MODELLING OF *PINUS RADIATA* WOOD PROPERTIES. PART 1: SPIRAL GRAIN

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ABSTRACT

Spiral grain in *Pinus radiata* D. Don is a well-known feature of the corewood region of the stem. The pattern of variation in a 25-year-old plantation was recently documented and detailed measurements in another two crops indicated that the general pattern established remained valid. The results were used to construct a model of spiral grain in *P. radiata* as part of a series of Single Tree Wood Property models.

Keywords: wood properties; spiral grain; modelling; simulation; *Pinus radiata.*

INTRODUCTION

The amount of spiral grain in a tree stem greatly influences the quality of sawlogs and the value of the lumber which can be produced from these logs. The grain deviation is often sufficient to cause significant problems in processing and marketing through drying degrade, strength loss, and movement in service (Cown *et al.* 1991). Research has demonstrated that if the distribution, direction, and angle of spiral grain in a log are known, it may be possible to select a sawing procedure and a drying method to at least partially alleviate the problems.

Unfortunately, current processes for converting logs into lumber are hampered because there is a lack of knowledge about the incidence and effects of spiral grain in trees, logs, and timber. At best, only preliminary patterns capable of estimating a rough tendency have been established for *P. radiata*.

Spiral grain refers to the alignment of tracheids at an angle to the vertical tree axis or pith in a tangential plane. Spirality is a common characteristic of almost all forest trees, and it has been suggested that spiral grain may be the normal condition while straight-grained wood is a relatively rare occurrence (Harris 1973, 1989).

The presence of spiral grain generally decreases the strength of the wood and causes warp when the timber is seasoned. It can also have a serious effect on wood machining and in veneers it contributes to splits or tears in the sheet.

A large number of factors have been cited as probable causes of spiral grain, but none satisfactorily explains its occurrence. In common with other wood properties there is wide variation between species and individual trees which is normally attributed to the effect of genetic variation. The high average corewood spiral grain and the degree of variability between trees in *P. radiata* reinforce the possibility of a strong genetic component (Cown *et al.* 1991).

When spiral angle is measured within and among trees, complex and highly variable patterns are found, as well as variations that do not follow any discernible pattern. Cown *et al.* (1983) pointed out that in *Pinus caribaea* Morelet no consistent pattern was found and grain angles could only be described as highly variable and unpredictable both within and between trees. This has made it difficult to evaluate the effects of spiral grain on wood quality, and has caused problems in comparing tree and site effects.

Even though a lack of detailed scientific knowledge prevents the development of a physiological model, information about spiral grain in *P. radiata* is urgently required for technological reasons. The present regression model was developed to arrange a large collection of empirical data into a user-friendly form.

This study was initiated to provide basic information concerning the magnitude and pattern of spiral grain in *P. radiata*. Using data collected in recent studies, a whole-tree model of variable spiral grain was created using multiple non-linear regression analysis (Androws 1974; Iman & Conover 1979; Draper & Smith 1981; Zeigler 1979a, b). This model can automatically calculate a grain angle anywhere in the log and it also has been programmed into the software system by using C++.

MATERIALS AND METHODS

Resource Description

The spiral grain data used in this report come from previous studies carried out on three different crops in Kaingaroa Forest (Compartments 1302, 1013, and 1350). The sample areas were originally selected to yield information on the effects of site and silviculture on wood properties and sawmill recoveries, and study results were included in a sawing model (Cown *et al.* 1987).

- Compartment 1350 contained 22-year-old trees. Thirty were selected for sawing and to establish outerwood to whole-tree density relationships.
- Compartment 1013 contained 26-year-old trees, high pruned and thinned to 350 stems/ha. Thirty trees were selected to provide logs with a range of branch sizes. This study was undertaken to establish timber grade recoveries and typical values of wood properties.
- Compartment 1302 had 28-year-old trees which had been production thinned. Thirty trees were selected for sawing to cover the range of log branch size and wood density.

Logs for all studies were 4.9 m and all trees were sampled up to a minimum small-end diameter of 200 mm. A range of wood properties were measured, spiral grain being the property relevant to this report. Wood discs, 50 mm thick, were removed from the top end of each log for wood property determination.

Spiral Grain Measurement

Spiral grain was measured on each disc along one diameter. Tracheid orientation was measured on every second growth ring by exposing the latewood with a chisel and scribing along the grain direction with a "swinging arm grain scribe" (Harris 1989). Deviation angle was measured in relation to the lower surface of the disc using a perspex protractor. By assessing the two opposite radii in this way, any deviation of the disc axis from the "true" horizontal plane is compensated for and a good average grain angle is obtained.

STATISTICAL ANALYSES OF SAMPLE DATA

Between-tree Variation

Of a total of 1200 observations of spiral grain in the stem, 74% were left-handed, 20% were right-handed, and only 6% represented straight grain. The magnitude of the slope for all observations ranged from 0° to 18° in absolute value, with a mean of 3.75°, and 84% of the measurements from –2° to 8° (Table 1).

TABLE 1–Individual tree mean slope and direction values.

Tree No.	No. of observ.	Grain direction			Slope		
		Left (%)	Light (%)	Straight (%)	Mean degrees	Observ. ≤ –2° (%)	Observ. ≥ 8° (%)
2	71	64	32	4	2.66	7	1
7	71	64	35	1	2.99	3	4
8	43	65	28	7	1.98	14	0
9	67	85	15	0	4.35	0	10
10	73	82	16	2	5.34	11	20
14	70	80	19	1	3.56	6	9
17	65	63	35	2	3.66	18	5
18	73	100	0	0	5.60	0	12
19	57	72	28	0	3.05	15	0
25	72	93	7	0	4.68	1	18
27	75	76	21	3	3.25	5	8
34	64	94	6	0	4.37	0	6
38	48	92	8	0	3.64	4	2
43	69	77	22	1	3.52	3	1
45	66	83	14	3	3.82	6	9
47	68	66	28	6	3.01	12	0
50	63	72	25	3	3.01	8	3
60	78	82	18	0	4.39	10	15
62	63	94	4	2	6.43	0	38
66	61	69	28	3	3.84	10	9
67	61	57	41	2	3.14	21	3
69	69	61	39	0	3.52	29	6
70	72	69	28	3	3.32	13	3
72	66	71	29	0	4.35	14	11
78	65	72	25	3	3.68	11	11
79	65	68	30	2	2.69	8	0
81	66	70	21	9	3.14	6	5
85	55	95	5	0	3.61	2	7
87	59	61	36	3	3.62	12	3
88	63	87	10	3	3.47	3	5
All	1958	74	20	6	3.75	8	8

Pinus radiata has a strong tendency to spiral to the left, especially at younger ages and in the inner 10 growth rings (Harris 1973, 1989; Cown *et al.* 1991). This corresponds well with the part of the stem often referred to as the juvenile wood or corewood zone (Cown 1992a, b). Outside this zone, grain angles are generally close to 0° and show a higher proportion of right-handed spirals.

Radial Variation

Some of the variation in spiral grain found from the pith outwards in different trees at 5 m is indicated in Fig. 1.

The patterns were not very consistent, either between trees or even within the stem in the same tree. However, comparisons of mean values of all observations in relation to ring number yielded useful information. The mean grain angle values were related to ring number from the pith (cambial age) and decreased steadily from a maximum positive (left spiral) angle at ring 2 to 0° at about 10 years, followed by a gradual decrease to negative angle (right spiral) in the outer rings.

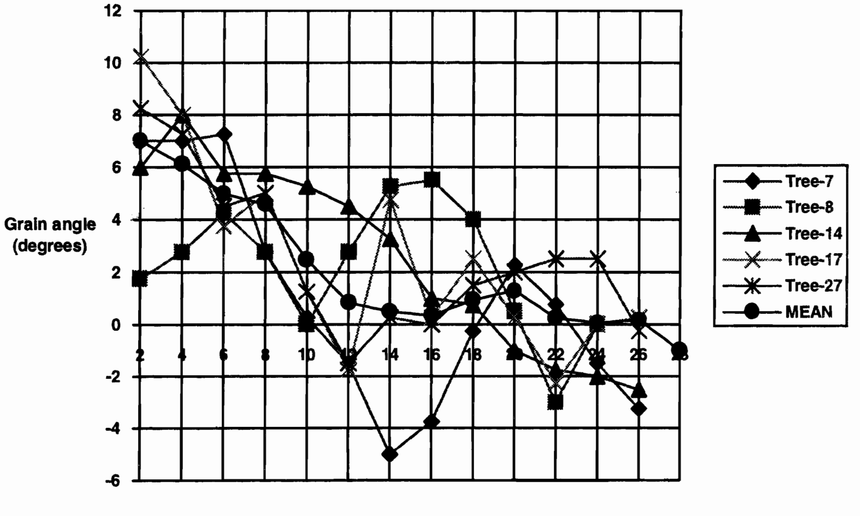

FIG. 1—Radial pattern of spiral grain in five trees and mean value at 5 m. (Note: grain value = mean angle averaged across both radii)

Variation with Stem Height

Vertical variation patterns for rings 2, 4, and 6 from the pith of a single representative stem (tree No. 80) (Fig. 2) indicated that there was enough of a grain angle trend to make the generalisation of patterns possible.

With increasing height in the stem, a fairly consistent decrease in right-hand grain deviation occurred (Table 2). From 0 m (butt) slope increased steadily until a maximum was reached at about 15 m, followed by a gradual decrease in the higher stem. The trends were parabolic.

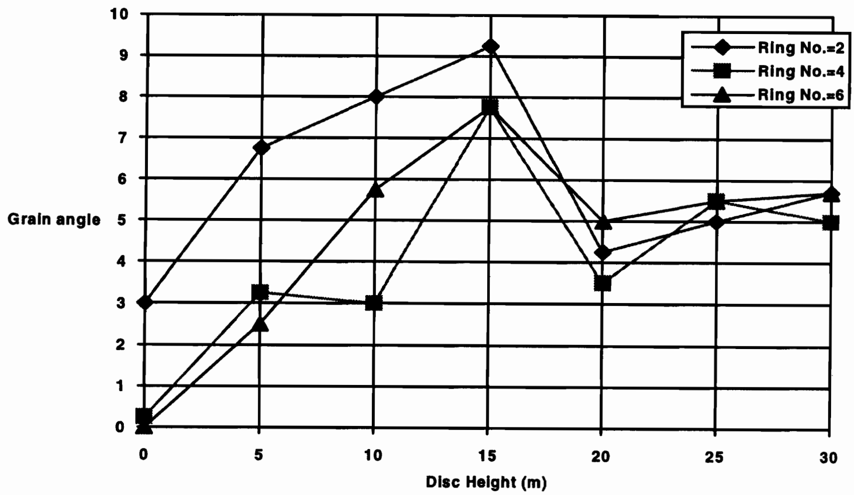

FIG. 2–Vertical pattern of spiral grain in rings 2, 4, and 6 from the pith of tree No.80.

TABLE 2–Grain direction and slope as related to height in the stem

Height (m)	Left-hand observations (%)	Right-hand observations (%)	Mean slope (°)
0	54	46	2.67
5	70	30	3.34
10	79	21	3.88
15	87	13	4.29
20	87	13	4.53
25	92	8	4.59
30	97	3	5.56

MODEL CONSTRUCTION

Analysis of Within-tree Grain Patterns

Spiral grain is a complex characteristic, comprising two disjunct factors, magnitude and direction. In the previous sections spiral grain was shown to vary greatly within and between the trees sampled.

Since within-tree variation is high, whole-tree estimates based on one or two or a few measurements would be unsatisfactory, and multiple measurements are needed. We must view and analyse this variation in a "general" and "stereoscopic" mode. Sample data of about 100 trees from three sites (as described above) were selected to design an accurate system for sampling whole-tree spiral grain. Mean grain angles by height and ring number from Compartment 1302 were calculated (Table 3). The data variation in this table (Fig. 3) is similar to "grain angles within a typical tree aged 35 years" (Harris 1989).

Modelling the Effect of Height in the Stem

To model the variation of spiral grain rationally, it was necessary to develop a mathematical relationship between the main factors and grain angle.

TABLE 3–Mean variation of spiral grain within all trees from Compartment 1302.

Height	Degree of spiral grain by ring number from pith														
(m)	2	4	6	8	10	12	14	16	18	20	22	24	26	28	30
0	4.8	3.4	1.9	1.9	1.7	1.1	0.2	–0.1	–0.4	–0.6	–0.7	–1.1	–1.6	–0.9	–3.2
5	7.0	6.1	5.0	4.6	2.5	0.9	0.5	0.3	0.9	1.3	0.23	0.06	0.16	–1.0	
10	6.7	5.4	6.6	5.2	3.0	1.6	1.3	1.9	2.3	1.0	0.68	1.18	0.75		
15	6.8	6.9	6.2	5.3	4.3	3.6	2.7	2.0	1.2	0.7	2.18				
20	5.8	6.3	6.0	6.1	4.8	4.5	2.8	1.3	0.9	1.2					
25	5.9	4.9	3.9	4.7	5.1	3.0	2.4	0.9							
30	6.4	6.1	6.2	6.6	4.8	4.1	4.3								
35	6.2	4.6	2.7	4.2	1.3										

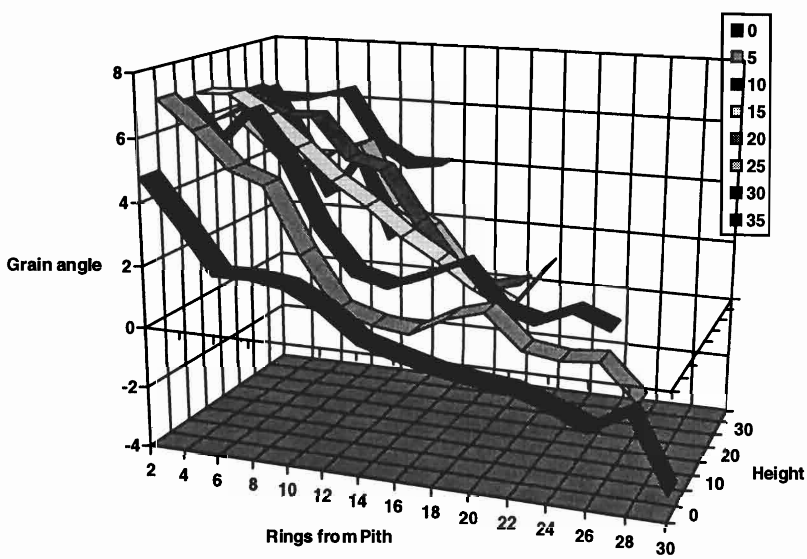

FIG. 3–Variation between rings, height, and grain angle shown in 3-D line mode.

A group of regression equations was created for each of the different height levels. If Z is the grain angle (°) at y m height at the earlywood to latewood boundary between X to X+1 rings,

X is the ring number
Y is the height(m)
σ^2 is mean square error
ε is random error.

Then using non-linear regression methods, a group of regression equations at different heights was created to represent the patterns from rings 1 to 30 (Androws 1974; Ratowsky 1989).

At 0 m: $\begin{cases} Z = 6.897 - 2.533 \cdot \mathrm{Ln}(X) + \varepsilon \\ \sigma^2 = 0.290 \end{cases}$

At 5 m: $\begin{cases} Z = 9.893 - 3.153 \cdot \mathrm{Ln}(X) + \varepsilon \\ \sigma^2 = 0.618 \end{cases}$

At 10 m: $\begin{cases} Z = 9.500 - 2.722 \cdot \mathrm{Ln}(X) + \varepsilon \\ \sigma^2 = 0.885 \end{cases}$

At 15 m: $\begin{cases} Z = 10.177 - 2.788 \cdot \mathrm{Ln}(X) + \varepsilon \\ \sigma^2 = 0.808 \end{cases}$

At 20 m: $\begin{cases} Z = 9.378 - 2.455 \cdot \mathrm{Ln}(X) + \varepsilon \\ \sigma^2 = 1.880 \end{cases}$

At 25 m: $\begin{cases} Z = 7.495 - 1.822 \cdot \mathrm{Ln}(X) + \varepsilon \\ \sigma^2 = 1.098 \end{cases}$

At 30 m: $\begin{cases} Z = 7.741352 - 1.163881 \cdot \mathrm{Ln}(X) + \varepsilon \\ \sigma^2 = 0.560 \end{cases}$

The curves of the regression equations are shown in Fig 4.

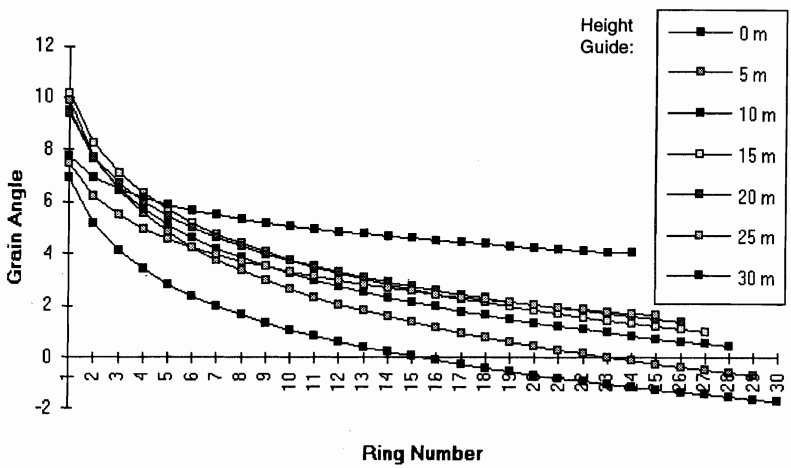

FIG. 4—Variation of grain angle from rings 1 to 30 according to the regression equations for different heights (2-D line mode).

MODELLING THE WHOLE TREE

From an overall point of view (Fig. 4), it can be seen that the magnitude of the grain angle increased as height increased, but at a given height, spiral grain decreased with distance from the pith.

To visualise the variation of spiral grain, a group of models is presented in Fig. 5 using 3-D Column and 3-D Line mode. The basic relationships between grain angle, height, and ring are obviously not linear.

So $Z = \boldsymbol{F}(X, Y, \theta_1, \theta_2, \ldots, \theta p) + \varepsilon$ (1)

where $\boldsymbol{F}$ = multiple non-linear function

Z = random variable (here grain angle)

X, Y = two independent variables (here rings and height)

$\theta = (\theta_1, \theta_2, \ldots, \theta p)$ = p unknown parameters

ε = random error and $\varepsilon \sim N(0, \sigma^2)$ normal distribution.

If there are n groups of measured data: (x_i, y_i, z_i), i=1,2, …, n

$X = (x_1, x_2, \ldots, x_n)$

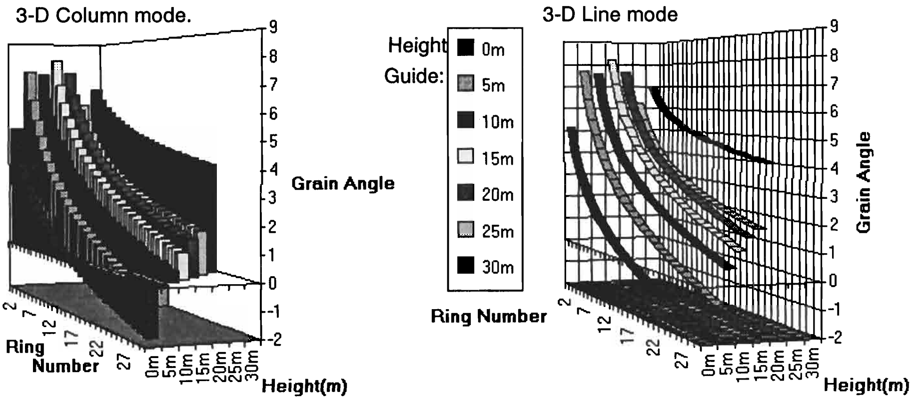

FIG. 5–Variation of grain angle from rings 1 to 30 at different heights using 3-D column mode and 3-D line mode.

$$Y = (y_1, y_2, \ldots, y_n)$$
$$Z = (z_1, z_2, \ldots, z_n)$$

then: $$\begin{cases} Z_i = \boldsymbol{F}(X_i, Y_i, \theta) + \varepsilon_i \\ \varepsilon_i \sim N(0, \sigma^2) \end{cases} \quad (2)$$

After simplifying,

$$\boldsymbol{F}(X_i, Y_i, \theta) = \boldsymbol{F}_i(\theta) \quad (3)$$

Suppose φ is the least square estimation of θ,

from Equations (2) and (3), $S(\theta) = \sum_{i=1}^{n} [Z_i - \boldsymbol{F}_i(\theta)]^2$ (4)

So φ must satisfy $S(\varphi) = \min_{\theta} S(\varphi)$

differential:

$$\left.\frac{\partial S(\theta)}{\partial \theta_j}\right|_{\theta=\varphi} = 0, j = 1, 2, \ldots, p$$

then:

$$\sum_{1} [Z_i - F_i(\theta)] \cdot \left.\frac{\partial F_i(\theta)}{\partial \theta_j}\right|_{\theta=\varphi} = 0, j = 1, 2, \ldots, p \quad (5)$$

When Equation (5) was solved, it was found to be a non-linear transcendental equation set; so a diagram method was used to determine the form of this equation (Fig. 6), then the Gauss-Newton iterative method was used (Draper & Smith 1981).

The following generalised equation was derived to predict the grain deviation in an "average" tree:

$$\begin{cases} Z = b_0 - b_1 \cdot \ln(X) + (b_2 - b_3 \cdot \ln(X)) \cdot Y - (b_4 - b_5 \cdot \ln(X)) \cdot Y^2 \\ X \geq 1 \end{cases} \quad (6)$$

Where X = Ring number from pith

Y = Height of tree (m)

Z = Spiral grain angle (degrees)

$b_0, b_1, \ldots, b_5$ = parameters, and they are $b_0 = 7.488$, $b_1 = 2.623$, $b_2 = 0.362$, $b_3 = 0.067$, $b_4 = 0.013$, $b_5 = 0.004$.

Mean standard deviation = 0.630.

If Z is positive, the grain spirals to the left; if Z is negative, the grain spirals to the right. For example:

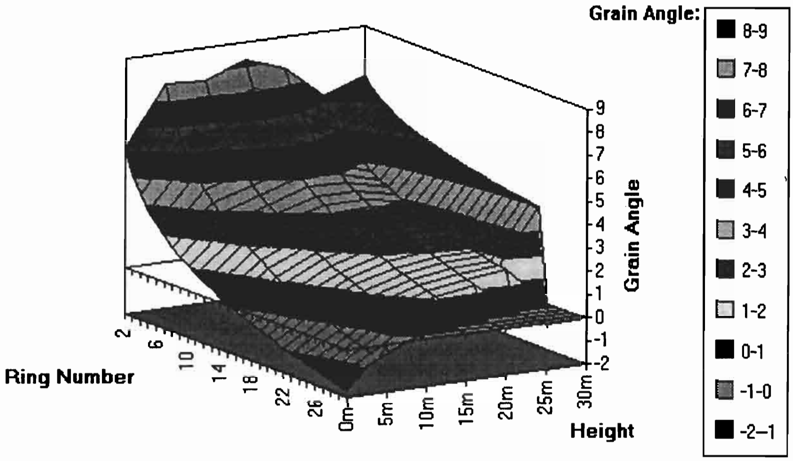

FIG. 6–Variation of grain angle from rings 1 to 30 at different heights using 3-D surface mode.

When ring number from pith is 4, X = 4; height of tree is 10 m, Y=10; hence

$\ln(X) = \ln(4) = 1.386.$

Substituting the values of 4, 10, and 1.386 in Equation (6) for X, Y, and ln(X),

$Z=7.488-2.623*1.386+(0.362-0.067*1.386)*10-(0.013-0.004*1.386)*100=5.795°\approx5.8°$

Between rings 4 and 5 at a height of 10 m the grain angle is about 5.8° with a left hand spiral.

Grain angles can be quickly calculated from Equation (6) for any position in the tree. The modelled variation of spiral grain within the whole tree is shown in Fig. 7 and grain angles can be calculated with this model (Table 4).

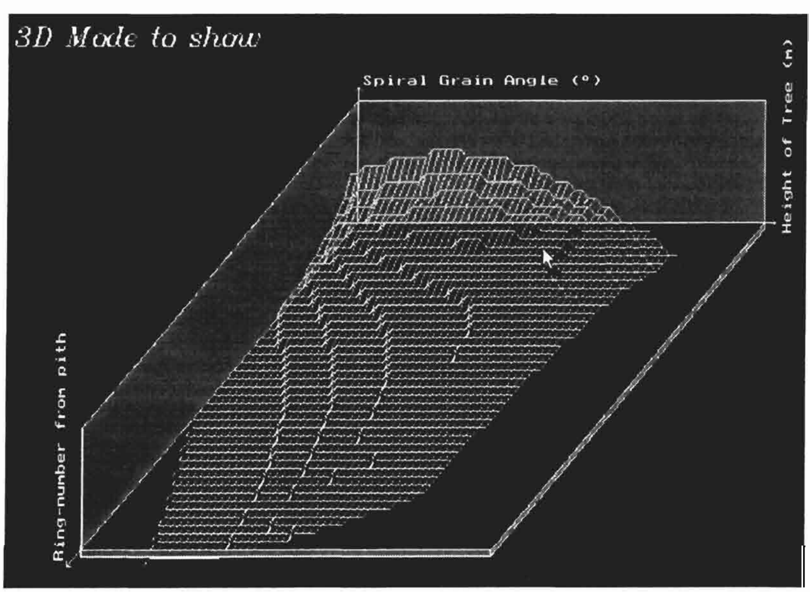

FIG. 7–Distribution of spiral grain within the tree using the 3-D surface mode.

TABLE 4–Grain angle values (°) within trees, using the model (Equation 6)

Height	Spiral grain angle by ring number from pith														
(m)	2	4	6	8	10	12	14	16	18	20	22	24	26	28	30
0	5.6	3.8	2.7	2.0	1.5	0.9	0.5	0.16	–0.2	–0.4	–0.7	–0.9	–1.2	–1.23	–1.25
5	7.0	5.0	3.9	3.0	2.4	1.8	1.4	0.10	0.66	0.36	0.8	–0.2	–0.4	–0.61	
10	7.8	5.8	4.6	3.8	3.1	2.6	2.1	1.80	1.4	1.9	0.81	0.56	0.33		
15	8.1	6.2	5.1	4.4	3.8	3.2	2.8	2.4	2.8	1.79	1.52				
20	8.0	6.3	5.4	4.7	4.2	3.7	3.3	2.97	2.6	2.43					
25	7.3	6.0	5.3	4.7	4.3	4.0	3.7	3.43							
30	6.2	5.5	5.0	4.8	4.4	4.2	4.1								
35	4.6	4.5	4.4	4.3	4.2										

MODELLING AND SIMULATION

Some models are deemed useful only if they succeed in simulating the essential features of the real system and lead to the prediction of previously unsuspected phenomena or relationships that are subsequently verified (Kiviat 1967). With some wood properties it can be very difficult to find the relationships between them and other factors without computer-aided analysis, because the relationships are usually very complex and almost impossible to analyse. For instance, in certain situations one parameter may be limiting. A module for spiral grain was developed using C++. A later paper will detail construction of a software package dealing with a range of wood properties.

Many scientists and programmers have developed models for forest research problems, but models of wood properties are very difficult to construct. A new and original computer simulation model has been designed for spiral grain, based on a spectral representation of grain angle (Fig. 8).

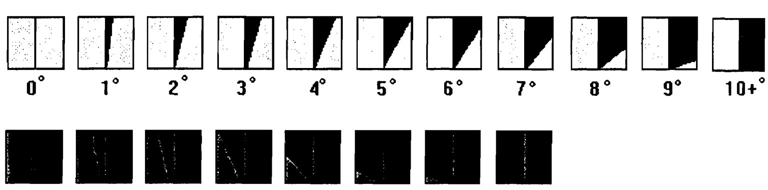

FIG. 8–Spectral representations of spiral grain

Model Validation and Error Analysis

Standard deviations of spiral grain by stem height and ring number from the pith are shown in Table 5. Generally, effective domain of the model (Equation 6) is [Z–0.63, Z+0.63].

Testing the Model with Residual Plots

The model was tested using residual plots. The residuals were plotted against ring number from the pith at each stem height and the data for tree height = 0 m are shown in Fig. 9. The

TABLE 5–Mathematical standard deviation of the model (compare Tables 4 and 5)

Height	Standard deviation of spiral grain by ring number from pith														
(m)	2	4	6	8	10	12	14	16	18	20	22	24	26	28	30
0	0.8	0.4	0.8	0.1	0.2	0.2	0.3	0.2	0.2	0.2	0.0	0.2	0.4	0.4	0.9
5	0.0	1.1	1.1	1.6	0.1	0.9	0.9	0.2	0.2	1.0	0.5	0.1	0.2	0.4	
10	1.1	0.4	2.6	1.4	0.1	1.0	0.7	0.1	0.9	0.9	0.1	0.4	0.4		
15	1.3	0.7	0.9	0.9	0.4	0.4	0.1	0.4	1.6	1.0	0.6				
20	2.2	0.0	0.6	1.3	0.6	0.8	0.5	1.6	1.7	1.2					
25	1.4	1.1	1.4	0.0	0.7	1.0	1.3	2.1							
30	0.2	0.5	1.2	1.6	0.4	0.1	0.2								
35	1.2	0.1	1.6	0.1	2.1										

Mean standard deviation = 0.63

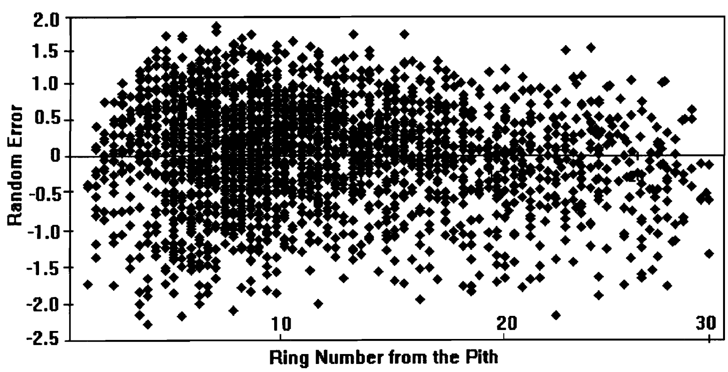

FIG. 9–Residual plot at tree height = 0 m

overwhelming majority of data points were between 2.0 and –2.0°, with random distribution and no systematic tendency, so that the regression equations fit the sample data very well.

Testing the Model on Additional Data

Data from Compartment 1302 were used to build the model (Equation 6). For model validation, spiral-grain patterns from Compartments 1013 and 1350 were simulated (Fig. 10, 11, and 12) and it was found that the model corresponded well to the observed patterns. This further testifies to the accuracy and efficiency of the model. The sample size in this study (93 trees) was sufficiently large to give confidence in the model.

DISCUSSION AND CONCLUSION

This model is the first known mathematical model of spiral grain in a softwood species. The study provided a new method for investigation of this and other wood properties as it fully revealed the laws of variation of spiral grain within stems of *P. radiata*:

- Spiral grain exhibits a more complex pattern than many other properties. However, there was still an overall tendency toward radial and vertical symmetry.

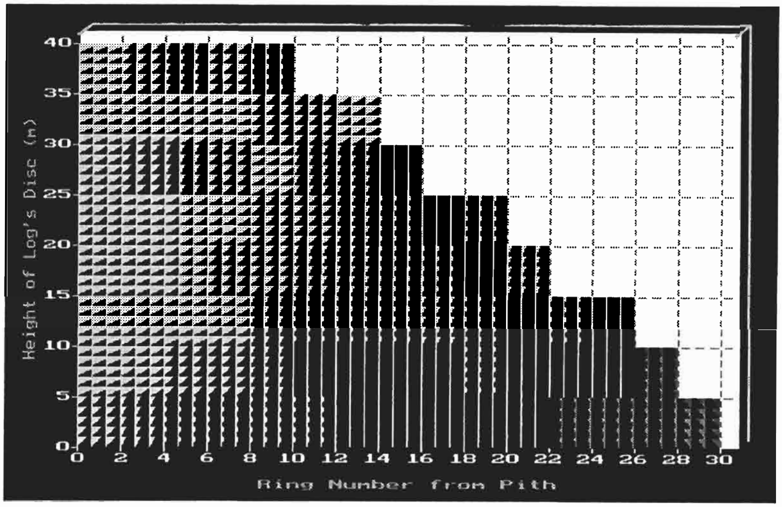

FIG. 10–Spiral grain pattern (Compartment 1302)

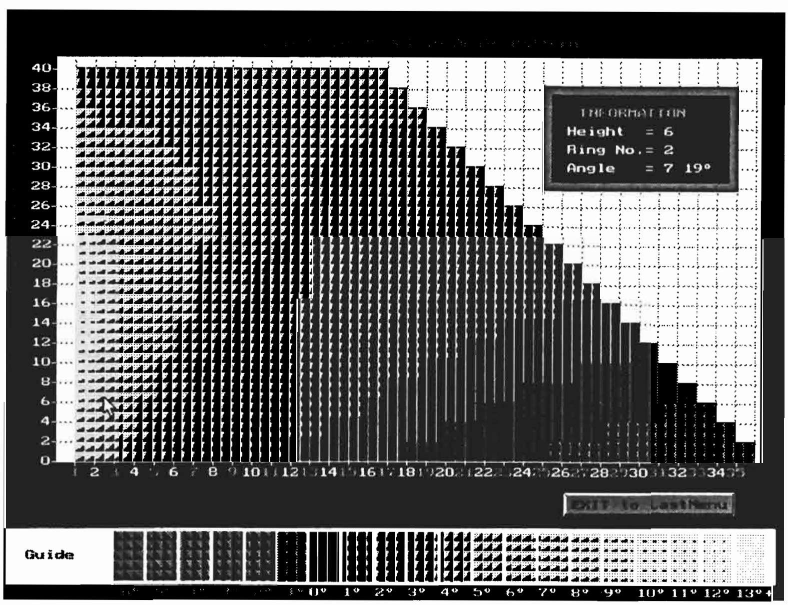

FIG. 11–Spiral grain pattern using the model (Equation 6)

- Predictions by the model reported in this paper indicated where grain angle is high or low, and where variation is large or small. This provides a basis for better control in wood processing.
- With this model, it is easy to locate the stem regions where radical changes in spiral grain occur that could affect mechanical properties and machining characteristics.

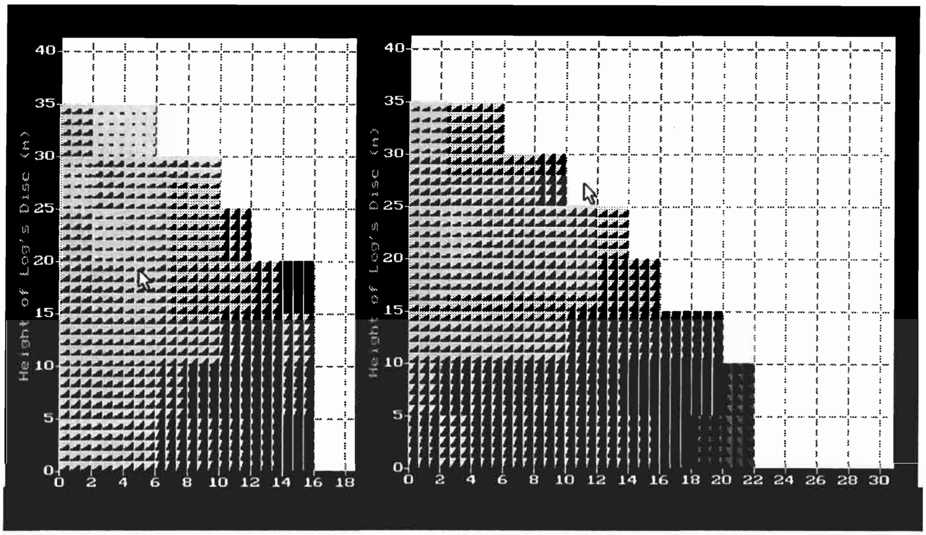

FIG. 12–Spiral grain patterns for Compartments 1013 and 1350

Further development is needed in the following areas:

- The model should be linked to Stem Taper Equations to develop the relationship between stem diameter and spiral grain under different growing conditions
- Relationships between diameter growth rate and the magnitude of grain angle require further study.
- The genetic basis for variation in spiral grain needs investigation.

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