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Three-Dimensional Spiral Grain Pattern in Five Large Norway Spruce Stems

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There is a great deal of interest involved in investigating and understanding grain angle in trees. The objective of the study presented in this paper has been to identify a joint, three-dimensional model for grain angle in stems of Norway spruce (*Picea abies* (L.) Karst.) Five large spruce trees were sampled. Transverse disks were extracted at regular intervals along the stem, split through the pith with a blunt knife, and observed for grain angle and cambial age along the north radius, setting pith observation to zero angle. The overall finding confirmed grain pattern congruent to distance from pith along the stem, a pattern that varies from tree to tree. Models expressing distance from the pith in cambial age performed slightly better than models in spatial distance. Grain pattern changed slightly along the stem, and this change was found to be consistent for the five stems: the left-handed grain angle in the juvenile wood was more pronounced upwards in the stem, and the angle changed faster towards right-handed spiralling. The model did not account for grain variation related to knots, undulating pith or other irregularities. Model residuals were normally distributed and seemingly homogeneous for all trees and for all height levels. The model is an extension of existing two-dimensional models for stem cross-cuts. After verification in a wider sample, the results should be applicable in tree and wood modelling.

Keywords grain angle, 3D-model, tree helix, split disk
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1 Introduction

Grain helixes as a phenomenon have engaged wood technologists and tree physiologists as well as building engineers and scanner scientists. Most commercial grading rules restrict the slope of grain in sawn timber. Any pronounced grain angle will reduce sawn timber bending strength and stiffness (Bodig and Jayne 1993, Pope et al. 2005) and increase warp (Rault and Marsh 1952, Forsberg 1999). Rejecting logs with left-handed spiral grain angles exceeding 3° has been proposed to improve the number of accepted studs in terms of twist (Johansson and Kliger 2000). If known prior to conversion, grain angle should be taken into account when deciding the actual timber to be produced from each log. For this reason, the efficiency of automated scanner systems for grain angle detection in timber is now being investigated (Sarén et al. 2006, Nyström and Grundberg 2007, Bucknowitz et al. 2008). A recent doctoral work (Sjödén 2008) evaluates application of electromagnetic wave scattering and polarisation for revealing grain angle in stems. Any of these methods might find industrial application in the near future.

The term spiral grain is used in two distinct yet related senses. Some people tend to restrict the use to the infrequent, severe grain angle seen on the surface of a few, usually quite old, trees, while others include grain deviation regularly occurring inside any stem, noticeably in the juvenile wood in softwoods, in the definition. The two are connected through the continuous change in the grain angle during the lifetime of any tree (Gjerdrum et al. 2002). The change in grain angle has traditionally been attributed to the pseudotransversal and anticlinal divisions in the vascular cambium (Larson 1994). Despite intensive research, the fundamental cause of grain angle changes in individual trees has remained much of a mystery. Several models have been proposed. One model presents spiral grain as allowing the root of a tree to distribute sap uniformly to all branches, even in partly damaged stems (Vité and Rudinsky 1959, Kubler 1991). Another model is founded on the hypothesis that spiral grain will improve the ability of a tree to withstand torsion induced in an asymmetric crown by wind (Skatter and Kucera 1997, Eklund and Säll 2000). Recently a new explanation was presented: "A constant, incessant tendency of all maturing cells (which are predominantly the result of periclinal divisions) to change their orientation in a given direction. … Thus it is concluded that neither the slant of pseudotransverse divisions nor other "isolated events" (imperfect periclinal division, biased intrusive growth) are causative, but that they rather result from the fact that there is a radial gradient of the inclination angle (in the tangential plane) of fusiform cells, i.e. from the general tendency of a maturing cell to take on a preferred inclination with respect to the cell which immediately preceded it in its file." (Cited from Schulgasser and Witztum 2007).

Traditionally, the shift in grain angle in the radial direction has been described in qualitative terms like "a left spiral during youth passing through zero spiral to right spiral at maturity" (Northcott 1957) or classified into distinct groups of different grain patterns (Bues 1992). In the radial direction, grain angle to distance from pith has been modelled as a quite complex curve in the juvenile zone of young conifers (Danborg 1994, Tian et al. 1995). Mature wood, however, is known to differ in several aspects from juvenile wood. Ormarsson (1995) was the first to propose a linear model for the relation between grain angle and distance from the pith, to be applied in his numerical simulation models for wood warp and distortion. Recent work has confirmed this model (Eq. 1) for the mature part of any cross-cut sample of Norway spruce (Kliger and Säll 2000, Gjerdrum et al. 2002, Säll 2002).

$$\mathrm{GA}(R) = a_i + b_i \cdot R \tag{1}$$

After having estimated the parameters for a given specimen i, the grain angle GA in mature wood at an arbitrary radial distance R from the pith can be calculated. Equally valid models have been obtained using spatial or temporal (i.e. cambial age, number of rings, Säll 2002) distance from the pith. The parameters a and b, estimated from observations in cross-cut samples, were found to be bivariate normally distributed $a \sim \mathrm{N}(2.74, 1.92)$ and $b \sim \mathrm{N}(-0.0387, 0.0371)$ and slightly correlated ($r = -0.27$) in a sample of 1046 crosscuts (Gjerdrum et al. 2002). This model, corresponding to the causative explanation proposed by Schulgasser and Witztum (2007), implies a constant change rate in grain angle throughout the life of a tree, irrespective of external stimuli. Both the initial angle near the pith *a* and the change rate *b* vary randomly between trees. No correlation for these parameters with other tree or wood characteristics has been identified (Gjerdrum et al. 2002, Sarén et al. 2006).

By combining Eq. 1 with the results reported by Danborg (1994), the following model (Eq. 2) for all $R \geq 0$ has been proposed (slightly modified after Gjerdrum 2002):

$$\mathrm{GA}(R) = a_i \cdot \left[1 - k \cdot \left(1 - \sqrt{R/r}\right)\right] + b_i \cdot R \qquad (2)$$

In the stem kernel, when $R < r$, the parameter k evaluates to 1 and zero otherwise. This model is identical to Eq. 1 outside of a suitable limit r from the pith; this limit might be interpreted as the transition from juvenile to mature wood with respect to grain angle. In the juvenile zone, the model forms an s-shape through the pith (i.e. the origin in Fig. 3).

Säll (2002) analysed the variation of grain angle at three selected heights from ca. 5 to ca. 18 m, and reported different sets of *a* and *b*, *a* increasing from 3.3 to 4.1 and *b* decreasing from –0.023 to –0.039 upwards; however, no simultaneous formula was reported. In addition, a slight outward trend for the GA culmination in the juvenile wood was observed, corresponding to r in Eq. 2, from the 4th ring at the base to the 8th ring at the top.

The objective of this paper has been to study the joint, three-dimensional model for grain angle in mature wood sampled from a limited number of Norway spruce stems, as an improvement to Eq. 2 in which height is included as predictor.

2 Materials and Methods

Five large spruce trees, DBH at least 40 cm and height ca. 30 m, were sampled from one, quite fertile, stand; these were trees available from another experiment (Barszcz et al. 2008). The trees were felled, debranched, and marked along the stem for the north direction. The stems were bucked and cross-cut to ca. 5 m long logs. Each trunk yielded from four to six logs, in total 25 logs. From the butt end of each log, the basal cross-cut inclusive, a ca 10 cm thick transverse disk of the trunk was extracted, taking care to avoid knot nodes and other perceptible irregularities (Fig. 1). All 25 specimens, each with a unique identification number, were brought to

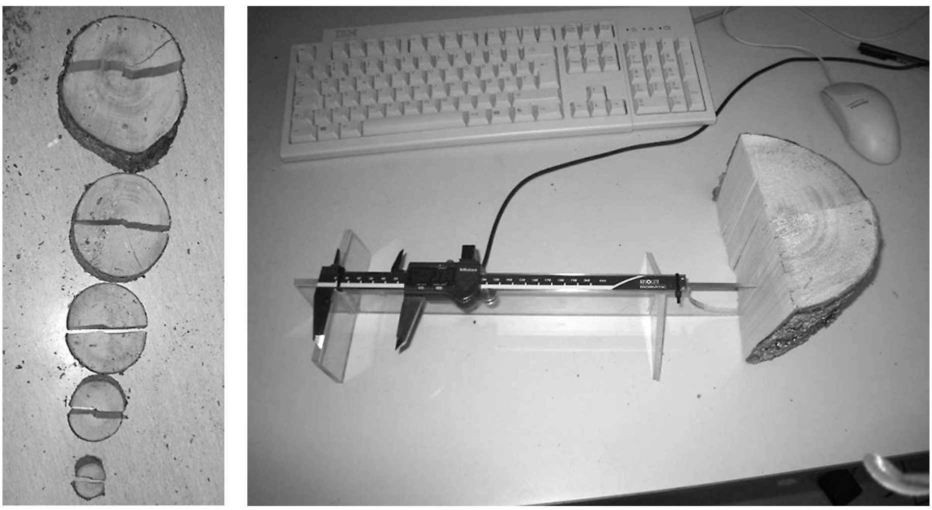

Fig. 1. Five consecutive disks from one stem (left, example); illustration of equipment used to read the offset (right).

the laboratory and allowed to dry during storage until observation. Trees were identified by letters A…E and disks by numbers 0…6, starting with zero at the base cut.

Each disk was split in a plane through the pith in the north-south direction using a blunt knife following the grain direction. The grain angle could then be calculated up to the offset, which was measured by applying a ruler at a fixed height of 50 mm. Offset readings (Fig. 1) and the corresponding number of annual rings were taken along one radius, from pith to north, at regular intervals of 15 mm from the pith outwards; this was taken to be the mature part of the stem. For the purpose of this investigation, no observations in the innermost, mostly juvenile, zone closer than 15 mm to the pith were included. The readings for each disk were corrected, taking the pith as a reference, to adjust for any angular discrepancies introduced during crosscutting. This method complies with Northcott (1957), Brazier (1965), Bues (1992) and Gjerdrum et al. (2002). The disk-split method is considered to be less accurate than the scribe test/protractor method (e.g. Säll 2002), but also less costly and sufficiently accurate for our purpose. Left-handed (clock-wise) angles were denoted as positive and right-handed angles as negative. A summary description of the observations is given in Table 3.

Assuming that both the intercept and inclination change somewhat along the stem, as indicated in Säll (2002), and constant grain angle in all azimuth directions Θ, a family of models (Eq. 3) with five parameters *a*, *b*, *c*, *d* and *r* for each stem *i*, was set up to be tested against the observations:

$$\mathrm{GA}(R,H) = (1 + c_i \cdot f(H)) \cdot a_i \cdot \left[1 - k \cdot \left(1 - \sqrt{R/r}\right)\right] + (1 + d_i \cdot f(H)) \cdot b_i \cdot R \quad (3)$$

The model is given in cylindrical coordinates, assuming an arbitrary azimuth $0 \le \theta < 2\Pi$. Again, k evaluates to 1 inside the radial limit r and zero outside this limit. Radial distance $R > 0$ might be given both in spatial distance and in cambial age. The limit r was set to the arbitrary value 12 mm, which is inside of the first observation at 15 mm; for cambial age, values from Säll (2002) were applied. Height H is given in metres above the basal cut. With rather few observations, five or six disks, along each stem at regular intervals, we would expect to identify only rectilinear effect of height. Nevertheless, to allow declining effects upwards, the logarithm and square root transformations of H, indicated by $f(H)$ in Eq. 3, were tested, as was completely omitting the effect of height, along with H given in natural measurements. Further, acknowledging that the basal part due to butt swell etc. might be more irregular than the rest of the stem, separate models were estimated with and without the basal disk. These initial analyses pointed towards a combined model with simultaneous estimation for all five stems applying the non-linear estimation approach in Statistica (2008). Observations made along the radius in one disk are known to be positively autocorrelated (Gjerdrum et al. 2002), and this must even be expected for adjacent observations along the stem. Consequently, statistical tests should be used cautiously.

3 Results

A typical example for grain angle variation in a stem is given in Fig. 2. The pattern is rather similar for all disks in the same tree. The lines seem quite parallel, i.e. with uniform change rate (inclination), albeit with some variation in the intercept parameters.

The parameters *c* and *d* were fairly consistent between trees. Consequently, common *c* and *d*

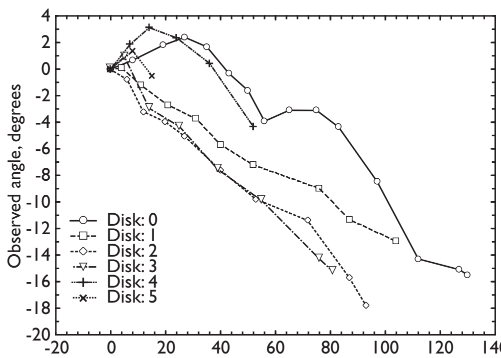

Fig. 2. Observed grain angle for all disks from tree C (example) plotted against cambial age

Table 1. Explained proportion of the variance (R^2) in GA for the models given by Eq. 3.

		Full stem — Radial distance R given as: Spatial distance	Cambial age
Height in stem given as	Natural H	0.764	0.779
	$\sqrt{H}$	0.784	0.791
	(omitted)	0.674	0.728

parameters for all stems were used in the subsequent analyses. All the tested models resulted in a fair proportion of the grain angle variance being explained, mostly more than 75% (Table 1), and with similar results for varying model approaches. The square root of H was chosen as the best predictor; however, performing only slightly better than natural H. The logarithmic transform, which requires $H>0$, demonstrated no advantage and was abandoned.

Full model parameters for all stems are given in Table 2. Height significantly and consistently affected either the inclination (for the model in cambial age) or both intercept and inclination (for the spatial model). For any given tree, c and d from Table 2 should apply, while (a, b) must be estimated separately. The final model for spatial coordinates is given in Eq. 3a and demonstrated in Fig. 3.

Model residuals were rather homogeneous for the five trees (Table 3). The residuals were marginally lower in models estimated by omitting the basal cross-cut, but were otherwise homogeneous from bottom to top of the stems.

$$\mathrm{GA}(R,H) = (1+0.18\cdot\sqrt{H})\cdot a_i\cdot\left[1-k\cdot\left(1-\sqrt{R/12}\right)\right] + (1+0.34\cdot\sqrt{H})\cdot b_i\cdot R \qquad (3A)$$

Table 2. The effect of height in the stem; the parameters ± std. error for $\sqrt{H}$ in Eq. 3a.

		Full stem — Radial distance R given as: Spatial distance	Cambial age
Parameters (a, b) for tree:	A	(0.9, –0.019 *)	(0.9, –0.021 *)
	B	(2.0 *, –0.022 *)	(1.9 *, –0.026 *)
	C	(3.0 *, –0.077 *)	(1.9 *, –0.115 *)
	D	(1.4 *, –0.018 *)	(1.3 *, –0.034 *)
	E	(2.1 *, –0.014 *)	(2.4 *, –0.026 *)
Parameters for the term $\sqrt{H}$	c_i	0.18 * ± 0.08	0.13 ± 0.08
	d_i	0.34 * ± 0.05	0.22 * ± 0.04
R^2		0.784	0.791

* Significance: $p<5\%$

Table 3. Summary of observations and model residuals by tree for spatial model Eq. 3a.

Tree	Observations, angle in ° — Range		Mean	Std. dev	No. of obs.	Model residuals, ° — Mean	RMSE
A	–4.0	+1.9	–0.15	1.3	29	+0.04	1.1
B	–3.1	+5.3	+0.58	2.3	39	–0.10	1.9
C	–17.7	+3.1	–4.65	5.8	52	+0.08	2.5
D	–7.9	+3.0	–0.75	2.1	72	+0.01	1.3
E	–5.1	+4.5	+8.83	2.1	59	–0.05	1.7
All	–17.8	+5.3	–0.91	3.8	251	0.00	1.8

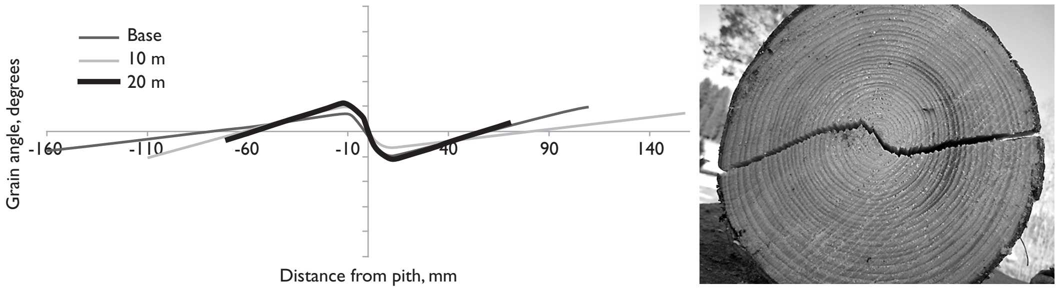

Fig. 3. Spatial model presentation (Eq. 3a) for $a=2$ and $b=-0.02$ (left); example split disk (right)

This model is valid for any azimuth direction; k evaluates to 1 inside the limit $r=12$ mm and zero otherwise.

4 Discussion

The 3D model for grain angle given in Eq. 3a is the main outcome of this work. The change in grain pattern upwards in the stem was found to be consistent for the five examined trees, leading to a model where only two parameters, intercept and inclination at the stem base, are required to estimate the grain angle for the full stem. However, due to the small sample, the model can only indicate a tendency. The full variation in grain pattern along stems should be examined in a wider material. The model does not take into account grain variation due to knots, undulating pith, un-round crosscuts, and other irregularities in grain pattern.

The model accounted almost completely for the overall tree pattern, indicated by the tree mean residuals being close to zero (Table 3) and three quarters of the total variation (Table 1). Root mean squared error, RMSE, was reduced most (compared to the standard deviation of the initial observations) for tree C (Table 3), i.e. the tree with the highest initial variation. The model residuals were normally distributed and RMSE was of the same magnitude for all trees and all height levels in the trees. The values for the parameter c were consistently larger than zero, indicating that the intercept (related to the a parameter) increases upwards in the stem, i.e. there tends to be more pronounced leftwards spiralling near the pith (Fig. 3). Similarly, d is larger than zero, signifying that the inclination (related to the b parameter) increases, i.e. there is a faster tendency towards right-hand spiralling in the upper part of the stem. The magnitudes of c and d were in good accordance with the results reported by Säll (2002) for the spatial model. The need for separate parameters for a and b for each tree, and the ranges for these parameters, comply with results reported by Säll (2002) and Gjerdrum et al. (2002).

The split disk method is efficient and reliable for crosscut observations. This method requires that a reference axis be identified or defined. This is typically done either from the outer form of the disk or from the pith. Identifying the vertical position from a disk is not straightforward; consequently, the pith was chosen as the origin in this work. This worked well for two-dimensional analyses in single disks (Gjerdrum et al. 2002). The pith is known to slightly undulate inside any trunk. Some of the variation in intercept between disks from the same stem, as illustrated in Fig. 2, might be due to this undulation. For future analyses, care should be taken to identify consistent axes. As might be expected, RMSE for the 3D model is somewhat higher than for the 2D model reported by Gjerdrum et al. (2002), 1.8° compared to 0.7°. Both the offset caused by the undulating pith and the higher grain irregularity in the base crosscuts included in the present work contribute to these higher residuals.

5 Conclusions

The main finding has been a verification of the prospect of building quite simple three-dimensional models for grain angle in spruce stems. The change in grain pattern upwards in a stem seems weak, but consistent between the investigated trees: the left-handed grain angle in the juvenile wood is slightly more pronounced upwards in the stem and the change towards right-handed spiralling goes faster. The faster change towards right-handed spiralling will counteract the smaller radius, so that the observable surface grain angle might not change much along large parts of the stem. The square root transformation of height in the stem seems to be a reasonable predictor. Cambial age is a slightly better predictor than spatial distance from the pith. Grain pattern seems more irregular in the basal cut. However, this three-dimensional grain angle model will need to be verified for a wider sample including trees from various locations. Careful definition of the reference axes should make it possible to reduce the residuals. The model is an extension of existing two-dimensional models for stem cross-cuts. After verification in a wider sample, the results should be applicable in tree and wood modelling.

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