This is the published version of a paper presented at WCTE 2014, World Conference on Timber Engineering, Quebec City, Canada, August 10-14, 2014.

Citation for the original published paper:

Olsson, A., Oscarsson, J. (2014)
Three dimensional fibre orientation models for wood based on laser scanning utilizing the tracheid effect.
In: Proceedings of the 2014 World Conference on Timber Engineering (WCTE), Quebec City, Canada, August 10−14, 2014

N.B. When citing this work, cite the original published paper.

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THREE DIMENSIONAL FIBRE ORIENTATION MODELS FOR WOOD BASED ON LASER SCANNING UTILIZING THE TRACHEID EFFECT

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ABSTRACT: Recent research has shown that machine strength grading based on tracheid effect scanning of fibre directions projected on board surfaces can provide more accurate strength predictions than today’s grading methods. Scanning techniques in which 3D fibre orientations can be taken into account would most likely improve the strength grading results even further. In this investigation the possibility of determining such 3D orientations by dot laser scanning was investigated. For a set of 20 side boards, scanning data was used to calculate traversing knot directions which were in turn applied to determine pith location and root end of original logs. By means of the shape of laser dots, which due to the tracheid effect are turned elliptic on board surfaces, and the determined pith location, the size and direction of the diving angle of the fibres was calculated. The research showed that this angle can be accurately determined in the vicinity of knots.

KEYWORDS: Laser scanning, Tracheid effect, Fibre angle, Grain angle, Diving angle, Machine strength grading

1 INTRODUCTION

The bending strength of boards of Norway spruce generally varies between 10-80 MPa and the variation of average modulus of elasticity (MOE) is between 5-20 GPa. This large variation in properties between different boards makes grading of the material into different strength classes necessary. However, the grading techniques in use today take only to a limited degree account of the inner structural characteristics such as density, spiral grain, compression wood, annual-ring pattern, pith location and occurrence of knots, and as a consequence they give poor predictions of strength of boards. The present-day methods for strength grading of sawn boards result in a maximum characteristic strength of about 35-40 MPa, despite there being boards that in fact have a strength that is more than twice as high. This motivates the development of more accurate grading methods. Advancements in technology have made it possible to collect and analyze detailed information of individual boards in a speed that corresponds to the production speed at a sawmill and the new possibilities should, of course, be utilized in the development of new strength grading methods. In this context high resolution laser scanning of lumber has shown to have a very interesting potential that should be developed.

1.1 STRENGTH GRADING BASED ON LASER SCANNING

Today high resolution scanning of lumber is often performed at sawmills in order to detect defects that are not allowed in applications for which the wood is intended to be used. However, the information collected regarding fibre orientation on a very local scale is not yet utilized for grading of structural timber. Recently, however, Olsson et al [1] presented a new method for strength grading of timber based on a combination of laser scanning, dynamic excitation and weighing of boards. The scanning of face and edge surfaces was performed using a scanner of make WoodEye® equipped with four sets of multi-sensor cameras and dot lasers. Conveyor belts were used to feed boards in the longitudinal direction through the scanner. The laser scanning makes use of the so-called tracheid effect where one of the principal axes of the light intensity distribution around a laser dot indicates the fibre orientation in the plane of the surface. The fibre orientation information was then utilized for calculation of local stiffness in the longitudinal direction of the board and by integration over cross-sections a bending stiffness profile

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along the board, see Figure 1, was established. The lowest bending MOE found along the board was used as indicating property (IP) to bending strength. Information from dynamic excitation and weighing was used for calibration of material stiffness properties of each board. The method is currently being developed for commercial use and a letter of patent has been issued [2]. Noteworthy assumptions made, and conclusion drawn, from presented research are:

- The suggested IP could predict the bending strength with high accuracy. On a sample consisting of 105 boards of Norway spruce, \(45 \times 145 \times 3600\) mm, the coefficient of correlation between IP and bending strength was \(R^2 = 0.68\) (to be compared with \(R^2 = 0.59\) obtained for dynamic longitudinal MOE vs. bending strength)

- A simplifying assumption of the model was that the angle between wood fibres and the scanned surfaces, the so called diving angle, was ignored.

- Results indicated that a coefficient of determination of \(R^2 = 0.80\) or higher could be obtained between bending strength and an IP based on correct local edgewise bending stiffness.

Figure 1: Bending stiffness profile calculated on the basis of fibre orientation information from high resolution scanning, material transformation, integration of stiffness over cross sections and calibration with respect to resonance frequency and average board density

1.2 POSSIBILITIES TO ESTABLISH THREE DIMENSIONAL FIBRE ORIENTATION MODELS BASED ON LASER SCANNING

If knowledge can be obtained not only about the fibre angle projected on surfaces, which was utilized in [1], but also on the angle in relation to the surface being investigated the combined information would give a better basis for assessment of local stiffness and of the strength of the board. It has been shown [3] that the tracheid effect can be utilized for determination of the angle between the fibre and the surface investigated by considering the ratio between the two principal axes of the elliptically shaped light spot on the wood surface. It has not yet been thoroughly investigated, however, if this can be utilized for accurate and robust high-speed identification of the diving angle on timber surfaces of e.g. spruce consisting of a mixture of early wood and late wood, knots, compression wood and so on. Nor has it been shown that fibre orientation on surfaces identified using the tracheid effect give basis for accurate 3D fibre orientation for the entire volume of wooden boards.

Figure 2 is designed to explain how the tracheid effect can be used to assess the fibre orientation in 3D. It shows; (a) a wood surface with a round knot and a schematic line of laser dots; (b) the identified projection of fibre directions on the investigated surface; (c) the ratio between the length of the shorter and longer axes of the elliptic laser dots over the surface. The ratio is utilized for determination of the diving angle (higher ratio means steeper diving angle); (d) the calculated 3D orientation of fibres on the wood surface seen in a bird’s-eye view; (e) the same 3D orientation seen in a view from the right. Note that the ratio between the length of the shorter and longer axes of the elliptic laser dots in (a) give no indication regarding the signs of the diving angles, but only of the absolute value of them. Hence, the fibre orientations shown in (e), all fibres there seemingly directed as indicated by the arrow at \(\beta\), are not correct with respect to the sign. Some complementary information, in addition to the shape of the elliptic laser dots, is thus needed to decide the true sign of the local diving angles.

A recent work on the utilization of detailed information of 3D fibre orientation in timber for strength grading purposes is presented in [4] but the fibre orientation model employed there relied on general assumptions of fibre orientation around knots and not on detailed measurements of the particular board investigated.

1.3 AIMS AND LIMITATIONS

The first aim of this research is to evaluate to what extent the absolute value of the diving angle can be accurately determined for Norway spruce timber on basis of laser scanning and the tracheid effect. Since the tracheid effect will not give information on the sign of the diving angle, knowledge of timber and how trees grow must be considered in order to identify the sign of the diving angle in each position. Therefore the second aim is to evaluate if the information obtained through laser scanning of a board, in combination with general knowledge of trees and timber, give a sufficient base for identifying the true orientation in 3D of fibres on wood surfaces.

A limitation of the research is that only side boards of Norway spruce, i.e. boards cut from the tree with a distance to the pith, and where the annual rings are fairly
close to parallel with the wide face of the boards, are examined.

Figure 2: (a) A wood surface with a round knot and a schematic line of laser dots, (b) projected fibre orientation, (c) ratios indicating diving angles, (d) 3D fibre orientation seen in a bird’s-eye view, (e) the same 3D fibre orientation seen in a view from the right (erroneous with respect to the sign).

2 THEORY

In this section a brief account of the theory and assumptions involved are given. It concern the tracheid effect, basics regarding the growth of trees and branches and the modelling employed for identifying directions of branches and location of the pith.

2.1 THE TRACHEID EFFECT AND DETERMINATION OF DIVING ANGLE

A thorough account of the technique to identify the direction of fibres in soft wood by utilizing the tracheid effect is given by Simonaho et al [3]. They performed experiments on small samples of clear wood of Scots pine and Silver birch. Samples were cut in such a way that the diving angles to the saw planes were known and in the range of 0 to 90° in steps of 10°. They plotted the relation between the shape factor of the detected laser dots on the wood surfaces, i.e. the ratio between the shorter and the longer axes of the light spots, and the known diving angles of the investigated sawn wood surfaces and fitted a function to the data. No significant differences were found between Scots pine and Silver birch with respect to the relation between the ratio and the diving angle. For verification purposes they also investigated the fibre angle along a single line in a small piece of wood including a knot and reported a coefficient of correlation of $R^2 = 0.91$ between the true diving angle and the diving angle assessed in the way described. The true diving angle was assessed by determination of the in-plane fibre angle of the surface oriented in a 90° angle to the surface on which the diving angle was assessed.

2.2 FIBRE ORIENTATION WITHIN TREES

Different flow-grain models, e.g. Guindos and Guaita [5] and empirical expressions for the fibre orientation in wood, Foley [6], have been presented. They do not utilize information on actual fibre orientation from measurements based on the tracheid effect or the like but the models are based on and reflect the general structure of trees with respect to the relations between location of pith, directions of knots and directions of fibres. For the purposes of the present research, the fibre orientation in the $lr$-plane in a piece of wood including a knot was considered. Figure 3 shows photographs of such a piece of wood complemented with drawn lines indicating the location and direction of the pith of the log from which the piece of wood is cut, the pith of a branch/knot that is part of it and the fibre orientation in the $lr$-plane. One thing that can be noted is that the end of a fibre being closest to the pith of the log has a longer distance to the pith of the knot than what the other end of the fibre has. This observation can be used to decide whether a positive or negative sign should be assigned to a diving angle identified on a surface in the $lt$-plane close to a knot, provided of course that we are able to identify the three dimensional directions of the pith of the log and the pith of the branches/knots. Another thing that can be noted is that branches in trees are generally, though not always, directed slightly upward in direction from the pith towards the bark of the tree. The significance of this, for our purposes, will be returned to later.

Figure 3: Photographs of a piece of wood in the $lr$-plane and $lt$-plane of the log from which it is cut, respectively, complemented with drawn lines indicating the location and direction of the pith of the log, the pith of a branch/knot being present in the piece and the main fibre orientation of the wood in the $lr$-plane.

It would probably be possible to make use of this observation in order to decide the sign of the diving angle even if it is determined on a surface that is not very close to an $lt$-plane of the log.
It should be noted that some fibres in the vicinity of knots take other directions than the majority of the fibres, which is due to the integration of the branch to the stem [7]. The determination of fibre orientation aimed at in this paper should, however, represent the majority of the fibres in a certain position with a resolution within about one or a few millimetres. The total effect of the true, rather complex fibre orientation on the material properties of wood close to knots is largely unexplored but assumed important for the local stiffness and strength of timber.

3 MATERIAL

The study comprised in total 20 boards of Norway spruce with dimensions 24×95×2000 mm. They were selected, cut and planed from an original batch of 360 boards of dimensions 25×125×4800 mm sampled at Södra Timber’s sawmill in Torsås in the south east of Sweden. One of the wide faces of each board was planed while the other sides were sawn. All the boards contained both dead and live knots. Before scanning the boards had been stored in a climate room at a temperature of 20 °C and 65 % relative humidity for about eight months. After that, their average moisture content was 12.9 % with a standard deviation of 1.0 %.

4 IMPLEMENTATION

The implementation consists of scanning the boards, calibration of model parameters for a first interpretation of the axes of elliptic laser dots into fibre angles, modelling and calculation scheme for determination of location and direction of knots and final determination of fibre directions.

4.1 PERFORMANCE OF SCANNING

The boards were fed through a scanner of make WoodEye®, see Figure 4 (left), in a speed of about 75 meters per minute. All four longitudinal sides of the boards were exposed to laser rays and photographed, see illustration in Figure 4 (right) showing an overview of the WoodEye system with lasers, light and multisensor cameras. The resolution achieved regarding fibre orientation information was approximately 1.3 mm in the longitudinal board direction and 4 mm in the transversal direction for each of the examined surfaces.

4.2 CALIBRATION OF PARAMETERS

The basic information from the scanning consists of images of elliptic laser dots. For a wood surface including a knot the light intensity of laser dots may be visualized as in Figure 5. Of course, when the directions, and in particular the lengths, of the main axes of the elliptically shaped laser dots are to be determined from an image from the scanning it can be done in more or less sophisticated ways. A simple truncation at a fixed threshold value for the light intensity is the most simple but probably not the most accurate method to use for determination of the lengths of the axes. In the present research, truncation at a fixed threshold was applied. No alternative methods for assessment of lengths and directions of the main axes of the elliptic light spots are evaluated. The information relied on are the directions and lengths of the main axes determined by the WoodEye machine.

Here the ratio of the length between the shorter axis and the longer axis is denoted R, and it is used for determining the absolute value of diving angle, \( \beta \). The following equation expresses the employed relation between \( \beta \) and R.

\[
\beta = \cos^{-1}\left(\frac{\left(\frac{l_1 + l_2}{2} - R\right) \cdot 2}{l_2 - l_1}\right)
\]
Equation (1) expresses a similar relation as the one established in [3], which was established on the basis of experimental data, but it also contains the two parameters, $l_1$ and $l_2$, which may be used for further calibration. This calibration option in Equation (1) is motivated since different wood species are investigated, differences in the interpretation between elliptically shaped laser dots and $R$ may occur, the light intensity inside scanners may differ, and so on. The parameter $l_1$ is simply the value of $R$ below which $\beta$ should be set to zero degrees and $l_2$ is the value of $R$ above which $\beta$ should be set to 90 degrees. Figure 6 shows the relationship between $\beta$ and $R$ as expressed by Eq. (1) and the significance of the parameters $l_1$ and $l_2$. Figure 7 shows photographs of the two wide face surfaces of a part of a board, the side closest to the bark (a1) and the side closest to the pith (b1) along with colour plots showing the ratio $R$ which can be used for determination of diving angle. Colour plots (a2) and (b2) of Figure 7 show, for the two surfaces, $R$ in maximum resolution, i.e. in the resolution obtained from the scanner, while colour plots (a3) and (b3) show $R$ being averaged over surrounding areas of 5×5 mm. Of course, the most striking feature of the colour plots representing $R$ is the detection of knots, which are unmistakably different in colour compared to the rest of the wood. However, small differences in colour (lighter and darker blue, respectively, in Figure 7) representing clear early wood and clear late wood, respectively, are also noted. This difference is probably due to the thickness of the cell walls being different in early wood and late wood which may affect the spread of light, rather than due to different diving angles.

4.3 MODELLING AND CALCULATION SCHEME

A first objective in the calculation scheme is to identify knots on the two wide face surfaces of the boards on the basis of identified diving angles. In order to assess diving angles, values must be assigned for the parameters $l_1$ and $l_2$, see Equation 1, and to be able to conclude that a certain position on a surface is part of a knot a threshold value, $\beta_t$, for the diving angle must be set. Values employed here are $l_1 = 0.54$, $l_2 = 0.82$ and $\beta_t = 50^\circ$, the latter implying that each position on the wood surfaces at which a diving angle larger than 50$^\circ$ is identified is interpreted as being part of a knot. Regarding the values employed for $l_1$ and $l_2$, these are based on what gives a good visual resemblance between diving angles on a wide face with projected fibre angles on the adjacent narrow face. The comparisons were made where knots appeared on edges in a similar orientation as is shown in Figure 3. In order to reduce the influence of measurement noise the relationship between $R$ and $\beta$ according to Equation 1 is employed on values of $R$ being averaged over surrounding areas of 5×5 mm, corresponding to the images shown in Figure 7 (a3) and (b3).

Figure 6: Relationship between the shape factor, $R$, and the absolute value of the diving angle, $\beta$. The parameters $l_1$ and $l_2$ are used for calibration to experimental data.

Figure 7: Photographs of the wide face surfaces of a part of a board, the side closest to the bark (a1) and the side closest to the pith (b1) along with colour plots showing the ratio $R$ which can be used for determination of diving angle. Figures (a2) and (b2) show, for the two surfaces, $R$ in maximum resolution, i.e. in the resolution obtained from the scanner, while (a3) and (b3) show $R$ being averaged over surrounding areas of 5×5 mm.
The next step is to set up rules to decide if positions on one wood surface being identified as parts of knots are parts of the same knot or of different knots. Of course, if two adjacent positions in longitudinal or transversal direction are both identified as parts of a knot it is assumed that they are parts of the same knot. After first having identified knots as coherent areas in this way an additional rule is applied. If two different knot areas are closer to each other than a certain distance it is assumed that they are parts of the same knot. If the distance between the centre of one coherent knot area and the centre of another coherent knot area is less than

\[ r_{\text{crit}} = \sqrt{\frac{A_1}{\pi}} + \sqrt{\frac{A_2}{\pi}} + r_{\text{fix}} \]  

(2)

where \( A_1 \) and \( A_2 \) are the areas of the two coherent knot areas and \( r_{\text{fix}} \) is an additional fixed distance, the two coherent knot areas are considered as a single knot of size \( A_1 + A_2 \). In this investigation, the \( r_{\text{fix}} \) value was set to 20 mm. The procedure for possible connection of separate coherent knot areas is repeated for each board side until no more coherent areas are connected according to this rule. Finally, remaining knots being smaller that a critical knot area, \( A_{\text{crit}} \), here set to 10 mm\(^2\), are disregarded and not considered as knots at all in the subsequent procedure.

Knots identified within 50 mm from the ends of the boards are also disregarded. The reason for this is that identification marks of black ink were written on the wide face surfaces close to the ends. Where the text appears the black ink cause disturbances affecting the value of \( R \), which is the basis for identification of knots.

When knots have been identified with respect to size and position on each of the two wide surfaces a criterion is applied to assess if the same knot is visible on both sides of the board. If the coordinates in the plane of the wide face surfaces, i.e. the \( x_y \)-plane, of the centroid of a knot that is visible on one side is closer than 24 mm to the centroid of a knot visible on the other side, it is assumed that it is the same knot. The critical distance employed, 24 mm, corresponds to the thickness of the board.

For most boards, a number of knots are visible on both wide faces and for each such knot it is assumed that the pith of it crosses the centroid of the knot area identified on each surface. Thus, the pith of each such knot is determined with respect to both position and direction in a 3D Cartesian coordinate system. Having calculated the direction of a number of knots in a board, corresponding to the branches of the tree from which the board is cut, it is also possible to draw conclusion regarding the location of the pith of the log and to determine which end of the board that is closest to the root end of the tree. Figure 8 shows (a) a sketch of a board, along with a 3D Cartesian coordinate system, (b) the orientation in the \( xz \)-plane of identified centre axes of knots/braches and (c) the orientation in the \( yz \)-plane of the same knots. Clearly, for the example displayed, see Figure 8 (b), considering the growth properties of wood, the pith of the log must be located above the top surface of the board sketched in (a). Considering the direction of branches displayed in (c) it is then also evident that the end of the board with \( y \)-coordinate equal to zero must be the end closest to the root end of the tree from which the board is cut.

\[ \text{Figure 8: (a) A sketch of a board, along with a 3D Cartesian coordinate system, (b) the orientation in the \( xz \)-plane of identified centre axes of knots/braches and (c) the orientation in the \( yz \)-plane of the same knots.} \]

In order to determine the position of the pith of the log in the \( xz \)-plane a calculation is performed in the following way: (1) the small angle between each pair of knot directions in the \( xz \)-plane is calculated, (2) the median angle among all those calculated is identified, (3) for each pair of crossing knot directions, for which the small angle is larger than or equal to the mentioned median angle, the point of intersection is identified, (4) the average \( x \)- and \( z \)-coordinates of the identified points of intersection are calculated and regarded as the position of the pith of the log. In order to assess which end of the board that is closest to the root end of the log the angle in the \( yz \)-plane between the \( y \)-axis and the direction of each of the knots is calculated. The median angle and the corresponding knot are identified. If the \( y \)-coordinate of this knot, on the pith side of the board, is lower than the \( y \)-coordinate on the bark side, it is assumed that the end of the board with \( y \)-coordinate equal to zero is the root end, i.e. the end of the board closest to the root end of the tree from which it is cut.

Some knots are only identified on one of the wide faces of the board. Such knots are not used to determine the position of pith or for identification of the root end of the board. Instead, it is assumed that such knots are, in the \( xz \)-plane, directed towards the position of pith of the log, which is determined on the basis of the other knots. In the \( yz \)-plane the knots that are only visible on one wide face are assumed to have the same orientation as the one with the median angle to the \( z \)-axis, i.e. the knot used for assessing the root end of the board.

What now remains is to decide, for each position on the wide faces where the absolute value of the diving angle has
been determined, is if the diving angle is positive or negative. For each position on a wide face the closest knot is identified. If, when assuming a positive diving angle, the end of the fibre closest to the pith of the log has a longer distance to the pith of the knot than what the other end of the fibre has, cf. Figure 3, the positive sign of the diving angle is preserved. Otherwise it is changed to a negative sign.

5 RESULTS AND DISCUSSION

5.1 LOCATION OF PITH AND ROOT END

Figure 9 shows, for board number 1, the calculated location and direction of the knots and the pith of the log. The knots that were visible on both the wide faces, and thus useful for the assessment of the location of the pith of the log, are indicated by red solid lines and the knots visible only on one wide face are indicated by dashed black lines. The pith of the log is indicated by a solid black line and concentric circles are drawn around it at the ends of the board; (a) perspective image, (b) view in the xz-plane, (c) view in the yz-plane and (d) view in the xy-plane. It may be noted that also the drawings displayed in Figure 8 (b-c) originate from the analysis of board number 1.

Table 1 shows for each of the 20 boards the number of knots that could be used for assessment of the location of the pith of the log, the calculated x- and z-coordinates of the calculated location of pith (see the coordinate system defined in Figure 9) and a check on the accuracy of the assessment of the root end. For most of the boards the approximate location of the pith was correctly identified in the sense that the z-coordinate of the position of the pith was positive (it is known that the pith side of the board was always turned upward during scanning) and the root ends of the boards were accurately identified. There were, however, a few exceptions. For two of the boards, number 11 and number 17, only one knot was visible on both the wide face surfaces. Since the direction of at least two knots must be assessed, in order to have any crossing knot directions, no location of pith could be calculated for these two boards. For one of the boards, number 15, only two knots were visible on both wide faces. This is a very poor basis for calculating the position of the pith and for this board the result was quite erroneous. According to the calculation performed the pith side of this board should have been turned downwards during scanning, which it was not.

Table 1: For each of the 20 boards, number of knots visible on both wide faces, i.e. number of useful knots, calculated location of pith and identification of root end.

<table>
<thead>
<tr>
<th>Board</th>
<th>Number of useful knots detected</th>
<th>Location pith (mm)</th>
<th>Root end correctly identified</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>7</td>
<td>54    91</td>
<td>Yes</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>33    159</td>
<td>Yes</td>
</tr>
<tr>
<td>3</td>
<td>8</td>
<td>77    139</td>
<td>Yes</td>
</tr>
<tr>
<td>4</td>
<td>8</td>
<td>28    111</td>
<td>Yes</td>
</tr>
<tr>
<td>5</td>
<td>3</td>
<td>49    195</td>
<td>Yes</td>
</tr>
<tr>
<td>6</td>
<td>5</td>
<td>38    92</td>
<td>Yes</td>
</tr>
<tr>
<td>7</td>
<td>5</td>
<td>48    104</td>
<td>Yes</td>
</tr>
<tr>
<td>8</td>
<td>4</td>
<td>30    174</td>
<td>Yes</td>
</tr>
<tr>
<td>9</td>
<td>5</td>
<td>77    103</td>
<td>Yes</td>
</tr>
<tr>
<td>10</td>
<td>5</td>
<td>52    110</td>
<td>Yes</td>
</tr>
<tr>
<td>11</td>
<td>1</td>
<td>-     -</td>
<td>-</td>
</tr>
<tr>
<td>12</td>
<td>3</td>
<td>62    131</td>
<td>Yes</td>
</tr>
<tr>
<td>13</td>
<td>7</td>
<td>59    90</td>
<td>Yes</td>
</tr>
<tr>
<td>14</td>
<td>4</td>
<td>54    258</td>
<td>Yes</td>
</tr>
<tr>
<td>15</td>
<td>2</td>
<td>150   -386</td>
<td>No</td>
</tr>
<tr>
<td>16</td>
<td>8</td>
<td>67    107</td>
<td>Yes</td>
</tr>
<tr>
<td>17</td>
<td>1</td>
<td>-     -</td>
<td>-</td>
</tr>
<tr>
<td>18</td>
<td>10</td>
<td>73    151</td>
<td>Yes</td>
</tr>
<tr>
<td>19</td>
<td>5</td>
<td>59    54</td>
<td>Yes</td>
</tr>
<tr>
<td>20</td>
<td>4</td>
<td>37    115</td>
<td>Yes</td>
</tr>
</tbody>
</table>
Figure 10 shows photographs of the root and the top ends of four of the boards, namely board number five to eight, displayed in subplot (a), (b), (c) and (d), respectively, along with images showing calculated location and orientation of the knots of each board, indicated by red lines, and parts of concentric rings around the calculated position of the pith of the log in the $xz$-plane. By comparing the curvature of the parts of the concentric rings that are drawn with a black dashed line, with the curvature of the annual rings it is possible to assess, qualitatively, the accuracy of calculated locations of the piths of the logs. Board number five to eight were selected for demonstration without any consideration to how well the location of pith could be assessed for these boards compared to how well it could be done for other boards. They represent, however, different numbers of knots being useful for the calculation of the location of the pith and a wide range of calculated distances between board and pith.

For board number five, shown in Figure 10 (a), it is clear that the distance between the board and the pith of the log from which it is cut is overestimated. It can be seen that the annual rings of the board, both in the root end and in the top end, have a sharper curvature than the concentric rings around the calculated location of the pith. Since the location of the pith was calculated on the basis of only three different knots it is not surprising that the prediction of the location of the pith is rather poor for this board.

For board number six, shown in Figure 10 (b), the curvature of the concentric rings around the calculated location of the pith coincide almost perfectly with the annual rings, both in the root end and in the top end of the board. Thus it seems like the calculated location of the pith, which is here based on the assessed directions of five different knots, must be close to the actual position of the pith.

For board number seven, shown in Figure 10 (c), the shape of the annual rings are not very like concentric rings and thus it is hard to assess the true location of the pith on the basis of the annual rings. The curvatures of the concentric rings are, however, seemingly close to the average curvatures of the annual rings and thus it is likely that the calculated location of the pith is close to the true location.

For board number eight, shown in Figure 10 (d), the annual rings of both the top end and the root end are, just as the top end of board number seven, more or less disturbed by knots or other imperfections. The curvature of the annual rings of the root end suggest that the calculated distance between the board and the pith is slightly overestimated, but it is doubtful if the same can be said about the curvature of the annual rings of the top end. The calculated location of the pith is probably fairly close to the true location.

Figure 10: Photographs of the root and top ends of four different boards (number five to eight represented in subfigure (a-d), respectively) along with images showing the calculated location and orientation of knots, indicated by red lines, and parts of concentric rings around the calculated positions of the pith in the $xz$-plane.
5.2 IDENTIFIED DIVING ANGLES

Figure 9 shows the calculated 3D fibre orientation over the two wide faces of a 130 mm long part of a board including a knot; (a) a schematic perspective image; (b) the fibre orientation of the top surface in the \( xy \)-plane; (c) the fibre orientation of both the surfaces in the \( xz \)-plane; (d) the fibre orientation of both the surfaces in the \( yz \)-plane; (e) the fibre orientation of the bottom surface in the \( xy \)-plane. The knot is the same one that is shown in the photographs of Figure 6.

The fibre orientation that can be seen in the \( xy \)-plane, subplot (b) and (e) of Figure 9, follow the longer main axis of the elliptic laser dots on the surface from the scanning and in this plane the result is no doubt reliable. The ratio, \( R \) that determines the diving angle, \( \beta \), only affects the result in the \( xy \)-plane in the sense that the length of the lines representing the local fibre orientation are shorter in positions where the diving angle is substantial, which is in the area of the knot. In the \( xz \)-plane (c) and in the \( yz \)-plane (d) the picture depends more directly on the values of \( R \).

The results show, however, that the calculated orientation of fibres around a knot agrees quite well with what is known about the fibre orientation around knots in general. The rule applied for deciding the sign of the diving angle works very well. Any systematic differences between the true diving angle and the calculated diving angle can be handled by adjustment of the parameters \( l_1 \) and \( l_2 \) of Equation 1, or by replacing Equation 1 with a similar function. Of course, a thorough calibration with respect to the relation between \( R \) and \( \beta \) should be carried out for each scanner to be used for assessment of diving angles.

6 CONCLUSIONS AND FURTHER WORK

The research has shown that the 3D fibre orientation on wood surfaces of Norway spruce can be thoroughly investigated by means of laser scanning utilizing the tracheid effect, which in turn can be performed in a speed corresponding to the production speed at a sawmill.

For a set of 20 side boards of dimension 24×95×2000 mm knots were identified by first identifying areas with steep diving angles. The orientation and position of the pith or centreline of knots that could be identified on both wide faces of a board were calculated and used for identification of the location of the pith of the log from which the board was cut, and also for identification of the root end of the log. Results showed that the root end in most cases could be identified with certainty, and that the location of the pith of the log can be identified with accuracy. The location of the pith of the log was utilized in the assessment of the 3D fibre orientation in the sense that it provided information necessary for assigning a positive or negative sign of the local diving angles already known with respect to the absolute value on the basis of the tracheid effect.

The 3D orientation of wood fibres was primarily assessed in the surrounding of knots. When it comes to assessment of small diving angles different from zero that may occur
in clear wood it is concluded that these are probably hard to determine accurately, since different light spread in early wood and late wood may cause difficulties when trying to transform the shape of laser dots into diving angles on this level. However, this issue should be addressed more thoroughly in further research.

An important aim for the future is to develop the procedure of identifying the centreline of knots and the pith of the log so that it can be applied not only for assessment of side boards but also when the pith of the log is located very close to one of the sides of the board or even within the board. Of course, it would be easier to identify the centrelines of knots if the location of the pith of the log was first identified by means of scanning of the boards ends. Another aim is to model the 3D orientation of fibres within the entire volume of any type of board of Norway spruce on the basis of knowledge of the 3D fibre orientation on its longitudinal surfaces and the location of the pith. Successful results in these respects are within reach continuing the research presented herein. If complete 3D fibre orientation data of any individual board of Norway spruce can be attained through calculations in the same high speed as the basic information is attained through scanning it could be utilized for accurate prediction of stiffness, strength and even shape stability of structural timber in industrial processes.

REFERENCES