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PREDICTION OF TIMBER TWISTING BASED ON MEASURED SPIRAL GRAIN OF SPRUCE TRUNKS AND LOGS

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ABSTRACT: This work focuses on the prediction of timber (beam) twisting based on the measurement of spiral grain under the bark of spruce trees (using Fakopp) and the subsequent measurement of spiral grain of logs during manipulation using a slope of grain detector. When selecting wood, it is necessary to take account of the effect of spiral grain on sawing; based on international practice, a spiral grain up to 5% deviation per 1 m of log length is not considered a defect. However, it is important whether the spiral is left-handed or right-handed, as measured on the log perimeter. Left-handed spiral increases after log processing while right-handed spiral decreases. The perimeter of an element from a left-handed log that was within the acceptable 5% angle deviation per 1 m of length manifests a considerably higher deviation when machined, which markedly affects the timber twist during drying. By contrast, beams from right-handed logs with up to 5% deviation per 1 m of length have perimeter without spiral grain, and they are not defected by twist during drying. This phenomenon has been confirmed by the study conducted. Further, a good prediction of spiral grain in trees has been achieved using non-invasive equipment, Fakopp ArborSonic Microsecond Timer.

KEYWORDS: Timber, spiral grain, twist, structural repair.

1 INTRODUCTION

All trees (and also Norway spruce) can contain spiral grain under the bark. Spiral grain trees have better resistance to strong wind and it helps them prevent breaking. When straight grain trunks are loaded, the side closer to the loading force is under tensile stress while the other side is compressed, which causes tension. In spiral grain trunks, the compression and tensile forces are transferred along the spiral to the other side of the trunk, which balances the tension. Many trees begin to grow twisted under the strong pressure of wind and snow. Under such conditions, the grain can deviate up to 30° from the vertical direction of growth. This twisted growth provides the tree with a better protection against mechanical damage; it can be considered a type of protective response [1].

If a tree grew perfectly straight, only the needles above the roots would receive water from them, and the roots directly below the needles would receive nutrients. Damaged roots on one side would then lead to dying of branches on that side. Twisted trees supply water from one root to all the needles, and conversely, nutrients from one branch flow to all the roots [2].

Twisted growth means spiral grain along the pith. In the saw machining practice, the spiral grain within 5% of angle deviation per 1 m of length is not considered a defect, which is very tolerant and often unacceptable for the final user of the timber as the product is damaged by twist. The reasons for spiral grain vary, slanting of cambial cells is most often mentioned. Cambial cells - spindle-shaped initials - are elongated and capable of coordinated reorientation in response to internal and external stimuli. Their intensity decreases rapidly as the tree ages [3]. The bark is very different in this respect because it is produced outside the vascular cambium, without the oriented spindle cells [4]. Therefore, it is not possible to predict the twist on logs without debarking.

The direction of the spiral grain can be left-handed, right-handed, or there is straight grain. The spiral can change along the trunk and there is no regularity. Across the trunk, it can change from a left-handed to a right-handed spiral from the pith towards the perimeter [5][6]. In Norway spruce, the left-handed spiral is usually the greatest in the 4th to 10th tree ring, counted from the pith. Subsequently, the spiral usually decreases and the spruce becomes straight-grained somewhere between the 40th and the 70th tree ring [7]. With the increasing number of tree rings within the rotation period, the spiral gradually turns to the right. This pattern applies to all species within the *Picea*, *Abies* and *Larix* families, plus almost every member of the *Pinus* family [8].

Spiral grain is usually found in trees growing in sparse stands and in avenues of solitary standing trees, which testifies relation to the tree growth speed [9]. This suggests that the decrease in spiral is not only related to

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the effect of tree age or diameter, but may be influenced by the availability of nutrients and water to stimulate growth. The effect of wet snow and high winds on the spiral degree has been presented in the past [10], [11].

The spiral grain direction is the same whether you look from the crown to the roots or vice versa. Therefore, the spiral grain direction can be established also for short logs where the bottom and the top cannot be determined.

For Norway spruce, the undesirable left-handed spiral mainly appears in young trees, that is why timber from thin trunks twists more often than that from trunks from a mature stand [12]. Therefore, the central (juvenile) part of spruce logs is not suitable for use as structural timber. The general impact of spiral grain on timber utilization depends on the rate and duration of the development from the pith towards the cambium [8].

The spiral grain may have a considerable impact on the timber behaviour during drying, particularly twisting [13]. In consequence, the angle of spiral grain is an important parameter for each model that aims to describe the sawn timber deformation after drying and the subsequent moisture content changes during storage and use. The higher the spiral grain angle, the greater the timber twist when drying [15], [16], [17].

Various techniques have recently been proposed to determine the degree of the spiral, e.g. [18] developed an automated method for measuring twist on logs; the method uses the light-conducting properties of softwood tracheids to measure the grain orientation on the external side of debarked logs. This method has enabled high resolution measurements over large areas and segregation of material with visible spiral. The applicability of visible light and laser is limited by the presence of bark on the log [19].

Other non-destructive methods for measuring spiral of logs, e.g. using X-rays are presented by authors [20], [21]; use of microwaves is presented in [22], [23]. These techniques require expensive equipment and powerful mathematical modelling; yet, they are increasingly commercially applied. The variation there is up to 10 degrees. The most accurate method to determine the spiral is splitting [24].

A very precise yet simple method is pressing a sharp tip into the wood surface and marking the longitudinal direction of the grain with a slope of grain detector [25]. The slope of grain detector consists of a steel rod, which is loosely placed in a rotating wooden handle at one end, with a needle (tip), which is pressed into the wood, protruding at the other end. This simple tool allows for satisfactory results and can be used with great accuracy if its limitations are understood and measures are taken to eliminate them.

The tendency for spiral grain of tree trunks can be detected directly under the bark or can be seen in the roots [26] and also branches [27]. The spiral grain estimation from branches was used in the past by shingle manufacturers, who thus eliminated unsuitable left-handed logs. However, research has shown that the spiral of branches and trunks is not identical. For example, [27] took detailed measurements of 11 *Larix kaempferi*, *L. gmellinii* trees and found that the mean values for spiral and their standard deviations were twice as large in the trunk as in the branches.

The processes used to detect the spiral grain direction of wood need not be applied to sawn timber or debarked logs only. Some methods can be used for standing trees without permanent damage, e.g. bark stripping. [28] used ultrasonic testing equipment Pol-Tek to determine the direction - sound pulses propagate at maximum speed in the direction along the grain. Our measurements, made by indenting probes through the bark of standing trees, showed the method applicability to determine the spiral grain direction on the tree trunk perimeter under the bark with an accuracy approaching 90 %.

The study reported here was designed to provide information on the spatial variation in Norway spruce trunk spiral grain, using:

- the prediction of spiral grain based on trunk measurement by stress-wave;
- the prediction of timber twisting during drying based on trunk measurement by stress-wave;
- the prediction of timber twisting during drying based on sawlog measurement by a slope of grain detector;
- the prediction of timber twisting during drying based on the actual timber measurement by a slope of grain detector.

Thirty spruce logs from 22 trees were examined to improve our understanding of the spatial variation of spiral grain within a trunk and the ability to predict it given the potential distortion of beams during drying.

2 SPIRAL GRAIN MEASUREMENT

For the purpose of the experiment, the spiral grain was measured in 22 selected trees of Norway spruce (*Picea abies* (L.) H. Karst.) from the forest stand near Oblajovice municipality, which is a part of Natural Park Polánka, in the western part of the Českomoravská vrchovina Highlands (central area of the Czech Republic). The trees grew at an altitude of 650 m a.s.l., i.e. at the bottom line of Norway spruce natural occurrence. The selection of the trees was carried out with exclusion of damaged trees and other defects arising during tree growth (swollen rootstock, crooked trunk, cracks, branched lower part of the trunk, etc.). The breast height diameter of the trees ranged between 40 cm and 60 cm. After harvest, 6m logs were cut out.

The spiral grain was measured at the breast height by means of Fakopp ArborSonic Microsecond Timer. This device is supplied to the market by the Hungarian manufacturer Fakopp Enterprise. The principle consists in measuring the passage time of a stress wave through the trunk [29]. The equipment uses push-in sensors that provide the signal transfer and the contact with the wood. The wave passes through material in a constant speed, the frequency depends on the hammer force on the sensor head. The push-in sensors are fitted using a specialised template (Fig. 1) 50 cm apart from each other in the trunk longitudinal axis and 5 cm far from the trunk axis at the same time, so that the top sensor (excitation) is displaced to the left and the other sensor (receiver) to the right. This sensor placement allowed measuring the speed in the left-handed direction. When the sensors were changed to

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measure the right-handed direction, the top sensor was placed 5 cm to the right from the longitudinal axis and the lower sensor 5 cm to the left (Fig. 2).

Figure 1: *Measuring the tree spiral grain in the bark by means of Fakopp ArborSonic Microsecond Timer and a template*

After the time of stress wave passage through the left- and right-handed placement of sensors was measured, the propagation speed (m.s^{-1}) was calculated. The difference between right- and left-handed speed measurements were correlated with the real slope of grain on logs after harvest using the slope of grain detector (Fig. 3), consisting of a wooden handle in which a metal rod is inserted so that it can turn freely. The rod is bent in the right angle and its tip is fitted with a metal spike.

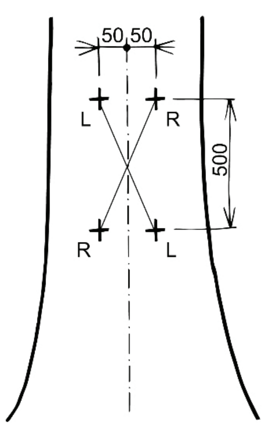

Figure 2: *Positions and placement (mm) of sensors for measuring the stress wave propagation speed in the longitudinal direction of the tree (L-left-handed and R-right-handed measurements)*

Before the slope of grain detector was used, the bark had been removed with a drawshave and the log axis had been marked with a carpenter pencil and a ruler. Then the spike was pushed in the axis marked on the trunk and the real grain deviation was carved. The grain deviation from the log longitudinal axis (mm/m) was measured along a distance of 20 cm and then calculated per 1 m of length, as standards apply, e.g. EN 1310:1997 [31]. The spiral grain established by means of the slope of grain detector was measured on both ends of 6m logs and then averaged for each log. In the case of trees with a large diameter, two 6m logs were used for the measurement: 0-6 m of the tree height (22 pcs) and 6-12 m of the tree height (17 pcs), 39 logs of spruce in total. The diameter of the upper logs had to be large enough to yield a beam of 20×25 cm profile. I.e., the log diameters corresponded to the common processing procedure, in which sometimes two 6m logs are taken out from one tree and sometimes only one is possible. The condition was applied that the final sawmill product (20×25 cm structural beam) needs to have sharp edges without rounding.

Figure 3: *Measuring the spiral grain under the bark by means of slope of grain detector*

When the measurement of logs was finished, they were sawn into 20x25cm beams, 6 m long, which were stored in a pile and dried in a natural way to 16% moisture content. Out of a total of 39 spruce logs, 30 were used for sawing. The naturally dried beams were subjected to twist measuring: one end of the beam was stabilised in the vertical position using a spirit level and the twist deflection was measured on the vertical surface of the other beam end (Fig. 4). The measured deflection was used to calculate the twist angle of the naturally dried beams.

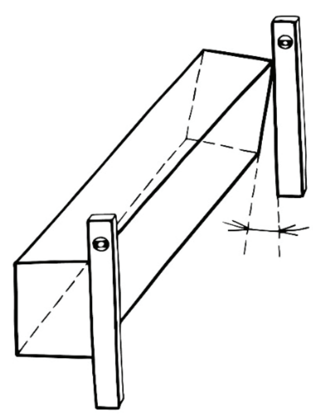

Figure 4: *Measuring the twist angle of beams after natural drying using a spirit level*

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3 RESULTS AND DISCUSSION

Recently, emphasis has been placed on the quality of timber, which is dependent on our understanding of spiral grain and its effect on sawmill products [32]. The selection of suitable logs based on the determination of the spiral grain and a prediction of timber behaviour during processing are essential for processing. In this study, a non-invasive approach of detecting spiral grain directly on the tree using the Fakopp 2D instrument has been proven to be effective; the probes of the instrument are arranged in an X-shaped pattern at the breast height of the trunk, i.e. both left- and right-handed directions of stress wave propagation are covered (Fig. 2). The differences in the propagation speed of the stress wave in both directions can predict the direction and especially the degree of the spiral grain with an accuracy of R^2=0.93, which is confirmed by the results presented in Fig. 5. The high accuracy is related to the bottom log, i.e. 0-6 m from the tree base. In the case of the spiral grain prediction for two 6m logs (0-12 m tree height), the coefficient of determination decreases slightly R^2=0.87 (Fig. 6.) In the case of predicting spiral grain only for the upper log (6-12 m tree height), the coefficient of determination is R^2=0.78 (Fig. 7).

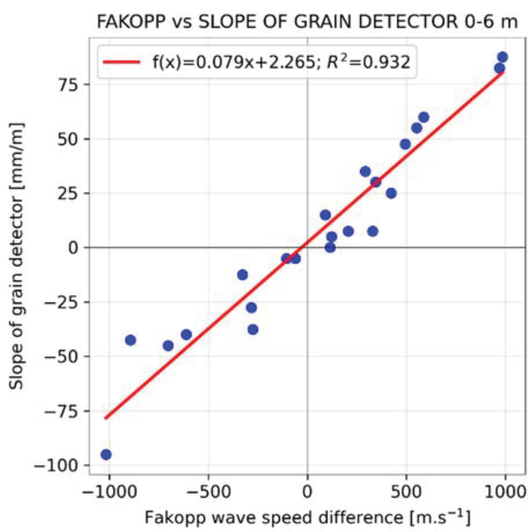

Figure 5: Dependence of the difference in longitudinal stress waves speed from Fakopp measured at tree breast height compared to spiral grain as measured by the slope of grain detector, measured on logs 0-6 m from the tree base

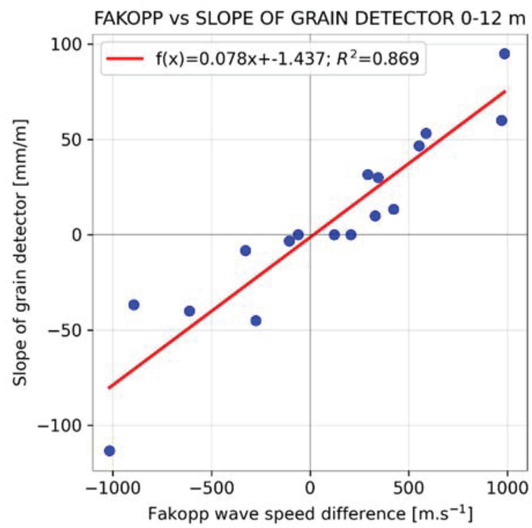

Figure 6: Dependence of the difference in longitudinal stress waves speed from Fakopp measured at tree breast height compared to spiral grain as measured by the slope of grain detector, measured on logs 0-12 m from the tree base

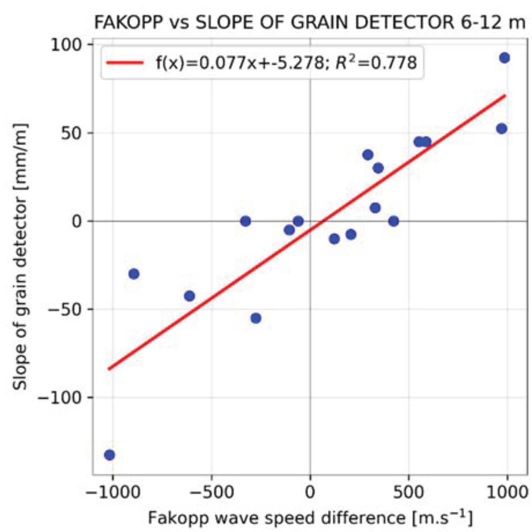

Figure 7: Dependence of the difference in longitudinal stress waves speed from Fakopp measured at tree breast height compared to spiral grain as measured by the slope of grain detector, measured on logs 6-12 m from the tree base

When trying to predict the timber twisting (0-6 m from the tree base) after natural drying from the differences in the stress wave propagation velocity for the two directions of spiral grain measured using the Fakopp 2D instrument, the coefficient of determination is R^2=0.81 (Fig. 8). The upper logs (6-12 m from the tree base) yield an even better coefficient of determination: R^2=0.92 (Fig. 9), and the combined logs (0-12 m from the tree base) reach a coefficient of R^2=0.95 (Fig. 10).

The graphs show that for left-handed spiral, we can accept speeds of up to 250 $m.s^{-1}$ when predicting the spiral grain from differences in the stress wave speed, in order to avoid the undesirable twist (greater than 5° in a 6 m long log) when drying the timber. Speed differences for left-handed spiral greater than 250 m.s-1 mean that such timber should be avoided as it will represent significant loss caused by material acquisition and cutting costs. On the contrary, the differences in the stress wave speed in the case of right-handed spiral indicate that the twist of the sawmill product will be minimal even if the differences in measured speeds reach 1000 m.s-1(Fig. 8-10).

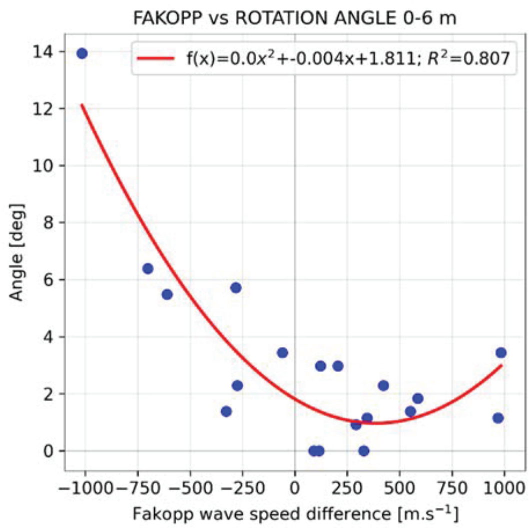

Figure 8: *Dependence of the difference in longitudinal stress wave speeds from Fakopp measured at the breast height compared to the twist of a 20×25×600 cm beam from a log cut at 0-6 m from the tree base*

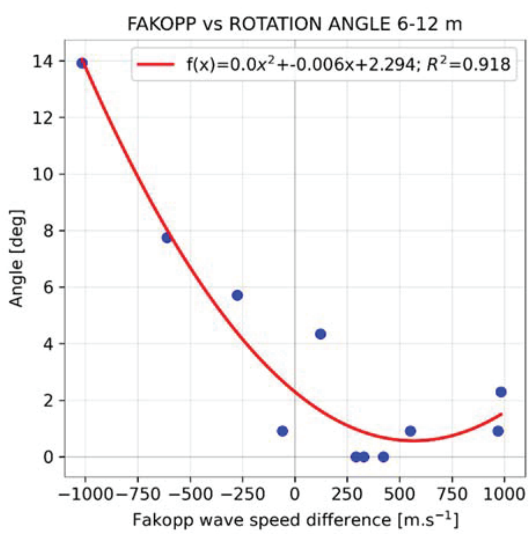

Figure 9: *Dependence of the difference in longitudinal stress wave speeds from Fakopp measured at the breast height compared to the twist of a 20×25×600 cm beam from a log cut at 6-12 m from the tree base*

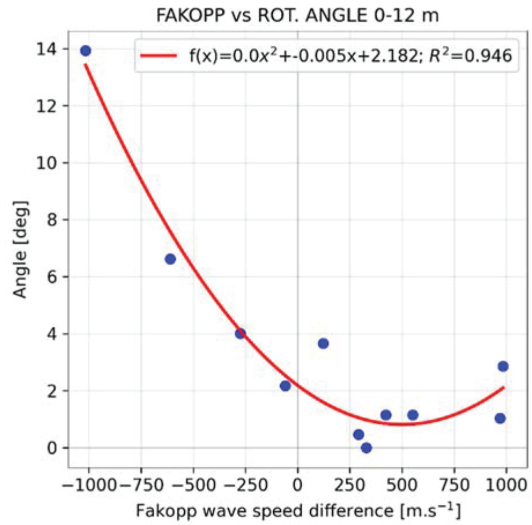

Figure 10: *Dependence of the difference in longitudinal stress wave speeds from Fakopp measured at the breast height compared to the twist of a 20×25×600 cm beam from a log cut at 0-12 m from the tree base*

The above dependences between the differences in the stress wave speeds measured on a tree with the Fakopp 2D instrument and the beam twisting show that this is a very accurate prediction, which can be obtained directly in the forest using totally non-invasive measurements on the tree. The prediction accuracy is also confirmed by the following graph in which timber twisting is in direct dependence on the spiral grain as measured by the slope of grain detector on logs - the coefficient of determination reaching R^2=0.82 (Fig. 11). It is therefore a prediction that can be carried out in the storage facility or directly in the forest during harvest.

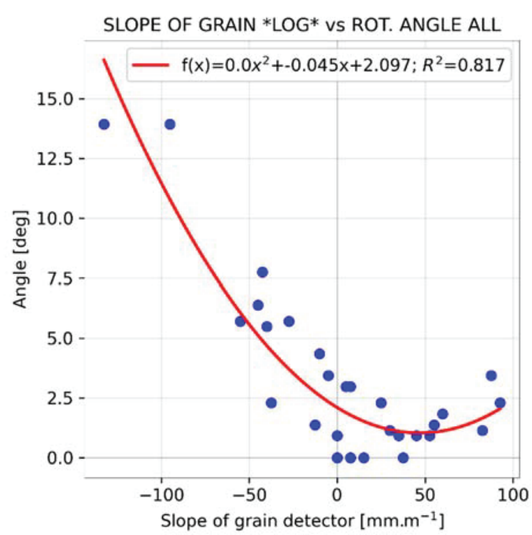

Figure 11: *Dependence between the spiral grain measured by the slope of grain detector in a 6m log and the timber twisting*

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The coefficients of determination reach a similar level to the prediction of speed differences using stress waves measured directly on the tree. In order to gain a twist of maximum 5° per length in a 6m beam, the grain deviation of the left-handed spiral can be 25 mm/m at maximum (Fig. 11). On the other hand, in the case of right-handed spiral, grain deviation detected by the slope of grain detector can be as high as 75 mm/m, and the beam twist will meet the maximum tolerance of 5°.

Therefore, it can be argued that spiral grain and the resulting problems with timber processing for construction purposes can be eliminated directly in the forest when selecting trees, or later in a storage place. Naturally, this concerns small volumes, for example, when selecting timber suitable for repairing structural elements of roof trusses, ceilings or other parts of historic buildings. The results of this study show that the spiral grain is an important variable affecting the twist of timber. Data analysis shows that the direction of spiral and its deviation have a significant effect on the twisting. The data on spirals show that the spiral pattern across the trunk starts from an initial left-handed direction, gradually decreases towards the log perimeter, and in about half of the cases it turns into a right-handed pattern, as already suggested by [13], [14], [17]. The above statement can be supported by the dependence between the grain deviation determined by the slope of grain detector directly on the beam and its twisting during natural drying (Fig. 12). The spiral grain variance at the same angle of beam twist is the same for the left-handed and right-handed sides (ideally 0 mm/m). This is different from the spiral grain found on the perimeter of logs, where the ideal degree was around 40 mm/m to the right.

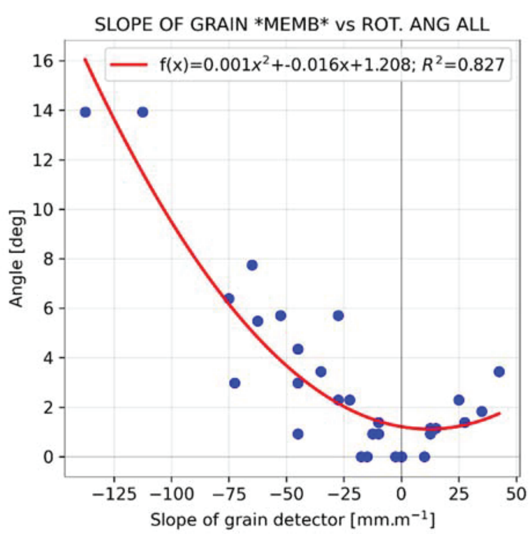

***Figure 12**: Dependence between the spiral grain measured by the slope of grain detector in a 6m beam and the beam twisting*

Previous observations suggested a shortage of straight-grained spruce timber [7]. This finding was confirmed in this study by measurements of 6m logs. Right-handed logs have greater torsion stability than left-handed logs. A likely reason for the greater stability in timber made from logs with a right-handed twist on the perimeter is the balancing of the shrinkage stress during drying [8]. The shrinkage stresses should work against each other, right-handed wood on the log perimeter against the left-handed wood in the central part of the log.

On the other hand, the logs that showed a left-handed spiral grain on the perimeter twist to the left with nothing to prevent them, after the required 20×25cm beams are made. The degree of spiral grain has also been proven to have a significant effect on the timber twist. In addition, previous research shows that left-handed wood has lower strength [21], [33].

4 CONCLUSIONS

The aim was to test the hypothesis that timber selection based on spiral grain measurement on the trunk surface can considerable help reduce the number of sawn timber prone to twist. The quality of timber is markedly affected by the wood spiral grain, which can be non-destructively investigated as early as during the selection of trees in a stand. Fakopp ArborSonic Micosecond Timer proved to be a suitable tool for the spiral grain determination through stress wave propagation speed measurement. The differences in stress wave propagation speed for the left- and right-handed directions, as measured at the breast height, allowed determining the spiral degree with up to 93% accuracy for 6m logs. The impact of left-handed spiral grain on the twist of timber during drying has been confirmed. The optimum log spiral grain proved to be in the range of 0 to 75 mm/m towards the right, then the twist during drying of the structural beams reached a maximum of 5° per 6 m of length. In the case of 0 to 50 mm/m slope of grain to the left, the logs are prone to twist, reaching 7,5° per 6 m of length. A grain deviation greater than 50 mm/m to the left represents a serious damage to timber and this cannot be used for structural purposes.

The problems of timber twisting during the drying process was pointed out by [7], [8], [13], [14]. A possible option to counter the damage is to reduce the tolerance in timber grading. Our recommendation for the production of structural members is to limit the use of logs with a left-handed spiral grain from the 50 mm/m stipulated in standards to 25 mm/m. In the case of right-handed logs, the spiral grain of 50 mm/m is usable as the twist of the final structural member reduces to required deviations close to 0°.

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