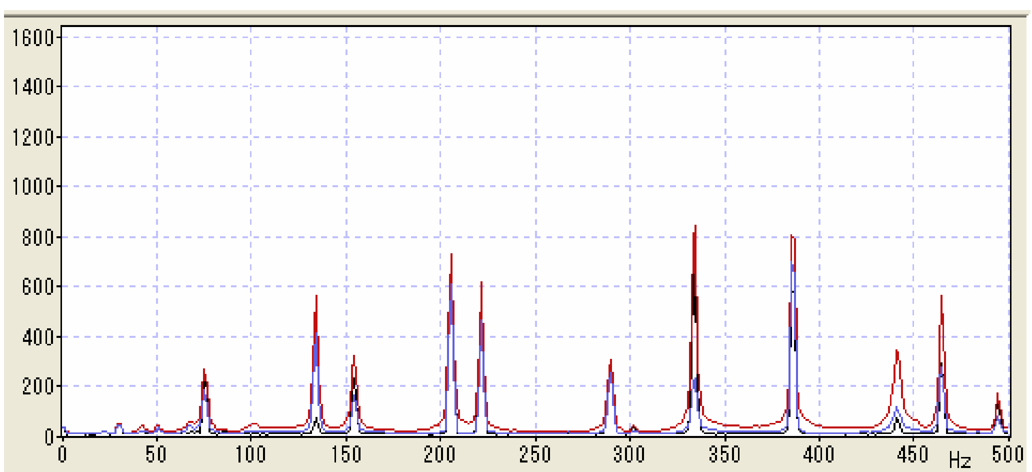


Fig. 5. Power spectrum of sawblade F after tensioning one groove

The natural frequencies of the sawblades were measured up to 500Hz. Mode shapes (number of nodal diameters and nodal circles) were not revealed directly by this method alone, but were instead determined by comparison with calculated mode shapes.

The FE (finite element) program Abaqus 6.10 (Simulia 2010) was used to calculate natural frequencies and mode shapes of the sawblades. Quadratic linear elastic elements were used and the boundary conditions were those of a completely free sawblade. Figure 1 shows an example of a mesh that was used. Tensioning was simulated by using a higher temperature in the grooves to represent the effect of residual stresses introduced by the rolling procedure. The groove widths in the calculations were set to the measured values 4.0 mm, 4.2 mm, and 4.5 mm for 10 kN, 13 kN, and 19.5 kN, respectively. A suitable temperature difference to use to simulate tensioning was determined by adjusting the calculated result to fit the test result for the lowest natural frequency, which had two nodal diameters and zero nodal circles. The temperature differences determined and used were 5°C, 35°C, and 75°C for tensioning forces of 10kN, 13.5kN, and 19.5kN, respectively. A detailed description of the tensioning method, using this approach, was reported earlier by Ekevad et al. (2009). The material properties used were an elastic modulus of $2.1 \cdot 10^{11}$ Pa, a Poisson's ratio of 0.3, a mass density of 7800 kgm^{-3}, and a coefficient of thermal expansion of $12 \cdot 10^{-6}$ C^{-1}.

Nodal diameters and nodal circles in the experiments were determined by comparing test results with calculation results. As only lower order vibration modes are of interest in the present analysis, the lowest eight nodal diameters were used.

RESULTS AND DISCUSSION

The untensioned sawblades were nearly identical when it came to untensioned natural frequencies (≤ 1 Hz difference in frequencies for the frequencies used for ND = 2), but they had some initial residual stresses, probably due to the manufacturing process. Frequency shifts due to these initial stresses were equal to or less than 8.0 Hz for ND = 2. This was revealed by comparing calculated frequency results with test results, and also qualitatively by using the opinion of a skilled sawblade filer who used his "feeling" for the sawblades. The effect of tensioning force on natural frequencies is presented in Figs. 6 through 8 for sawblades A, B, and C, which were tested with 10kN, 13kN, and 19.5kN, respectively. Five tensioning grooves were made for each sawblade from a tensioning radius of 117 mm (0.33Ry) to 157 mm (0.45Ry). The distance between grooves was 10 mm. For reference, the values of natural frequencies are presented as frequency ratios between tensioned and untensioned sawblades.

The frequencies for NC = 0 were in general raised by tensioning, and the frequencies for NC = 1 were in general lowered. A low tensioning force, as in sawblade A, gave a small increase in the natural frequencies for NC = 0. The highest rise in natural frequency for NC = 0 was observed when tensioning with a high tensioning force as in sawblade C. This highest tensioning force resulted in an indentation depth of less than 0.01 mm on each side of the sawblade and a groove width (*e*) of 4.5 mm. The rise in natural frequencies for NC = 0 produced by rolling five grooves in sawblade A was less than the change produced by a single groove rolled with 13kN, as in sawblade B. Also, the rise in natural frequencies for NC = 0 produced by rolling five grooves in sawblade B could be achieved by rolling two grooves in sawblade C.

It is interesting to observe that the values of natural frequencies for ND = 0 for NC = 1 were reduced very much with tensioning, and in particular the frequency for ND = 0 drops to zero (dishing) for blade C with five grooves. In contrast, the change in natural frequencies due to tensioning for NC = 2 in the tested sawblades was negligible.

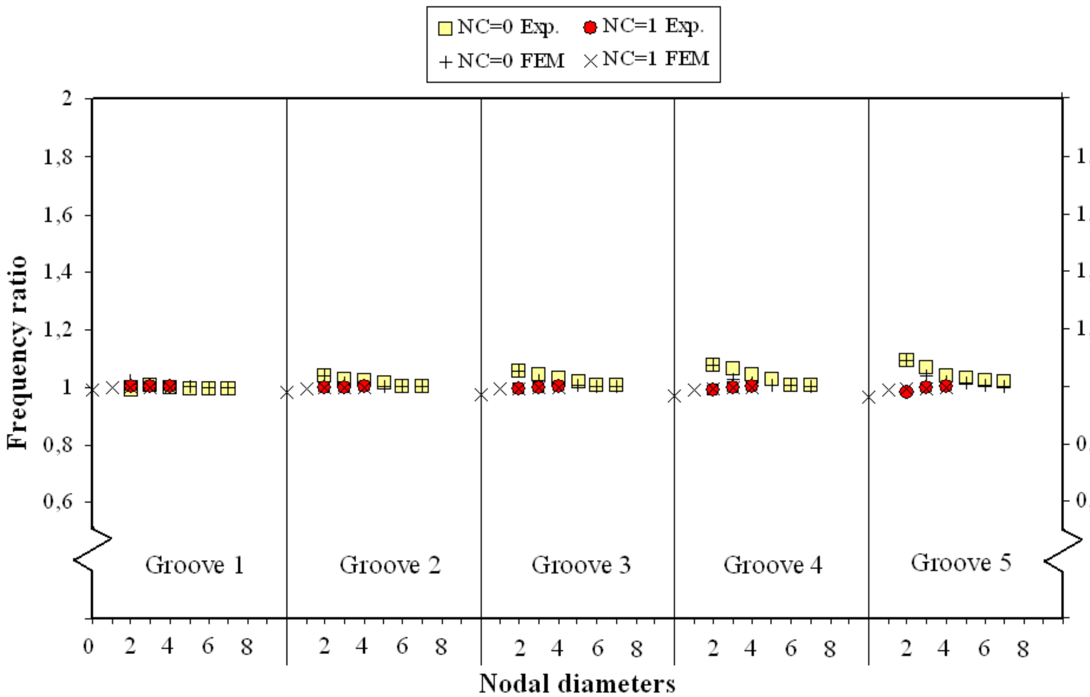


Fig. 6. Influence of tensioning force on natural frequency for sawblade A (10 kN)

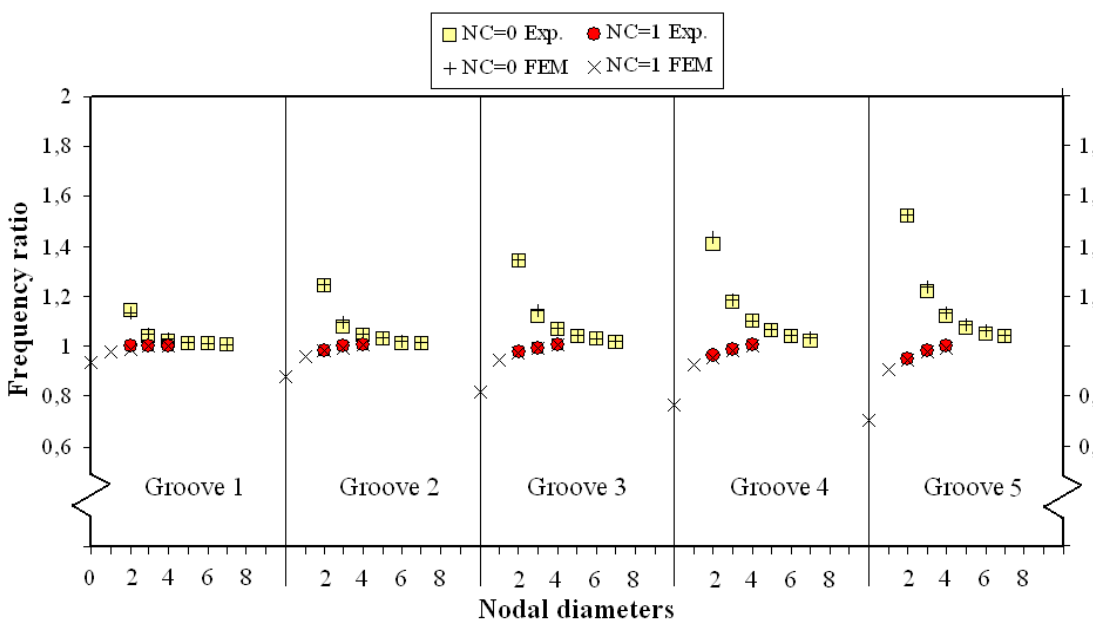


Fig. 7. Influence of tensioning force on natural frequency for sawblade B (13kN)

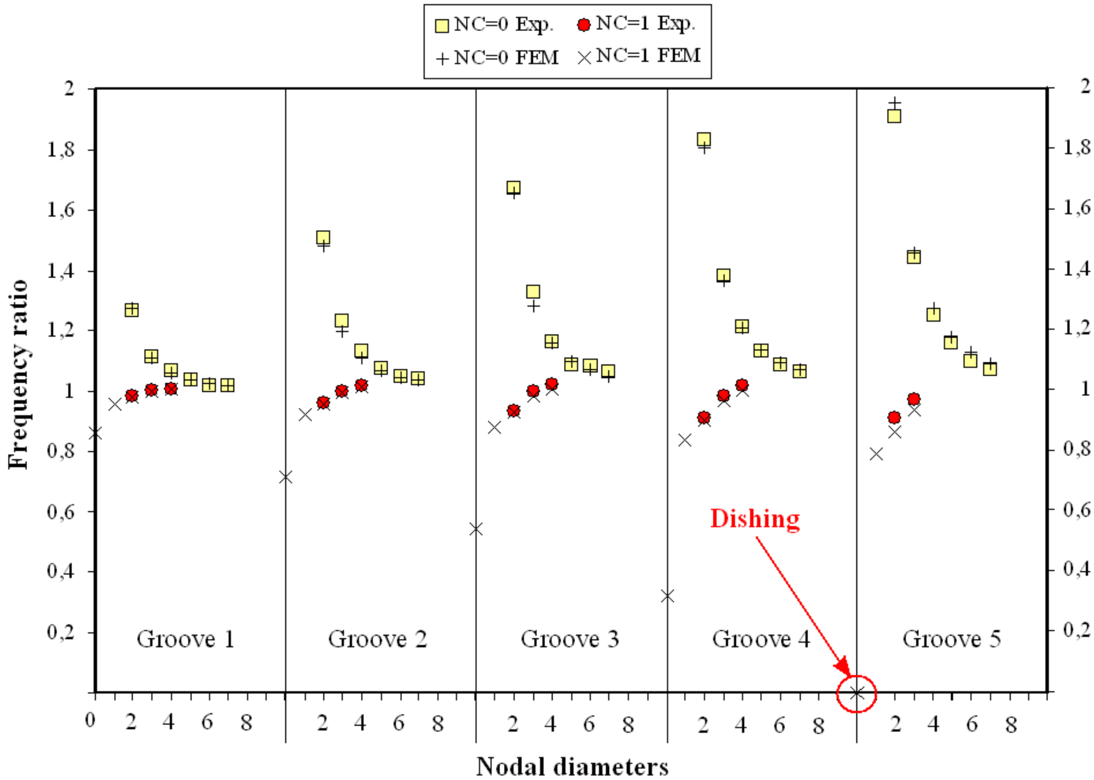


Fig. 8. Influence of tensioning force on natural frequency for sawblade C (19.5kN)

The natural frequencies measured are compared with those obtained from the numerical simulations. It can be seen that the natural frequencies obtained from the experiment were in reasonably good agreement with those obtained from the simulation.

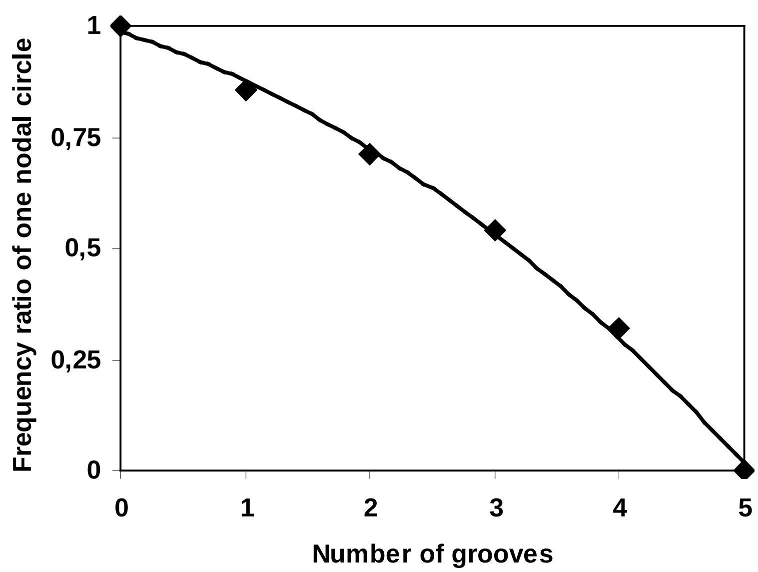


Fig. 9. Dishing phenomena

The dishing phenomenon was observed in sawblade C during tensioning of the fifth and last groove, *Gr* = 5 in Fig. 8. Excessive tensioning in its central area caused this phenomenon. It can be seen that the relative change in natural frequency for ND = 0 with NC = 1 with respect to the number of grooves was non-linear and was highest, 0.32, when tensioning from the fourth to the fifth groove (Fig. 9).

The sawblade was also evaluated by the light-gap method and the predicted dishing of sawblade C when it was tensioned with five grooves was also found in practice as a maximum flatness deviation observed by a gauge indicator of 0.1 mm. The allowed flatness deviation for sawblades of 350 mm radius was 0.18 mm, according to the tolerance stated by the sawblade manufacturer. The effect of dishing could be avoided if the tensioning of sawblade C was stopped at four grooves. However, it has been reported that sawblades that experience dishing will become flat when running at or above the dishing speed (Schajer and Kishimoto 1996).

Rolling loads of 13kN and 19.5kN were chosen as suitable for practical use for these sawblades. The choice of rolling load entails a compromise between the shifts in natural frequencies, time taken to perform the tensioning procedure, and avoidance of dishing. For example, the rise in natural frequencies produced by two grooves in sawblade C was similar to the rise produced by five grooves in sawblade B (Figs. 7 and 8). For practical reasons, it would take more time to achieve the same increase in frequencies by rolling a sawblade with 13kN (greater number of grooves) compared to rolling it with 19.5kN. Therefore, a tensioning force of 19.5kN was chosen for testing sawblades D, E, F, and G.

Sawblade D was tensioned between 175mm (0.5 *Ry*) and 215mm (0.61 *Ry*), that is, further outwards compared to sawblades A, B, and C. The distance between grooves was 10 mm. The results are shown in Fig. 10.

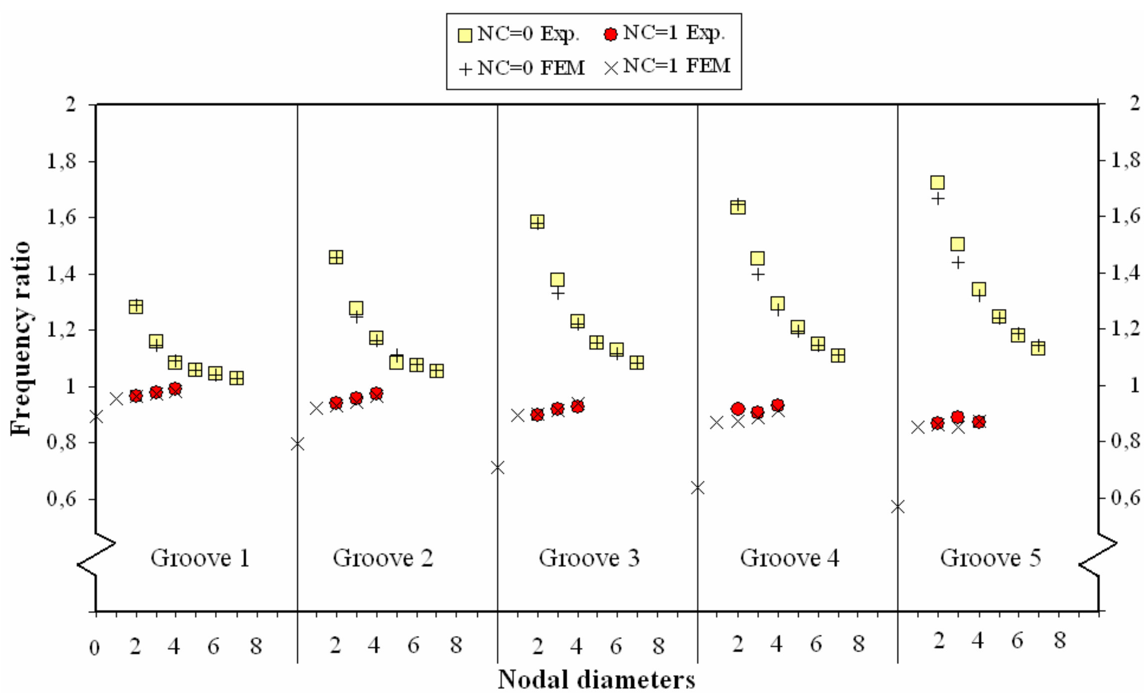


Fig. 10. Number of grooves and frequency ratios of sawblade D

The frequency ratios for five grooves for ND = 2 and 3 with NC = 0 became 1.79 and 1.50, respectively. The frequency ratio for ND = 0 with NC = 1 became 0.57. For the tested sawblade, the greatest change in natural frequencies was observed during tensioning with the first three grooves. The magnitude of the change in frequency ratio given by grooves 4 and 5 was very small (≤ 0.08 for ND = 2). In general, sawblade D had smaller changes in natural frequency than sawblade C when they were both tensioned with the same force. The simulation results are also shown for reference, showing that the assumptions made for the simulations are feasible.

Two sawblades, E and F, were tensioned from 175 mm (0.5 *Ry*) and outwards with evenly spaced grooves with distances between them of 7 and 14 mm, respectively. The results showed a negligible difference in the magnitude of change in natural frequencies (≤ 2 Hz for ND = 2) compared to sawblade D, which had a distance of 10 mm between grooves.

Sawblade G was tensioned using grooves from 233 mm (0.67 *Ry*) to 273 mm (0.78 *Ry*), which were the outermost positions used in these experiments. The distance between grooves was 10 mm. Figure 11 shows the frequency ratio for ND = 2 to 7 with NC = 0 and how it varies with increasing number of grooves. Lines for illustration purposes only connect the values of natural frequency ratios; the lines do not mean anything else, as the number of grooves is a discrete number. The results illustrate the existence of a limit between increasing (tensioning) and reducing (detensioning) the natural frequencies of the sawblade. In this work, this limit was called the critical tensioning radius (*Rtc*). *Rtc* is different for different modes and here it was determined for ND = 2 and ND = 3.

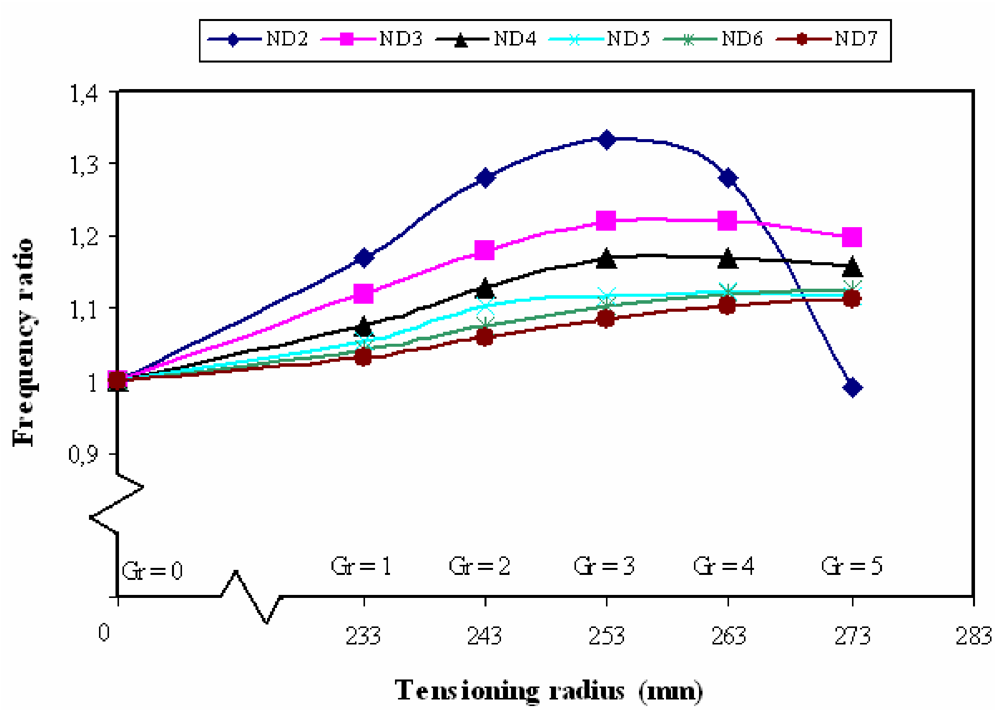


Fig. 11. Critical tensioning position for NC = 0 for blade G

The critical value of *Rt* for the tested sawblades was 253mm (0.72*Ry*). Tensioning the sawblade G to the critical radius (*Gr* = 3) resulted in a 33.5% rise in the frequency for ND = 2.

From the graphs presented above and knowledge of the operational rotation speed, the proper amount of tensioning force, number of grooves, and tensioning radius to use can be decided. Thus, a good cutting performance can be achieved. The results presented are for a specific geometry of sawblade and roller. Future work will be carried out to examine the effect of tensioning different geometries of circular sawblades.

CONCLUSIONS

1. The highest rise in natural frequencies when tensioning was found for ND = 2 and 3 for NC = 0. Frequencies for NC = 1 were lowered slightly by the tensioning procedure except in the case of ND = 0, for which they were lowered considerably.
2. Natural frequencies obtained with FEM using the temperature method were in good agreement with the experimental natural frequencies.
3. The most effective roller load among those tested was 19.5kN.
4. The critical tensioning radius was found to be 253 mm (0.72 *Ry*).
5. The effect of tensioning using many grooves was highest for the first two to three grooves and lower for the fourth and fifth grooves.
6. The distance between grooves showed a negligible influence on the variation in natural frequencies when the sawblade was tensioned in the range from 175 mm (0.5 *Ry*) to 231 mm (0.66 *Ry*).

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