Spiral Grain in Norway Spruce

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Abstract

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Wood is a major construction material that is used in many contexts, and for different purposes. Serious problems may arise, however, when moisture related deformations as twist occur in wood used in different types of building structures, joinery and furniture. Twist can be explained to a great degree by the helical deviation of the grain angle in relation to the longitudinal direction of the log or the sawn board. Wood fibres form a spiral within the tree, and this is a natural occurrence that is named spiral grain. The wood fibres close to the pith in Norway spruce form a left-handed spiral. In most trees the grain angle turns over to be right-handed with time. Sawn timber that exhibits large grain angles lead to problems of shape stability and stiffness in finished constructions. In this thesis the spiral grain in Norway spruce (*Picea abies* (L.) Karst.) was stated as well as the effect on sawn timber.

The material was based on sample trees from Sweden and Finland. Samples were taken in twenty-two stands at different heights in tree. From six stands studs were sawn and dried for measuring twist and other deformations. The spiral grain was measured with the method scribe test on 390 log discs taken at the top-end of the logs. Account was given concerning changes in grain angle from pith to bark, regarding both increasing annual ring numbers and distance from pith. The development of grain angle over tree age was utilized to study whether annual growth, size of tree, height in tree as well as silvicultural treatments affected spiral grain. Moreover, the relation between grain angle and distance to pith (in mm) was used to forecast twist in sawn timber.

The left-handed grain angle was at its greatest between the fourth and eighth annual rings. Thereafter for most trees the grain angle turned from left-handed to right-handed in a linear fashion, in a manner that was unique for each individual tree. The pattern of spiral grain differed significantly between different stands, regarding change of inclination with increasing age or distance from pith. The culmination of the grain angle close to the pith occurred at somewhat higher age higher up in the trunk. The grain angle decreased faster in top logs than it did in the butt logs. The largest trees within a stand had a grain angle that turned to right in a slower way than smaller ones. The thinning strength and type of thinning regime also affected the character of spiral grain in the remaining trees in a stand. There was an indication that strong thinnings, where fast growing trees are retained, may lead to more individuals in a stand that exhibit high grain angles under bark.

With knowledge of the size and direction of the grain angle under bark, and the diameter of the log, calculations can be made that show how twisted the sawn timber will be after drying. This can be used for deciding whether an individual log can profitably be sawn and processed further or not. The grain angle under bark can be used to remove trees showing the greatest degree of spiral grain already in the first thinning.

Silvicultural methods aiming at even and dense Norway spruce stands, which normally is practised in Scandinavia, will probably result in timber with relatively low risk concerning large grain angle and subsequent risk for twist in sawn wood.

Keywords: Spiral grain angle, drying deformation, warp, wood quality, Norway spruce, *Picea abies*.

Sammanfattning

Trä är ett material som används i många sammanhang och för olika ändamål. Vid användning i byggnader, snickerier och möbler uppstår ofta problem med att det ändrar form. Formförändringar uppstår då fuktkvoten förändras. Ett formfel är skevning som till stor del förklaras med fibervinkelns avvikelse i förhållande till stockens eller sågsnittets längdriktning. Vedfibrerna är alltid mer eller mindre spiralformigt orienterade i trädet, vilket är en naturlig förekomst som benämns växtvridenhet. Nära märgen bildar vedfibrerna hos granen en vänstervriden spiral. Med ökande avstånd från märgen övergår fiberlutningen till en högervriden spiral. Sågat virke med stora fibervinklar leder till problem med formstabilitet och lägre styvhet i den färdiga konstruktionen. Denna avhandling belyser växtvridenheten hos gran (*Picea abies* (L.) Karst.) och dess inverkan på sågat virke.

Materialet bygger på provträd från Sverige och Finland. Proverna är tagna i tjugotvå bestånd på olika höjd i träden. Sågat och torkat virke från sex av bestånden har använts för mätning av skevning och övriga formförändringar. Växtvridenheten mättes genom ritsning på 390 stamtrissor tagna från toppen i varje stock. I avhandlingen redovisas fibervinkelns förändring från märg till bark både med stigande årsringsnummer och med avståndet till märg. Sambandet mellan fibervinkeln och årsringsnummer från märg har använts för att studera om växtvridenheten påverkas av löpande tillväxt, trädets storlek, höjden i trädet likväl av skogliga ingrepp. Medan förhållandet mellan fibervinkeln och avståndet till märg (i mm) användes för beräkningar av skevheten på det sågade virket.

Fibervinkeln är som störst mellan årsring 4 och 8. Därefter förändras oftast fibervinkeln linjärt från vänster till högerlutande på ett för varje träd individuellt sätt. Växtvridenheten skiljer sig åt mellan olika bestånd både med avseende på stigande årsringsnummer och med ökande avstånd från märg. Fibervinkelns kulmination nära märg inträffar vid något högre årsringsnummer högre upp i stammen och avtar därefter snabbare än vad den gör i rotstockarna. De största träden inom bestånden har en mer långsamt avtagande fibervinkelförändring än de något mindre träden. Gallringsstyrka och gallringsform påverkar växtvridenhetens karaktär i det kvarvarande beståndet. Hårda gallringar och kvarlämnande av träd med stark tillväxt tycks ge fler individer i beståndet som får höga fibervinklar under bark.

Med vetskap om fibervinkelns storlek under bark och stockens diameter kan beräkningar utföras som visar hur skevt det sågade virket blir då det torkats. Detta kan användas för beslut om en enskilda stockars lönsamhet för vidareförädling som sågtimmer. Med utgångspunkt från fibervinkeln under bark kan de mest växtvridna träden gallras bort redan vid tidpunkten för första gallring.

Skogsskötselmetoder som syftar till jämna och täta granbestånd, vilka oftast används i Skandinavien, ger sågtimmer med liten risk för stora fibervinklar och följaktligen måttliga mängder med skevt virke.

Sökord: Växtvridenhet, fibervinkel, formfel, trä kvalitet, gran, *Picea abies*.

Preface

Which trees will give straight construction wood? This was a question from a technical Ph.D. student who participated in a course about forests and forestry. It was in 1993 and I couldn't answer the question. After years of trading timber for tens of millions of Swedish crowns, I felt embarrassed that this question had never crossed my mind.

Now I can tell which Norway spruce trees will give twisted studs!

The theoretical work presented in this thesis has been carried out at the School of Industrial Engineering, University of Växjö. The measurement of spiral grain was carried out at the Asa Forest Research Station, belonging to The Swedish University of Agricultural Science. The main part of the experimental work was carried out in co-operation with the EC-project: Improved Spruce Timber Utilisation, "STUD".

Financial support was provided by Södra Timber AB, Södra Skogsägarnas Stiftelse för Forskning, Utveckling och Utbildning, Stiftelsen för Kunskaps- och Kompetensutveckling (KK-foundation), Asa Forest Research Station, School of Industrial Engineering at the University of Växjö, and the sawmill companies Rörviksgruppen AB and AB Geijer & Söner. I gratefully acknowledge the financial support provided by each of these sponsors.

I would like to express special thanks to my supervisor Thomas Thörnqvist for his support and his aid in arranging financial backing. I would also like to thank Anders Baudin, Mats Nylinder, Hans Petersson and Göran Örlander, for their support and guidance during the course of this study.

Several additional people have contributed, in various ways, to this work and I would like to express my gratitude to – All the staff at Asa Forest Research Station, and special thanks to Kjell Rosén and Emil Nilsson who made most of the 28 336 measurements of spiral grain. In addition, I would like to thank Jörgen Filipsson, for the illustrations he has done, Robert Kliger for his co-operation in the "STUD" project, Ola Dahlblom, Peder Gjerdrum, Leif Eklund and Sune Linder for co-operation with proceedings and papers, and the English has been considerably improved by Jeff Winter.

Finally, I want to thank my beloved family, Gunilla for her loving support and my sons Joel, Henning and Jakob who are good at the sport orienteering.

Växjö in September 2002 Harald Säll

Notations

The major notations and symbols are listed below. These are explained in the text when they appear for the first time.

General notations

°	degrees
>	larger
<	smaller

Roman letters and abridgements

ARC	curvature: Defined as inverse of distance
D	dominant trees
DBH	diameter of breast height
Dist	distance from pith
deg	degrees
E_l	modulus of elasticity in longitudinal direction
G	site index for Norway spruce
GA	spiral grain angle
GAslope	linear slope of grain angle
GAstud	spiral grain angle in centre of stud
GAub	spiral grain angle under bark
GA50	grain angle 50mm from pith
H	height of tree
HD	highest of dominant trees
HGB	relative live crown height
H100	predicted dominant height (m) of 100 trees/ha at 100 years
ha	hectare
l	length of stud
l-, r-,t-	main directions in wood
m^3sk/ha	total volume over bark per hectare
mc	moisture content, the amount of water contained in wood, expressed as a percentage of the weight of oven-dry wood
MPa	mega Pascal
p	value of significance
RN	annual ring number from pith
RW	annual ring width

R^2	R-Squared
r	radius, distance from pith to centre of stud
S1,S2,S3	layers of cell wall
S&J	Stevens and Johnston's analytical model
STUD	EC-project: Improved Spruce Timber Utilisation
s	tangential shrinkage
s_e	standard error of estimate
Taper	taper of log
TW	twist of sawn wood
TW10%	twist at 10% moisture content
TW18%	twist at 18% moisture content

Greek letters

α	intercept coefficient
α	twist of stud
β	inclination coefficient
ε	random error
θ	spiral grain angle in centre of stud (GAstud)
σ^2	variance

Contents

1. Introduction

1.1 Background

Current knowledge of how the properties of wood affect sawn timber and furthermore affect the finished product is greatly deficient. A buyer of timber finds it difficult to specify exactly his quality requirements and demands, and if they are specified, they rarely reach the forest owner or sawmill. Some of the demands and requirements that can be made by the customer are precision of measurement, shape stability, stiffness, strength, rot resistance, density and appearance. One of most common reasons for a customer to avoid using wood is the lack of shape stability. Within the building industry, twist and spring are the two most serious shape defects, which lead to unacceptable problems both for the carpenter and within the finished construction.

There is a clear connection between spiral grain and how twisted the sawn timber will be when it is dried. Twisting increases as the timber dries. This sometimes results in changes in shape within a completed construction, leading to expensive claims being made. Norms and rules regarding the degree of errors in form that are acceptable on a building site have been studied by, amongst others, Johansson et al. 1990, 1994 and Bergman et al. 1997. Since twisted timber leads to problems for users, thereby damaging the reputation of timber as building material, there are good reasons for rejecting trees and logs that will show unacceptable deformation in the sawn product. To be able to make these decisions, knowledge is needed about spiral grain and how it affects the finished product.

In this project, spiral grain has been studied in Norway spruce (*Picea abies* (L.) Karst.) grown in Sweden and Finland, with the emphasis made on southern Sweden. The motive for this limitation is the dominance of Norway spruce in Swedish forests where approximately 60% of the volume of forest consists of spruce. The dominant position of spruce as construction timber in the building industry is also a reason for studying only Norway spruce in this project.

1.2 General about wood

Wood consists mainly of cellulose, hemicellulose and lignin. Furthermore, there are also between 2% and 15% extractives, which consist of a large number of chemical compounds. There are relatively large differences in the levels of extractives between different species of trees, and even between individuals of the same species. The differences in chemical composition that are found within a tree depend on, amongst other things, height in the tree, heartwood/sapwood, and early wood/late wood.

For the individual tree, the genetic inheritance and the social standing of the individual within the stand have a differing degree of influence on the various properties of the wood. Within the same species, there are also differences between different stands and regions. These differences depend upon which site the tree grows in. The site is characterised by the climate, the texture and nutritional status of the ground, plus the topography of the terrain, which affects the amount and accessibility of soil water available to the trees. These factors, together with human activity in the form of silviculture, affect properties of the wood.

It is also generally acknowledged that the technical properties of sawn timber differ between individuals of one species from within the same stand, and not least within the individual tree. The most obvious differences are variations in stiffness, strength, shape stability, and constancy. As far as individual trees are concerned, a number of properties change according to distance from pith (Bendtsen 1978). Regarding spiral grain, this varies according to distance from pith in a radial direction, in a mainly species-typical fashion (Harris 1989). Spiral grain means that the wood fibres are oriented in a spiral form around the pith. For spruce, Figure 1.1 illustrates this pattern.

(a) *(b)*

Figure 1.1.
(a) Cracks following the spiral grain pattern in a stem of a windthrown Norway spruce tree.
(b) An example of a split part of a log with spiral grain.

To be able to make accurate structural calculations for timber products, it is necessary to have extensive knowledge of the properties of timber. This knowledge can be gained by studying everything from the microstructure of the wood, to timber as a construction material, up to the whole structural system that timber is a part of, which is illustrated in Figure 1.2 and reported by Petersson (1996) and Petersson et al. (1997).

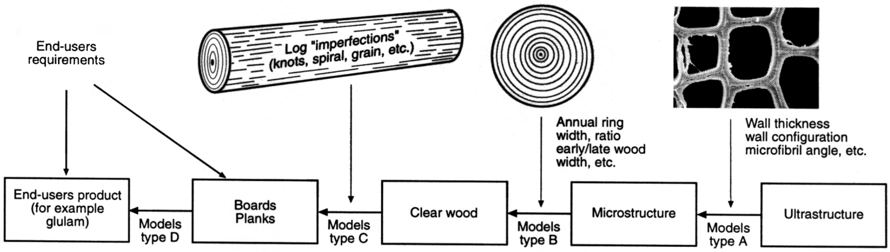

Figure 1.2. *Modelling chain for wood extending from ultra structure to end-user products.*

The construction of the cell, wood and the tree are described briefly in the following section, as an introduction to this work on spiral grain and its consequences regarding the use of wood as a construction material.

1.3 Structure of the wood cell

1.3.1 The formation of wood cells

Wooden material consists of wood cells. The shape and size of the cells depends on the physiological role they play in the tree. In a living tree there is both living and dead cells. The cells multiply via a process of cell division in the cambium layer. The cambium is a thin tissue between the bark and the wood. Bast, the phloem, is formed outwards. This is the layer that transports nutrients from the tree's crown down to the root system. Inwards, the cambium forms wood cells.

1.3.2 Types and the function of wood cells

The different types of cells in softwood are tracheids, ray tracheids and parenchymatous cells. More that 90% of wood cells are tracheids. The tracheids die soon after the cells are formed in the cambium layer, and the cell elongation. This means that the majority of cells in a living conifer are dead cells. In the sapwood the parenchymatous cells continue to live, but they are dead in the heartwood.

Within the forestry industry, the term wood fibre is more commonly used than wood cells or tracheids. The tracheids are between 0.5 mm and 5 mm long, and between 0.015 mm and 0.040 mm wide. They are somewhat thinner than a strand of human hair, which is about 0.05 mm thick. The main function of the cells is supporting, but in the sapwood they also transport water and nutrients from the roots to the needles. The tracheids in the heartwood contain no free water and stores extractives such as resins and phenols. The parenchymatous cells are large-pored and are found mainly in connection with the resin canals in the tree's longitudinal axis, in the trunks direction, where they transport and store nutrients in the sapwood. They often contain inclusions in the form of crystals, silicon, or substances of a composite chemical nature, such as resins, oils, tannins, colouring agents and gums.

Ray tracheids are those cells that have many pores for an exchange of water. They are found only in connection with rays, which transport water in a radial direction in the tree.

1.3.3 The cell wall

The cell is divided into three parts; the middle lamella, the cell wall and the cavity (cell lumen) in the cell's centre. The middle lamella is the combining layer between the cells and is composed mainly of lignin and pectin. The cell wall is composed of chains of cellulose that are joined together to form micelles, which in their turn form microfibrils, see Figure 1.3. The microfibrils are composed of cellulose chains that lay imbedded in a bed of hemicellulose and lignin. The structure of wood cells is treated by Dinwoodie (2000), Thörnqvist (1990), Saarman (1992) and Persson (2000).

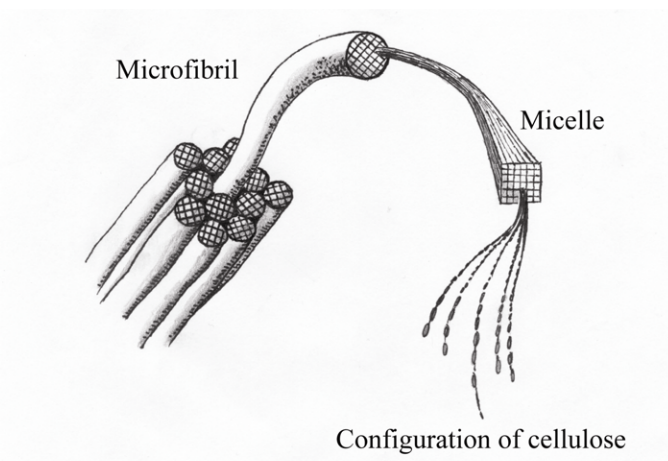

Figure 1.3 *The structure of cellulose, micelle and microfibril.*

The cell wall consists mainly of a primary wall, a secondary wall and, in a number of species of trees, such as spruce, a warty layer, see Figure 1.4. The primary wall has microfibrils in irregular patterns, which gives the cell elasticity during growth and cell elongation. The secondary wall is in turn composed of three layers, called S_1, S_2 and S_3. The microfibril layers in these three strata are orientated in parallel layers, at differing angles compared to the longitudinal axis of the wood cell. The secondary wall is formed after the cell has completed its growth and gives the cell its structural stiffness and strength.

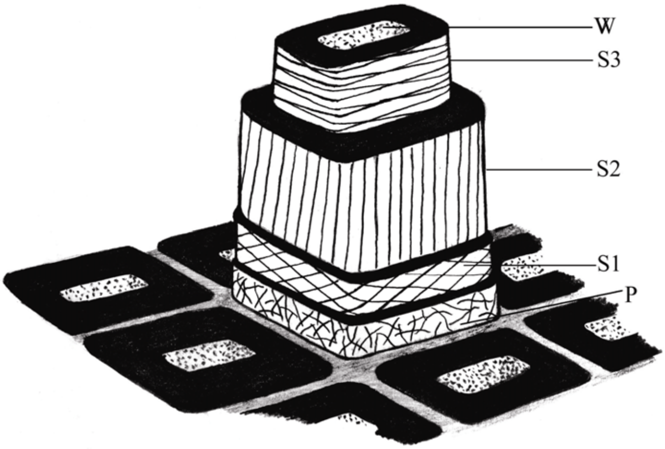

Figure 1.4. *The different parts of a mature cell wall.* (P) *primary wall,* (S) *the three layers* (S1, S2 and S3) *of the secondary wall,* (W) *warty layer*.

The microfibrils of the S_1 layer are inclined at an angle of 50-70° in both directions, which thereby forms a network. The next layer in the secondary wall is the S_2 layer, which is also the dominant layer in the cell wall and which composes almost 90% of the total mass of the wall. The microfibrils in this layer are all inclined in the same direction and seen from the outside, they are always inclined to the right. The angle of inclination of the microfibrils in this layer is mostly rather low in mature wood, but varies between early wood and late wood. The microfibril angle in the S_2 layer's early wood varies between 10° and 45° and in late wood between 0° and 30°. An average value for the microfibril angles in the S_2 layer is between 5° and 10°, in mature wood without defects such as compression wood. Corewood[1] and compression wood exhibit the largest microfibril angles in the S_2 layer.

The S_2 layer gives the cell its strength, and properties of shrinkage/expansion, mainly in the longitudinal direction. It is probable that the large microfibril angles in the corewood close to the pith result in high elasticity and flexibility in the young and slender trunk, which is

[1] The innermost layers of wood close to pith. Certain features such as cell structure and size, differ from those of outerwood. In this thesis defined as the 10 to 20 innermost growth rings. Also called innerwood, pith wood or juvenile wood.

important for coping with wind, snow and other loads. The microfibrils of the S_3 layer form a network that has an angle of inclination of between 60° and 90° in relation to the direction of the fibre. The very thin warty layer can sometimes be found within the S_3 layer.

The slope of the microfibrils in the S_2 layer does not appear to have any connection with the size and direction of the spiral grain angle (Preston 1949, Foulger 1966, Harris 1989). The spiral grain angle is dependent upon the initial cambium cell, which can incline both to the left and to the right, whilst the angle of the microfibrils in the S_2 layer is always right-handed. In the same manner, the microfibril angles in the S_1 and S_3 layer appear to be unconnected with the angle of grain.

1.4 Structure of wood

1.4.1 The annual rings

Softwood is characterized by the pronounced annual rings. An annual ring consists of two obvious layers, the light early wood and the narrower, darker layer of the late wood. The early wood consists of thin-walled and broad fibres, whilst the late wood has thicker and flatter fibres with a small cell lumen. The basic density[2] of early wood varies between 250-350 kg/m^3, whilst the density of the late wood is 600-900 kg/m^3. For a given species of softwood, the density of the late wood is approximately three times that of the early wood (Thörnqvist 1990). The average density of the cell wall is about 1500 kg/m^3 (Kollmann & Côté 1968). The density of the wood is sometimes used as a measure of a desired property in the wood, such as shape stability, or strength. Such relationships differ between different species of softwood and in different positions in the trunk, and the relationship is often weak or even non-existent. The density of the wood is a parameter that is dependent on several variables, but which is mainly governed by factors such as the density of the fibre wall, the proportion of cavities in the cell and the levels of extractives (Thörnqvist 1990).

In certain species of trees, the highest density is found closest to the pith. In spruce (*P. abies*) the density diminishes from the pith to about the tenth annual ring, and thereafter it increases until reaching the twentieth annual ring. After that, it remains at an almost constant level until it reaches the cambium, provided the forest is thinned in a suitable manner (Olesen 1977, Atmer & Thörnqvist 1982, Thörnqvist 1990). A higher proportion of extractives increases the density but does not affect the mechanical properties of the wood. On the other hand, the

[2] Basic density, quotient between dry mass and wet volume.

mechanical properties differ greatly between early wood and late wood (Holmberg 1999). Late wood, compared to early wood, has in general much greater mechanical property values regarding stiffness, hardness, tensile strength and compression strength.

1.4.2 Wood fibres

Fibre length can be of great importance for properties of strength in wood based products. A fibre length shorter than 2 mm results in lower tearing strength in paper (Senft 1986, Zobel 1981). Within the same annual ring, the fibre length is shorter in the early wood than in the late wood. An increased proportion of late wood in spruce results in an increase in the average length of the fibres. The longest fibres are found in spruce where the width of the annual rings is one to two millimetres (Nylinder & Hägglund 1954).

Fibre length is also influenced by position in the trunk. Vertically, the length of fibres increases as the living crown is approached; thereafter it decreases. In the radial direction, fibre length increases rapidly in the first fifteen to twenty annual rings in the corewood, from 1 mm to approximately 3 mm. After that the rate of increase levels out in the mature wood, and the maximum length of fibres in spruce trees is 5 mm. The shortest fibres (0.5 mm) are found at stump height, close to the pith, whilst the longest fibres (5 mm) are in the outermost annual rings at a height of 20% of the total height of the tree (Atmer & Thörnqvist 1982).

1.4.3 The properties of wood are influenced by direction

The inner structure of softwood is characterized by fibres that are mainly oriented in the tree's longitudinal direction. The fibre structure results in material properties that are greatly dependent upon direction; wood can be said to be an anisotropic material. The stiffness and structural strength of wood is considerably greater in the direction of the grain than at a perpendicular angle to it. In the same way, deformations caused by variations in moisture content are much greater in the direction perpendicular the grain than in the grain direction.

Normally the grain direction deviates somewhat from the vertical line or longitudinal axis of the tree. This spiral grain or deviation has several causes. It can be local disturbances at knots, but usually the mayor cause is spiral grain, see Figure 1.1.

Stiffness is up to 40 times greater in the direction of the grain, the l-direction, than along the annual rings in a tangential t-direction, see Figure 1.5. The shrinkage/swelling is approximately 40 times greater in the t-direction than in the direction of the grain (Dinwoodie 2000). There are also substantial differences in properties between the t-direction and the radial r-direction (from pith to bark). The stiffness in the r-direction is approximately double compared to the t-direction. And shrinkage/swelling is about the halt in r-direction compared to the t-direction. Taking into account the considerable differences in mechanical properties between l-, t- and r-directions, and that the annual rings are formed as slightly tapering cylinders it is obvious that a sawn product will have differing qualities dependent upon how it is sawn from the log.

Figure 1.5 *Main orthotropic directions in wood.*

1.5 Structure of trees

1.5.1 Taper

Tree is more or less cone-shaped. This property can be denoted as the taper of the log and is measured in mm/m. The height in the tree influences the degree of taper. At the base of the trunk, at a height of 0.5 to 1.5 m, the taper can be greater than 30 mm/m. Between the height 1.5 meter and up to the live crown base taper is between 5 to 15 mm/m. Taper increases again in the tree’s crown, where it is normally 15 to 30 mm/m. Conicity differs in the annual rings according to distance from pith (Zobel 1981).

1.5.2 Knots

Knots cause the majority of disturbances of the grain in a sawn product. The structure and direction of the fibres are altered in a three-dimensional pattern in conjunction with knots, which has negative effects on wood properties like strength, stiffness and shape stability (Foley 2001). If the timber is coarsely knotty compared to the sawn product's dimensions (thickness and width), this might result in the sawn timber being weaker and less shape stable.

1.5.3 Sapwood and heartwood

The stem wood in a young tree consists solely of sapwood. Sapwood consists of living parenchymatous cells, plus dead lignified tracheids. At a certain age, which depends on the species of tree, surroundings and geographic location, the sapwood in the stump closest to the pith is transformed to dead heartwood. The formation of heartwood begins with all of the extractives being secreted from the living parenchymatous cells, and the resin being expelled from the resin canal's. The pores are then blocked and the cell dies from lack of water. When heartwood is formed, the free water is expelled from the cell lumen. Additionally, extractives are forced into, and stored in, the cell walls, which results in a reduced content of bound water. This is why the moisture content in the heartwood is much lower than in the sapwood. The heartwood then spreads, annual ring by annual ring, through the tree (Haygreen et al. 1996, Thörnqvist 1983).

The heart of the spruce tree has no visible border between heartwood and sapwood when the wood is dried. According to Sjöström (1992), the levels of extractives are greater in the heartwood of the pine tree than in its sapwood, whilst the opposite is true for the spruce tree. In the pine tree, the levels of extractives in the heart can increase up to 12% to 14%. Ekman (1979) states that the composition of extractives in the sapwood and heartwood of the spruce tree is relatively constant. The levels are, however, considerably higher in the sapwood. Since fatty acids dominate in the spruce tree, above all these increase in the sapwood. The levels in the heartwood increase with increasing age, but they depend also upon rate of growth (Haygreen & Bowyer 1996).

1.5.4 Compression wood

Compression wood is reaction wood in coniferous trees. It is relatively easy to identify since the annual rings are darker; it appears to be wide bands consisting solely of late wood. In a trunk, compression wood redistribute the tree's biomass and retain a straight trunk. Compression wood is found on the underside of branches and on the convex side of crooked trees. Oval shaped trunks usually contain compression wood. Compression wood is commoner in corewood than in mature wood.

Factors that can lead to the formation of compression wood are gravity, wind and light.

Compression wood is characterised by high levels of lignin and low levels of cellulose. The cell walls are thicker and the angle of the microfibrils in the S2 layer is very large, between 30° and 50°. As a result of this, compression wood has increased sensitivity to changes in moisture content; when dried, it shrinks in excess of ten times more than normal wood, in the direction of the grain. In compression wood the S3 layer is absent in the cell wall. Regarding shrinkage, the opposite is true concerning t- and r-directions, where shrinkage is less than in normal wood. The material properties of compression wood are characterized by low stiffness and low tensile strength whilst compression strength, on the other hand, is high. Density is higher and permeability is lower than for normal wood. Compression wood can lead to problems during sawing, since tensions are released, resulting in crooked timber and cracking. (Haygreen & Bowyer 1996, Kyrkjeeide & Thörnqvist 1993, Ormarsson 1999).

1.5.5 Material properties

Material properties of density, shrinkage/expansion, stiffness properties and even tensile properties vary in a radial direction. Two material properties of importance to the user are stiffness and shrinkage/swelling in a longitudinal direction. Module of elasticity, E_l, is a measure of stiffness concerning deformation under a given load in the longitudinal direction. This parameter is a good reflection of how much a beam or a joist will bend under load.

For timber constructions within a house, it is of great importance that e.g. floor joists do not sag. Wood with a low module of elasticity can be used for those parts of house constructions that are not subjected to loads. The module of elasticity, E_l, can be more than twice as high in mature wood as it is in the corewood, see Figure 1.6 (Dahlbom et al. 1996, Ormarsson 1999).

Regarding shrinkage in the direction of the grain, it can be more than three times as high in corewood as in the mature wood (Dahlbom et al. 1996, Ormarsson 1999). Shrinkage is also of vital importance to the user, when wood is subjected to natural changes in humidity, or when wood dries in a finished construction. Corewood can thus cause undesirable distortions that may have serious consequences in a completed construction.

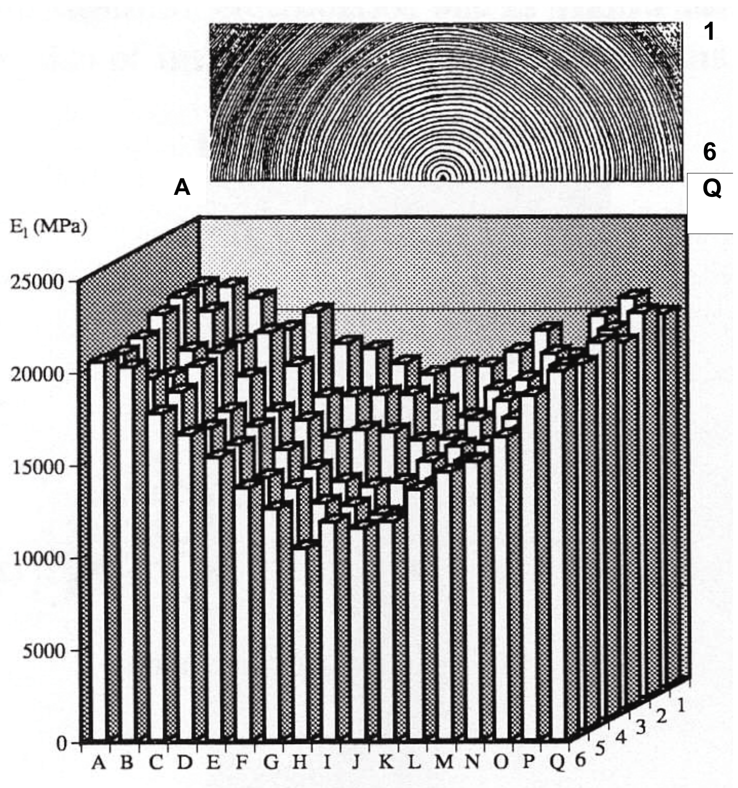

Figure 1.6. *Experimentally obtained variations in longitudinal elastic modulus over a cross section of a sawn board of Norway spruce. From Ormarsson (1999) and Wormuth (1993).*

1.6 Spiral grain

1.6.1 General facts about spiral grain

Most people have seen the spiral pattern that is made by cracks in dead trees. In older softwood trees, the cracks lean mostly to the right. This means that the grain angle is right handed, and the visible cracks create a spiral in an anti-clockwise direction, looking from the base to the top of the tree, see Figure 1.7. In spruce trees, however, the grain angle close to the pith is always left-handed, which means that the fibres follow a clockwise spiral up the trunk.

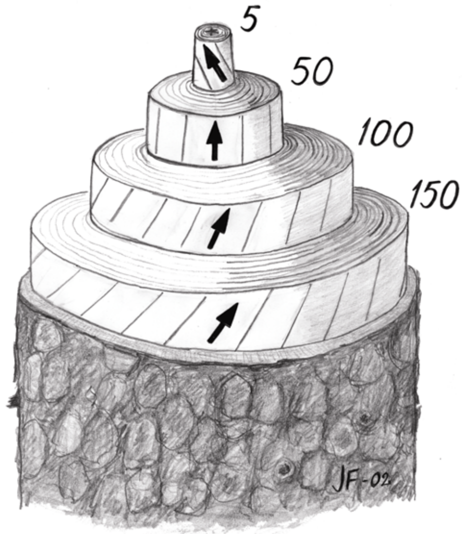

Figure 1.7. *Spiral grain orientation in a log at different annual rings (5, 50, 100 and 150) in an old spruce tree.*

A grain angle towards the left is normally denoted as having a positive value, whilst a grain angle to the right is denoted as having a negative value. In Norway spruce the grain angle is usually largest in the 4th to the 10th annual ring, counted from the pith. Subsequently, the grain angle diminishes in most cases, and the spruce tree normally becomes straight grained somewhere between the 40th and 70th annual ring. Subsequently, it is normally the case that later annual rings become successively more and more right-handed as the tree continues to grow, see Figure 1.7. This pattern applies to all species within the families *Picea*, *Abies* and *Larix*, plus almost every member species of the *Pinus* family (Vité & Rudinsky 1959, Harris 1989).

The same pattern is also found in the deciduous trees, but the mirrored version is also found, where the grain angle is right-handed close to the pith and left-handed further outwards in the trunk. Our commonest deciduous trees, the downy birch (*Betula pubescens*) and silver birch (*Betula pendula*), are similar to spruce, concerning spiral grain. The common alder, (*Alnus glutinosa*) has a right-handed grain angle close to the pith and has often a strongly left-handed grain angle in the mature part of the wood; this is the opposite case compared to Norway spruce (Kennedy & Elliot 1957, Enquist & Petersson 2000).

Another commonly occurring pattern in deciduous trees is that the grain angle varies, and changes direction between the annual rings (alternately right-handed and left-handed). This is referred to as "interlocked". The different types of spiral grain are described by, amongst others, Vité & Rudinsky (1959) and Harris (1989).

Much has been written during the 1900:s concerning spiral grain, and above all J. M. Harris's compilation of the subject has led to increased understanding of the peculiarities of spiral grain (Harris 1989). The subject has also been treated by Hartig (1895), Burger (1941), Elliot (1958), Noskowiak (1963), Krempl (1970), Danborg (1994), Jensen (1994), Pape (1999 a) and Säll & Dahlblom (1999).

1.6.2 Biology of spiral grain

The formation of spiral grain is genetically controlled, but there are also environmental factors involved (Pyszynski 1977, Mattheck 1991, Eklund & Säll 2000). Most data indicate that the genetic control of spiral grain is localised in the cambium and that spiral grain formation can be coupled to cell divisions taking place in that region (Harris 1989) and may be regulated by plant hormones (Zagorska-Marek & Little 1986).

There are three cell division processes which are believed to cause the development of spiral grain (Hejnowicz & Zagorska-Marek 1974). Hejnowicz (1980) proposed that the spiral grain angle is related to the frequency of pseudo-transverse divisions of the vertically oriented cambial cells. The cumulative effect arising when pseudo-transverse divisions are accompanied by intrusive growth has been given much attention for more than a century (Hartig 1895, Bannan 1966, Kubler 1991).

Intrusive growth alone, without pseudo-transverse division, the second potentially important factor, means that the pointed tips of elongating cambial derivatives slide past one another, thereby changing their relative orientation. The two ends of a cell move in opposite directions leading to a slight rotation of the cell. This results in a change in the angle between the cell and the stem axis.

A third process that is suggested to be involved in the development of spiral grain is imperfect periclinal divisions and the cell differentiation that accompanies such divisions (Savidge & Farrar 1984). The division is said to be incomplete if it is partial and the newly formed wall does not extend from one end of the cell to the other. There is, however, still no evidence that any one of the three theories is more probable or improbable than the others.

Several theories have been put forward to explain the function or potential advantages of spiral grain for trees to withstand environmental constraints. Soil conditions (Whyte et al. 1980, Danborg 1994) and facilitation of water and nutrient distribution (Vité 1967) are proposed, but the experimental data obtained so far are not conclusive. It has been suggested that spiral grain could be an adaptation to withstand wet snow and strong winds (Thunell 1951, Rouvinen & Kuuvulainen 1997, Skatter & Kucera 1997 and 1998, Eklund & Säll 2000). The latter investigated the correlation between spiral grain formation and crown asymmetry in clones of Norway spruce (*Picea abies*) and Scots pine (*Pinus sylvestris*). In both species the angle had its highest left handed value when the crown was asymmetric to the north and the least left handed, or a right handed, angle when the crown was asymmetric to the south.

Growth rate has also been suggested to affect spiral grain formation. In *Pseudostuga mensiezii* (Elliott 1958), *Tsuga heterophylla* (Elliott 1958, Wellwood & Smith 1962), *Pinus ponderosa* (Paul 1955), and *Pinus patula* (Paterson 1967) a correlation was found between slow growth and increased spiral grain. On the other hand in *Pinus radiata* (Jacobs 1935, Burdon 1980)*, Pinus pseudostrobus* (Turnbull 1942), *Pinus roxburgi* (Rault & Marsh 1952), *Picea sitchensis* (Brazier 1967), and *Pinus caribaea* (Smith 1973) a fast growth rate was reported to correlate with increased spiral grain. In many studies on conifers, however, no correlation was found between spiral grain and increased growth rate (Krempl 1970, Nicholls 1971, Cown & McConchie 1981, Fielding 1967).

Recent investigations (Eklund, Säll & Linder 2002) indicate, however, that an enhanced growth rate is critical for the development of spiral grain. 25 year old stands of Norway spruce trees, which had a growth rate increased approximately 200 % by watering and fertilising, and maintained a high degree of left handed angle many years after the controls, have started to decrease their left handed angle of spiral grain, see Figure 1.8. These results indicate that the decrease in spiral grain angle is not an effect of age or tree diameter and can be affected by nutrient and water availability stimulating growth.

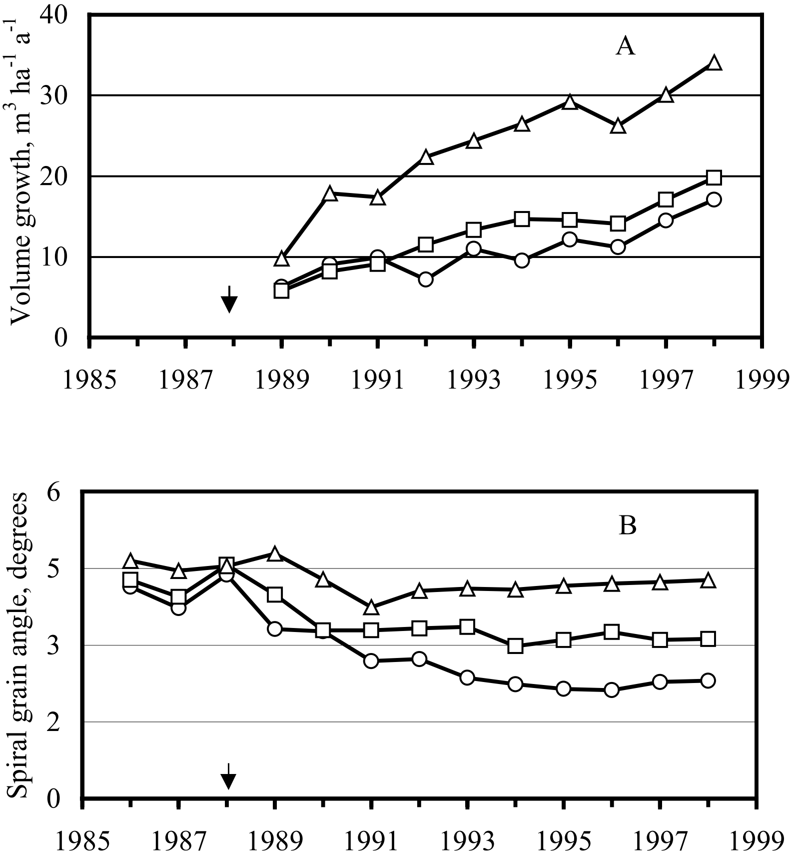

Figure 1.8. *Annual stem wood production* (A) *and left handed spiral grain angle* (B) *in control* (O)*, irrigated* (□)*, and irrigated-fertilised* (△) *stands of Norway spruce. The data on annual stem volume production are from Bergh et al. (1999) and inventories of four replicated plots in autumn 1997 and 1998. The arrows indicate the commencement of treatments in 1988.*

Plant hormone

The plant hormone ethylene has been shown to regulate the rate of cambial divisions (Neel & Harris 1971, Savidge et al. 1983, Yamamoto & Kozlowski 1987, Eklund & Little 1998, Eklund & Tiltu 1999). Ethylene also regulates tracheid cell wall biochemistry (Eklund 1991, Ingemarsson et al. 1991), and the morphology of tracheids (Telewski & Jaffe 1986, Little & Eklund 1999).

The relation between ethylene and the formation of spiral grain in Norway spruce has been studied by Eklund, Säll & Linder (2002). There was a positive relationship between spiral grain angle in the last growth ring and ethylene concentration in the stems. This is in agreement with a number of studies in Norway spruce (Eklund 1990, Eklund et al. 1992) and Scots pine (Ingemarsson et al. 1991, Klintborg et al. 2002) where it was shown that ethylene evolution correlates to the period of most intense growth.

Number and size of tracheids formed in the annual ring

The relation between the total number or size of tracheids formed in the annual rings of 40-year-old Norway spruce trees and the formation of spiral grain has been shown by Eklund, Säll & Linder (2002). There was a positive significant correlation between the average spiral grain angle and the total number of tracheids, se Figure 1.9. This relationship was based on the number of tracheids in early wood rather than the number of tracheids in late wood. No correlation was found between the spiral grain angle and the radial diameter of the early wood tracheids. This investigation shows that an increased number of early wood tracheids correlates to a more left-handed spiral grain angle under bark.

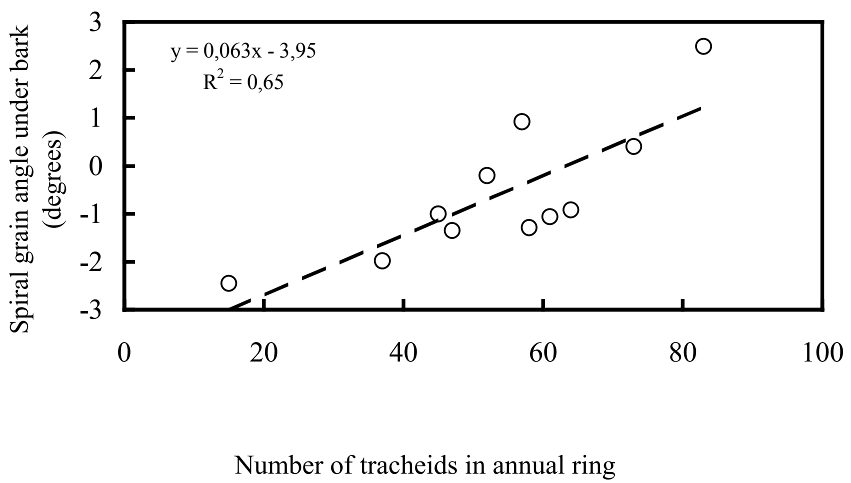

Figure 1.9. *The relationship between spiral grain angle under bark in 40-year-old Norway spruce trees and total number of tracheids in the growth ring. (n = 11).*

Silviculture and spiral grain

Harris (1989) and Kubler (1991) considered many silvicultural influences on spiral grain in their reviews. Owing to spiral grain, each root should be able to distribute sap uniformly to all branches, allowing transportation between the root and the crown even in an injured stem or if water and nutrient supply are found only in parts of the root sphere (Vité & Rudinsky 1959).

In several articles the authors confirms that open stands, stands on rocky and "one-sided" ground produced considerable more trees with large spiral grain (Wellner & Lowery 1967). Trees growing in open stands with irregular individual distance between each tree have environmental conditions similar to trees growing in the vicinity of the border of stands. These border trees in the stands are often dominant, have wider growth rings and a relatively large living crown compared to the average trees in the same stand. According to several reports "border trees" are supposed to have a more pronounced grain angle than the trees inside a stand (Rault & Marsh 1952, Lowery 1967, Wellner & Lowery 1967).

1.6.3 Long-established knowledge of spiral grain

The most serious aberration for users of timber is found in those spruce trees that continue to develop a left-handed grain angle with increasing age. This is described in both older and more recent research literature. When the grain angle under bark in normal and coarse timber exceeds +4° or is below -4°, this has a greatly detrimental effect on both twist and strength. Posts, logs and sawn timber from trees with a pronounced grain angle always lead to the largest problems for users (Rault & Marsh 1952, Lowery et al. 1967, Danborg 1996, Perstorper et al. 1995, Forsberg 1999, Ormarsson 1999, Pape 1999a, Woxblom 1999, Kliger & Säll 2000, Johansson et al. 2001).

Telegraph poles with a pronounced left hand grain, that have been conditioned outdoors from a raw state, twist approximately 40°, whilst equivalent poles with a right hand grain twist half as much, according to Lowery et al. (1967). Furthermore, the angular deformation in poles and logs with a left handed grain is greater, compared to those with a right handed grain, when they are subjected to normal climatic changes, with normal variations in moisture content. A grain angle of 5° to 7° on the mantel surface of telegraph poles gives a 50% to 60% reduction of bending strength if the angle is left handed, whereas a right-handed twist of the same degree has no effect on strength compared with straight grained posts (Lowery et al. 1967). This property of a low degree of stiffness was desirable formerly in shipbuilding, to give certain parts of ships better qualities. Certain types of construction are better suited to their purpose if stiffness is lower.

In older Swedish literature, trees with a left-handed twist were regarded as unusable. Christopher Polhem writes in his literary work "On household building" from the beginning of the 18th Century (Polhem 1739 and 1740, Sjömar 1988)

"*Amongst those trees that otherwise are suitable and satisfactory in material and permanency, there are a number of twisted trees that are unsuitable as material for building, viz. those which are clockwise warped…anticlockwise warped are generally twisted only on the very surface, and in their hearts are straight-split, whereas the former are mostly twisted even to their very hearts".*

It is certainly true that mankind learned at an early stage to utilize or avoid wood which was excessively spirally grown, when manufacturing utility articles and buildings. Before effective methods of sawing were developed, all wood was split from suitable logs. To ensure that the planking in the prow of a boat swept, sloped, in the right direction, it was suitable to choose a clockwise twisted log for the starboard planking, and an anticlockwise twisted log for the port planking. Straight grained logs were split to obtain planks for objects that required flat surfaces, such as tables.

Using a splitting technique to obtain materials for different objects is only found today when making instruments and in the production of smaller utility articles. When manufacturing a table made of split ash *(Fraxinus excelsior)* at Carl Malmsten's school, Capellagården, it was found that the time needed for conditioning the wood was reduced and the stability and strength of the planks was improved, The table could thereby be made in relatively smaller dimensions (Nilsson 2001).

1.6.4 Sawn timber

Twisting in sawn timber is a serious shape defect, which to the greatest degree is dependent on the moisture content of the wood, and the extent to which it is spirally grained (Northcott 1965, Danborg 1994, Ormarsson 1999, Forsberg 1999, Woxblom 1999, Kliger & Säll 2000, Johansson et al. 2001). When timber is sawn, the saw cut deviates more or less from the direction of the grain. This deviation is caused by spiral grain, oblique sawing, the shape of the log, and knots. The size of the angle of grain, its direction and how the direction varies are all of importance. This is especially important for twisting, but even tensile properties in the sawn timber are affected negatively (Lowery et al. 1967, Kollmann & Côté 1968, Johansson 2002).

Using appropriate dimensions of sawing yield and proper drying methods can to some extent avoid twist caused by moderate spiral grain. Other shape defects, such as bow and spring are caused mainly by variations in shrinkage properties from pith to bark, and indirectly by compression wood, the proportion of corewood and variations in the width of the annual rings, see Figure 1.10, (Kollmann & Côté 1968, Thörnqvist 1990). Cup is caused by the fact that shrinkage differs in tangential and radial directions and by the orientation of the annual rings and the radius of curvature in the cross section of the sawn timber (Kollmann & Côté 1968).

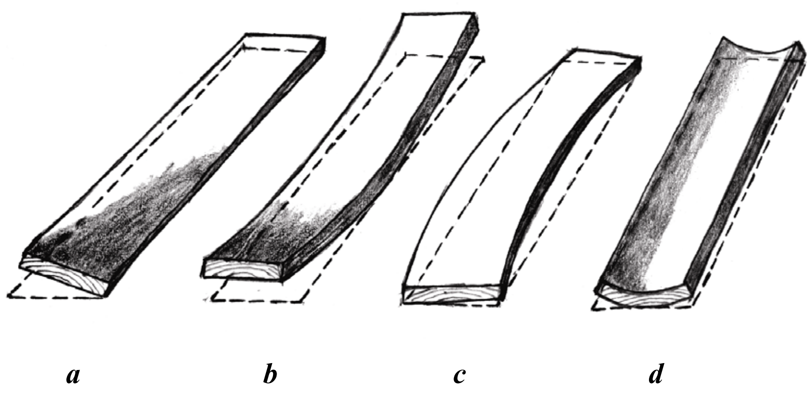

Figure 1.10. *Illustration of different forms of warp (a) Twist, (b) Bow, (c) Spring /Crook, (d) Cup*

The four shape defects are affected in differing degrees by changes in the wood's moisture content. Providing the moisture content exceeds the fibre saturation point, approximately 28% for Norway spruce, there is no shrinkage in the cell walls and thereby no deformation. The defect of twist is minimal provided the moisture content of the wood exceeds the fibre saturation point (Kollmann & Côté 1968). This is also the case for cup. The water that is bound in the cell walls begins to evaporate when the moisture content sinks below the fibre saturation point. Twist increases in proportion to the reduction in moisture content as the wood dries. Defects of shape such as spring and bow, on the other hand, arise both during the process of sawing, and in the drying process.

The tendency of sawn spruce to twist is strongly connected both to the angle of grain under bark and to changes in the angle of grain in a radial direction. According to Rault & Marsh (1952), twist is greater in timber that is sawn from a log with a grain angle under bark of 10° and a diameter of 12 cm than in a log with the same grain angle and a diameter of 25 cm. This was also shown to be true in the material that was analysed in the EU project STUD (Kliger & Säll 2000). This implies that trees that are unsuitable as timber are to be found to a greater or lesser degree in the varying diameter classes in a given stand. For the timber that is sawn close to the pith and from thin logs, less than 18 cm, the tendency for twist is also connected to distance from pith (Woxblom 1999, Johansson et al. 2001, Kliger & Säll 2000). Corewood and the properties of corewood have a negative influence on the quality of the sawn timber, from several aspects (Thörnqvist 1990).

1.6.5 Sawn timber of low quality

Earlier studies have shown that the proportion of Norway spruce trees that retain their left handed rotation is approximately 5% (Krempl 1970). A large proportion of these left hand grained trees produce sawn timber that is of too inferior quality (scant-sawn wood) for the majority of users (Lowery et al. 1967, Kollmann & Côté 1968, Sjömar 1988, Kliger & Säll 2000, Johansson 2002).

When building timbered houses, these so called clockwise twisted ("solvinda") logs were avoided, whilst using logs with a right hand rotation, so called anti clockwise twisted ("motvinda"), was not assumed detrimental to the building (Sjömar 1988). This depends upon the fact that the forces that attempt to twist the log during drying are neutralized by the presence of different grain angles through the log; left hand grained close to the pith, right hand grained in the mature wood under the bark. The proportion of trees that are suitable for sawing is not well known. In the EU-project ("STUD") it was shown that 11% of the 178 chosen trees had an angle of grain under bark that exceeded 3°. Only 14% of the beams sawn from these trees were acceptably straight (Kliger 2001).

1.6.6 Quality requirements for timber

Trees with extreme spiral grain angles are unacceptable as raw materials for sawing. The process of dividing logs with extreme right-hand twists will result in timber with a tendency for twist, as the individual piece of timber will contain slope of grain that cannot be compensated for by the fact that grain in another direction counteracts the forces leading to twist.

In the applicable quality requirements for timber, specified in instructions from The Swedish Timber Measurement Council (Virkesmätningsrådet) (VMR 1/99), there are limitations for what is an acceptable degree of spiral grain (Anon 1999). It can be given as an example that for Class 1 spruce it is permissible to have spiral grain up to half a revolution per 45 dm log length; for class 2 and 3, one revolution is allowable for the same length, and for class 4 there is no limitation. These quality requirements are independent of both direction and degree of grain angle, and log diameter. When considering coarser logs, with a top-diameter of more than 20 cm, these demands are reasonable. For small saw timber (less than 20 cm) this rule has little or no practical use, as the properties of the wood close to the pith have a greater effect on twist. The permitted tolerances in the current regulations are however too coarse concerning grain angle. This is caused by the fact that the moisture content in wood used indoors sinks as low as 8-10%, which it rarely did in the past.

Tolerances and requirements made previously in the 1900:s concerning grain angle were in much greater detail, and have been found in regulations governing timber measurement for a very long period (Forsberg 2001). Knowledge of the fact that spiral grain may only form a part of a rotation per 45 dm log length if the log is to be straight is extremely old and is based on empirical experience (Forsberg 2001). It should be borne in mind that when this rule was formulated, hundreds of years ago, the minimum diameter of saw logs was considerably greater than current standards, 10-12 cm. According to Stadling (1894) was it not allowed to cut trees in northern Sweden which were smaller than 250 mm in diameter at the height of 6 meter above ground. Smaller trees were not suitable for saw timber.

Even though current rules for timber measurement specify standards for the permissible amount of spiral grain (VMR 1/99), these are seldom applied in normal scaling. The rules are only applied during control measurement of randomly chosen logs.

The next example will show that current quality requirements are too tolerant. A log with a diameter of 30 cm and a length of 4.5 m can exhibit 6° grain angle under bark before the standards set for class 1 timber are exceeded (spiral grain of more than half a revolution per 4.5 m). If the diameter of the log is increased to 45 cm, a grain angle of 9° is permitted. If the standards for class 2 and 3 timber are applied, the grain angle in the above examples is doubled to 12° and 18°, respectively. In all of mentioned cases, much of the resulting timber would be more or less unfit for use when dried to a moisture content of 12%.

Figure 1.11 shows a log from a tree with a grain angle under bark that exceeds 10°. The log has a pronounced left hand grain (“solvind"). 35 boards were sawn from this tree. The boards were dried in a kiln at a sawmill industry, as package number two from the top. All of the sawn boards greatly exceeded the maximum allowable values for shape defects specified by the building industry. Figure 1.12 shows some of the boards sawn from the log in Figure 1.11 (top layer) together with boards from trees with a low grain angle (the six lower layers). The left hand grained tree was crosscut as normal saw timber and would have produced timber of very little value to the user.

Figure 1.11. *Log from tree with spiral grain turning left. Yxkullsund, Småland. Diameter at breast height: 50 cm.*

Figure 1.12. *Picture of sawn boards from four normally grained trees (six layers from bottom) and boards from a tree with strong left hand grain (top-layer). Locality: Attsjö and Yxkullsund, Småland.*

1.6.7 Rot-resistance

Large grain angles can also influence the resistance properties of the wood. The proportion of sawn fibres in the lateral surface increases as the grain angle increases, and this leads to the fact that the lateral surfaces in many ways behave more like end faces, regarding absorption properties etc (Meijer et al. 1998). Wood that contains tension perpendicular to grain, due to changes in moisture content, is prone to developing cracks. This also allows water to penetrate further into the wood, leading to a higher moisture content. Increases in moisture content lead to increased risk for attacks by rot fungus.

1.6.8 Strength and stiffness properties

Properties such as the module of elasticity, bending strength, tensile strength and compression strength are affected negatively as the grain angle increases and deviates to a greater degree from the longitudinal direction of the piece of sawn timber (Kollmann & Côté 1968, Dinwoodie 2000).

The tensile strength and bending strength of wood, where the angle of grain exceeds 15°, is reduced by 40% and 50% respectively, compared to wood with straight grain (Dinwoodie 2000). The angle of the microfibrils in the cell walls is also greater in corewood, and this also affects tensile properties negatively. This leads to the fact that even a moderate grain angle in corewood, of 3° to 5°, together with high microfibril angles, reduce the bending strength and the tensile strength by more than 50% compared to mature wood with the same grain angle (Dinwoodie 2000).

The angle of grain in relation to the saw cut in sawn timber can be caused partly by spiral grain but can also be a result of the log being conical or crooked. An angle of grain can also arise when the saw cut is not parallel to the direction of the pith. Bending strength and compression strength are not affected to any great degree providing the proportion of grain angle is less than 1:20, or 3°, see Table 1.1. Bending strength is reduced by approximately 50% and stiffness in bending is reduced by 33%, when slope of grain is about the proportion of 1:8, or 7°, see Table 1.1. It should be mentioned that the grain angle negatively affects the tensile strength of the wood to a greater degree than it affects bending strength (Haygreen & Bowery 1996).

Table 1.1. *Strength and stiffness reduction in bending in lumber resulting from slope of grain. Experimental strength reduction in bending as shown in ASTM standard D245 from Haygreen & Bowery (1996). Numerical stiffness reduction simulated by Ormarsson (1999).*

	Strength reduction in bending: Experimental	Stiffness reduction in bending: Numerical simulation
Slope of grain	(%)	(%)
1 in 6 10°	60	50
1 in 8 7°	47	33
1 in 10 6°	39	25
1 in 15 4°	24	15
1 in 20 3°	0	10

1.6.9 Economic consequences

In Sweden in the year 2000, every one percent of the timber costs of sawmills represented 170 million SEK (19 million €). If 3 to 5% of the volume of saw logs exhibits pronounced grain angle, this is equivalent to a cost for timber in excess of 500 million SEK. This volume of logs with extreme grain angle causes production difficulties in the sawmill, which ceratinly leads to an annual loss of turnover in today's monetary value in excess of 1000 million SEK.

The logs with the highest grain angle should be marked for pulpwood. The economic value of the volumes that have been sawn from logs with pronounced spiral grain is considerably lower for the customers than for first class timber. Furthermore, twisted and crooked timber damages the reputation of wood as a suitable construction material. Current studies show that 20% to 30% (equivalent to approx. 3000 million SEK) of the timber used in building does not comply with the building industry's requirements for stability of shape (Trätek 2000). A large proportion of this volume and value consists of twisted timber caused by trees and logs with an excessive grain angle.

1.7 Aim and scope of the study

The overall objective of this thesis was to investigate the pattern of spiral grain in Norway spruce, to illustrate its normal variation, and to show the influence that external factors have on spiral grain. Data on spiral grain was used to analyse its correlation with twist in sawn wood.

In the future there will probably be an increasing demand for solid timber products, with god straightness, high shape stability and required stiffness. Therefore it is necessary to avoid lumber with high spiral grain angle to be processed in the sawmills. Therefore emphasis was made to find out if it was possible, at early age in the forest stand, to identify and reject those trees and logs that give unsuitable as saw logs.

The specific objectives of this study can be summarised as follows:

- To give a broad overview of the structure of wood and in particular facts about spiral grain.
- Describe typical spiral grain formations in Norway spruce forest in Sweden and Finland in general and for individual trees. The spiral grain angle was related to annual ring number from pith as well as to the distance from pith.
- Evaluate differences of spiral grain patterns between stands in relation silvicultural methods.
- Investigate spiral grain in relation to relative height and size of tree.
- To find methods to select trees at thinning operations in the forest who are predestined to aberrant grain angles at time for clear cutting.
- Evaluate statistical models that can be used to decide if a tree or a log is suitable for the purpose of solid sawn timber.
- Give suggestions to the wood industry about how to use knowledge about spiral grain to produce straighter and non-twisting construction wood.
- Give ideas about future research and developments.

2. Material and methods

2.1 Main study of spiral grain

2.1.1 Stand description

The sample trees used in this study originated from 20 stands situated in Sweden and Finland. The stands were a part of the EC-project [3] "STUD". In Sweden the stands were chosen from eight different localities; six localities with one stand and two localities with three stands. In Finland the eight stands were chosen from four different localities. The stands were selected, when possible, among old and well-documented research plots dominated by Norway spruce (*Picea abies* (L.) Karst.). The selection aimed at obtaining a variation of stand characteristics such as latitude, site index, spacing and silvicultural strategy.

With respect to the annual growth increment of spruce in the north and south parts of Sweden, about two-thirds of the growth increment is south of 62° latitude. In this study, 5 selected stands, from a total of 13, were from the south part of Sweden.

The stand age ranged between 50 and 152 years, and the mean diameter in breast height (DBH) for all trees ranged between 18 cm and 45 cm. The site index (H100)[4] ranged between 16 m and 36 m. Fourteen of the twenty stands had a site index of 26 m or more. The average site index for spruce in Scandinavia is 26 m. The fieldwork was carried out by personnel from the department SIMS, and Asa Forest Research Station, both belonging to the Swedish University of Agricultural Science (SUAS). Most of the fieldwork was done between October and February, 1997 to 1998 and included:

- Documenting the stands and selection of trees. Felling trees and measuring exterior characteristics (branch diameters at different heights, total height to first dead and live branch).

[3] EC-project: FAIR CT 96-1915, Improved Spruce Timber Utilisation.

[4] Site index "H100" is the predicted dominant height (m) of 100 trees/ha at 100 years of age (Hägglund & Lundmark 1977).

- Marking a common reference line through the tree with respect to North.
- Cross cutting the trees into lengths of approximately 4.5 m and marking the logs with identification numbers.
- Cutting stem discs with a thickness of 4 cm to 6 cm from the top end of each butt, middle and top log, and marking them with a code number. Stem discs were as knot-free as possible and were taken between whorls. Discs in logs 1, 3 and 5 were taken at a sampling height of 4, 13 and 22 meters above stump.
- Storing the discs in plastic bags in a cold storage room, at a temperature of -15° C.

Location and data for the stands are given in Figure 2.1 and Table 2.1.

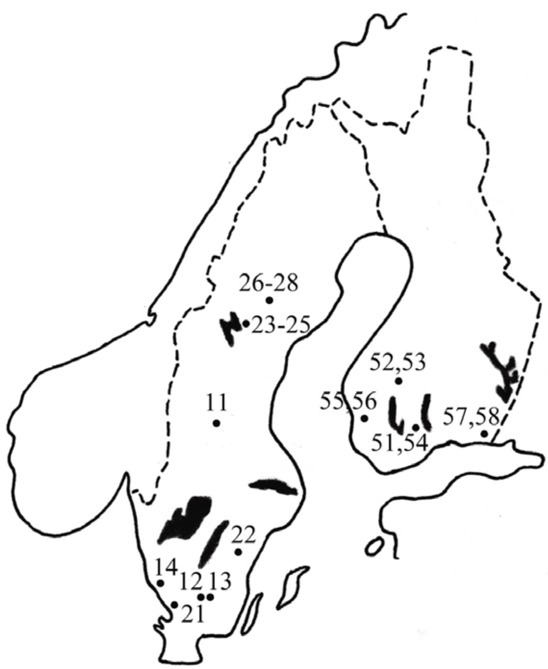

Figure 2.1. *Location of the stands.*

Table 2.1. *Stand data for the 20 stands from Sweden (above the dashed line) and Finland (below the dashed line). Altitude: Meter above sea level (M.a.s.l.), Latitude (Lat.), Longitude (Long.), total age of stand (Age), diameter at breast height (DBH), height (H), Site index (H100), total volume over bark/ha (VOL), stems/ha (in italic estimated) (St/ha), percentage of Picea abies (P. abi).*

	Location									
Stand No	Altitude M.a.s.l. (m)	Lat.	Long.	Age	DBH (mm)	H (m)	H100 (m)	VOL (m3/ha)	St (St/ha)	P.abi (%)
11	220	60°53'	14°23'	135	314	29.3	26	350	340	90
12	225	57°08’	14°44’	120	290	28.0	28	370	680	90
13	185	57°09’	14°46’	110	330	30.0	34	460	430	100
14	170	56°56'	12°48'	60	340	26.4	36	720	680	100
21	95	56°42'	13°07'	101	445	32.5	33	520	300	100
22	120	58°12'	15°56'	76	330	28.0	32	580	550	100
23	310	63°13'	14°30'	82	201	19.0	25	280	950	100
24	310	63°13'	14°30'	82	264	22.1	26	300	550	100
25	310	63°13'	14°30'	82	250	21.6	26	290	580	100
26	270	64°05'	16°08'	152	219	23.4	16	280	490	95
27	270	64°05'	16°08'	152	222	23.0	17	270	560	95
28	270	64°05'	16°08'	152	179	21.4	16	250	1120	100
51	140	61°13'	25°10'	90	300	26.0	27	260	*300*	70
52	170	62°32'	24°10'	100	300	24.0	25	240	*300*	100
53	170	62°32'	24°10'	100	300	28.0	29	320	*300*	100
54	135	61°13'	25°10'	90	300	26.0	29	290	*350*	100
55	45	61°25'	22°10'	100	280	25.0	27	350	*500*	60
56	45	61°25'	22°10'	50	220	22.0	27	270	*550*	70
57	64	60°40'	27°30'	95	280	26.0	26	300	*400*	100
58	65	60°40'	27°30'	100	250	24.0	24	290	*600*	70

2.1.2 Selection of trees

One important criterion for the selection of trees was that they should be of a dimension sufficient to enable the required sawing pattern, matching the subproject in the above-mentioned STUD project. This meant that most of the trees were amongst the largest of each stand and predominantly taken in the dominant[5] tree class. The trees sampled for

[5] Dominant trees: Tree height = At least 5/6 of the height of the highest trees in the stand.

the study did not have any major defects and were free from root rot. A total of 390 log discs from 161 trees were examined. Average data for selected trees from each stand is given in Section 4.2. Four of the twelve stands selected in Sweden were also used for a subproject, where a number of trees and logs were taken out for studying shape stability in sawn timber. These four stands were stands 11 to 14, and they also included a greater number of sampled trees compared to the rest of the stands. In stand 13, extra trees were chosen to obtain a sub-sample of trees corresponding to the co-dominant[6] and intermediate[7] tree class. Connected to this project, one solitary tree (16) were chosen from extreme natural environments. This tree was from a promontory in the lake Helgasjön, north of Växjö in the south of Sweden.

2.1.3 Measuring spiral grain

There are several methods available for the measurement of spiral grain, from simple hands-on methods to methods using modern technology. Independent of the method used, a left handed angle is given a positive number and a right handed angle is given a negative number. The spiral grain angle was measured at Asa Forest Research Station.

Scribe test

Measurement started by marking up a line through the pith, showing the north-south orientation of the stem disc. Marks were made along the line at every second annual ring, between the pith and ring number ten. After that every fourth annual ring was marked, see Figure 2.2. Diametrical strips, with a width of 4 cm to 5 cm and a thickness of 4 cm to 6 cm, were sawn from the stem discs in the direction of the line, see Figure 2.2. Care was taken to avoid knots and irregularities of the stem, which could affect the measurement.

---

[6] Co dominant trees: Tree height = Between 4 and 5/6 of the height of the height of the highest trees in the stand.

[7] Intermediate trees: Tree height = Between 3 and 4/6 of the height of the height of the highest trees in the stand.

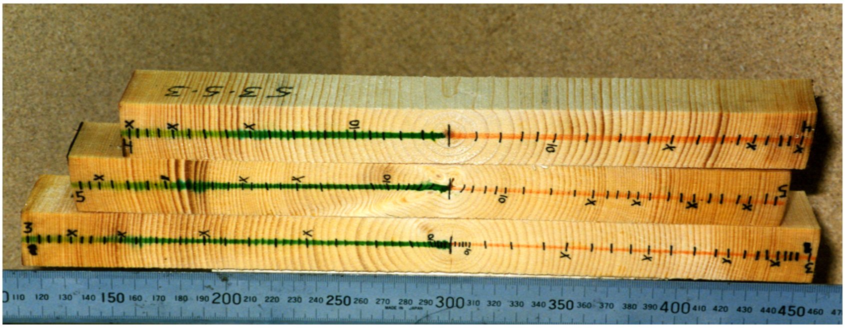

Figure 2.2. *Diametrical strips of stem discs.*

Measurement started at the outermost annual ring and proceeded inwards. At every marked position in both directions, the distance between the annual ring and the pith was measured. On the tangential surface, a sharp point was used to mark the direction of the grain (Koehler 1955), see Figure 2.3.

Three or four marks were made to ensure that the grain orientation was uniform over the whole area to be tested, and the grain angle was measured twice for each direction (north and south) see Figure 2.4. The next marked tangential surface (fourth or second annual ring, depending on position) was uncovered with a wood chisel. The average value of inclination in one annual ring results from four measurements at opposing radii (two from north and two from south). This process eliminates errors related to sample preparation, and leaning of stem, and minimizes the effect of grain deviation around knots (Brazier 1965).

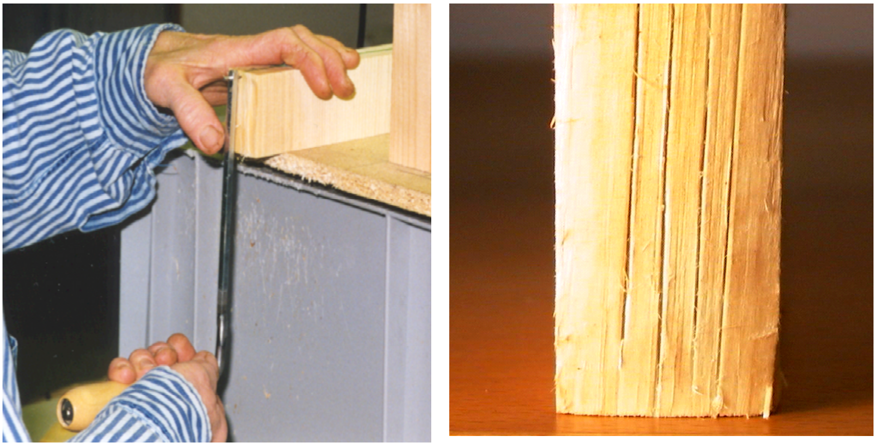

Figure 2.3. *Marking fibre direction with scriber and the scribe pattern.*

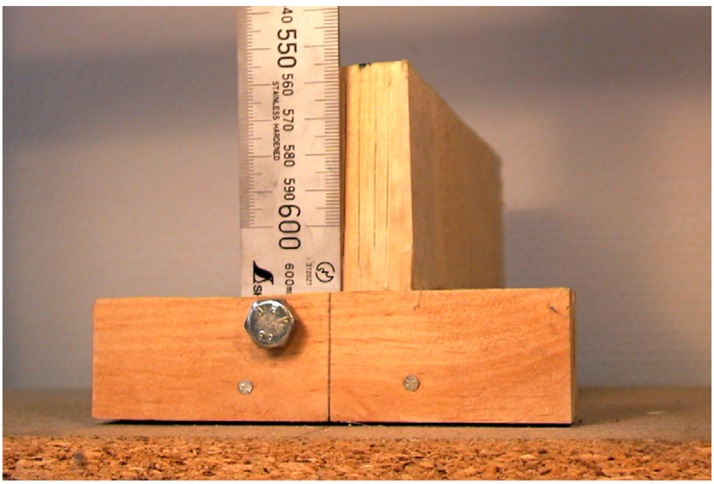

Figure 2.4. *Measuring grain angle.*

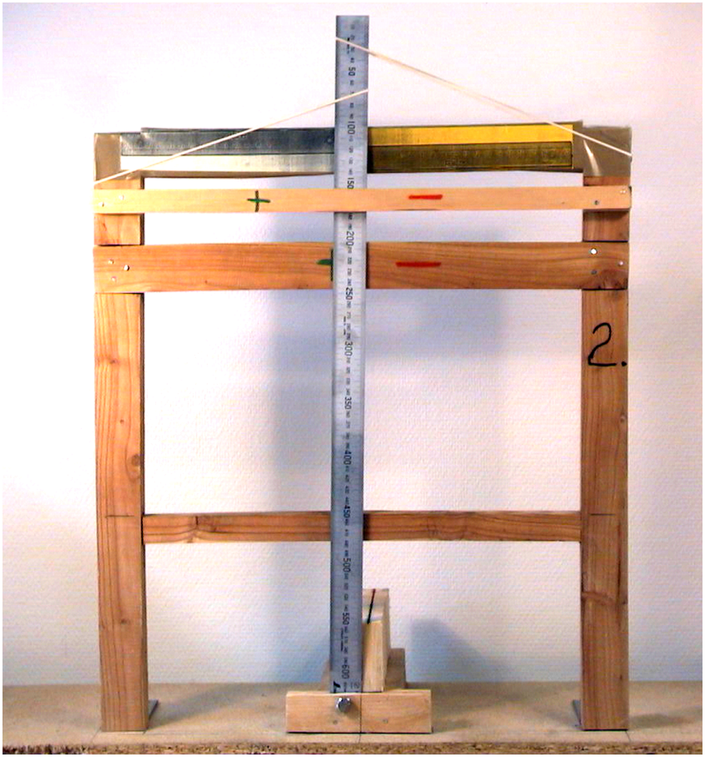

Figure 2.5. *Instrument for measuring grain angle.*

The spiral grain angle was measured with a measurement frame, see Figure 2.5. The frame was made of a board, to which a flexible ruler was fixed with a screw. A millimetre-scale was fixed to the upper part of the frame, which was parallel to and at a distance of 500 mm from the board. Zero on the horizontal millimetre-scale corresponds to a vertical position for the ruler, and 0° spiral grain angle. The vertical line and the horizontal millimetre-scale form the smaller sides of a right-angled triangle. The smaller cathetus was read on the millimetre-scale and the longer cathetus was fixed at 500 mm. A positive value was assigned if the ruler leans to the left, and a negative value if the ruler leans to the right.

Calculation of readings from millimetre-scale converted to degrees was made with the trigonometric function:

$$\mathbf{GA_1=arctan\ (k_1\ /500)}$$

where GA_1 is the spiral grain angle and k_1 is the value read on the smaller cathetus. The precision of readings was about ± 0.5°.

A total of 28336 registrations were made for spiral grain angle measurement and 14168 for the measurement of distance between the annual ring and the pith.

2.1.4 Statistical evaluation

Data registration, generation of diagrams and common statistical calculations were made using Microsoft Excel software. To test violations of the assumption of normality and constant variance, and even more complex data analyses such as multiple regression, models were made using Statgraphics *plus* software. The level of significance was 0.05 if not specified.

In this report most processing of data was done without measurement values from the innermost annual rings. Observations for annual ring number two and four were often excluded, see Chapter 3.

The general linear regression model was used to describe the relationship between grain angle and different parameters, such as ring number and distance from pith as well as twist of sawn wood. For the model with relation between grain angle (GA_i) and ring number from pith (RN_i) we will get:

$$GA_i = \alpha + \beta * RN_i + \varepsilon_i \qquad i = 1,2,\ldots\ldots, \textit{number of observations}$$

where ε_i denotes the random error with expectation $E(\varepsilon_i) = 0$ and variance $V(\varepsilon_i) = \sigma^2$ for all i.

Considering the possibilities for request multiple regression analysis a covariance analysis model was applied with included dummy variables, denoted D_j, $j = 1,2\ldots\ldots, n$

$$GA_{ij} = \alpha + \sum_{j=1}^{21} D_j \alpha_j + \beta * RN_{ij} + \sum_{j=1}^{21} \beta_j D_j RN_{ij} + \varepsilon_{ij}$$

$i =$ *number of observations*
$j = 1,\ldots..,$ *number of stands*
$D_j =$ *1 for stand j, 0 otherwise*

and ε_{ij} denotes a random variable with expection $\mathrm{E}(\varepsilon_{ij}) = 0$ and variance $V(\varepsilon_{ij}) = \sigma^2$ for all i and j.

When the corresponding statistical model for relation between grain angle and distance are written RN_i are changed to $Dist_i$.

In some analysis residual plots for the linear models were as a diagnostic cheque of the stability of the statistical model when the factors increased or decreased. If the residuals were consistent, low heteroskedasticity, when the value of factors was changed. The model together with a high value of R-squared (R^2) and low heteroskedasticity is expected to give good prediction.

2.2 Study of twist

2.2.1 Stand description and sampling of trees

Materials and methods for prediction of twist in this part were taken from a subproject in the EC-project [8] "STUD" (Kliger & Säll 2000).

The sampled trees originated from two stands situated in the South of Sweden. Both stands were dominated by Norway spruce (*Picea abies* (L.) Karst) and had a substantial difference between there Site indexes. Site index G28 is the average index in this part of Sweden and G38 is a high index. The mean ring width for stands 1 and 2 were 2.0 mm and 3,5 mm respectively. Stand no 2 should be regarded as a fast-grown stand. Data for the stands are given in Table 2.2.

[8] EC-project: FAIR CT 96-1915, Improved Spruce Timber Utilisation.

Table 2.2. Description of stands according to the Forest Management Plan.

	Stand no 1	Stand no 2
Latitude (°)	57	57
Longitude (°)	15	14
Altitude (m.a.s.l.)	230	160
Site index (H 100, m)	G26	G38
Stand age (years)	80	75
Total volume over bark (m^3sk/ha)	235	580
Diameter at breast height (mm, arithm.)	290	380
Average height (m)	23.5	33.4
Proportional distribution of tree species (%)		
Norway spruce	80	100
Scotch pine	20	-

Five trees from these two stands were included in this study. Three trees with a positive spiral grain angle under bark were chosen and the others with a negative spiral grain angle under bark, see Table 2.3. However, the negative spiral grain angle under bark (right-hand spiral) was very close to zero. All the sampled trees were from the tree class of dominant trees. Trees from other tree classes would have been too small to obtain sawn timber using the sawing pattern proposed for the industrial validation. The trees sampled for the study did not have any major defects.

Before felling, four of the five trees were numbered, and total height, green crown height and diameter at breast height were measured. Crown height for trees number 1 and 4 was asymmetrical. The reason for this was that distance to one neighbouring tree was small. As the variation in spiral grain angle measured under bark was fairly small between four of the trees it was important to find an additional tree with a larger spiral grain under bark.

To test the possibilities of predicting twist, one extra tree, no 5, with a high degree of left-hand spiral grain angle, was added. This extra tree was felled and cut in logs and was on its way to be delivered to a sawmill for conversion into sawn timber. Data for the sampled trees is given in Table 2.3.

Table 2.3. *Description of sampled trees. (– = Data missing).*

Stand	Tree	DBH (mm)	Ring width (mm/y-ring)	Height (m)	Height to first living branch (m)	Height to crown limit (m)	No of logs/ studs	Grain angle under bark (deg)
1	1	270	1.9	23.3	5.0	8-12	3/10	2.2
1	2	330	2.3	24.8	4.0	7	3/16	-0.1
2	3	480	3.4	34.5	12.5	18	3/35	-0.1
2	4	470	3.4	36.0	17.0	17-25	3/28	1.7
2 (2B)	5	*500*	*3.6*	*36.5*	–	–	5/40	15.0

2.2.2 Measurements of spiral grain in logs

The log was placed in a horizontal position. All of the butt-logs were measured at two longitudinal positions on the surface under bark, i.e. 1.3 meters from the butt end and 0.5 meters from the top end of the log. Other logs from the same tree were only measured at the top end, see Figure 2.6. The spiral grain value found at the top end was assumed to be the same as the spiral grain at the butt end of the adjacent log, i.e. higher up in a tree.

A small area, a window, with dimensions of 200 mm x 400 mm, was de-barked on opposite sides of the log's surface. The pith was marked at both ends of the log, by drawing a vertical line through the pith, using a spirit level. A line was drawn at right angles to the vertical line, out to the bark. By using a coloured string, a line was marked on the surface of the log and on the debarked window, showing the axis of the log. Three lines, all longer than 200 mm, were inscribed in each window (the de-barked area). The string ran through the window and through a point A on the inscribed line. A line, denoted as GM, from the coloured line to the scribed line, was measured, see Figure 2.6. Positive GM (+) was defined as being to the left of the coloured line and negative GM (-) to the right of the coloured line.

The length of logs varied and all the studs were sawn with a length of 2.6 m from the top end of each log, a value for the spiral grain angle was interpolated at 1.3 m from the top end of each log (corresponding to the middle part of studs). These values were denoted as grain angle under bark (GAub).

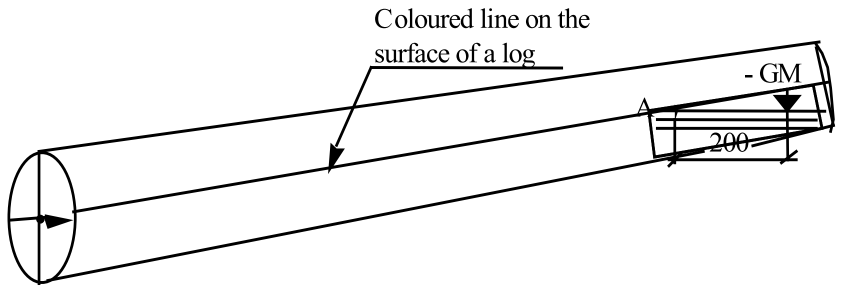

Figure 2.6. *Measuring spiral grain angle on a middle-log lying on the ground.*

2.2.3 Sawing, drying and measured distortion

A total of 17 logs were sawn from the five trees with three to five logs per tree. 129 structural studs with dimensions of 50 x 100 mm^2 were sawn using a conventional sawing pattern, see Figure 2.7. The nominal distance from the pith to the centre of each stud was measured regarding the sawing pattern. If the studs with a centre closer than 50 mm from pith were disregarded, 104 studs were obtained.

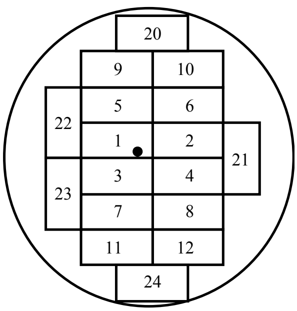

Figure 2.7. *Notation for studs with regard to the position from the pith.*

All the studs were dried in a ordinary kiln at a sawmill industry to a moisture content[9] of about 12%. A conventional drying schedule was used: low-temperature drying (wet bulb temperature of 55°) and with loading during drying. No planing of timber took place. Directly after drying, all the timber was sent to the laboratory at the Department of Structural Engineering, Chalmers University of Technology. Both packs were then opened and the timber was separated and placed vertically, unloaded, against a wall in the laboratory, for four weeks. Moisture

[9] Moisture content: The amount of water contained in wood, usually expressed as a percentage of the weight of oven-dry wood.

content and distortion were measured for all pieces. At the time of the measurements of distortion, the average moisture content was estimated to be 11%, using an electrical device for the registration of moisture content.

It was assumed that at the time of distortion measurements, the timber was dried to approximately the same moisture content as it would have been in practical use, and stored without restraints, which also resembles real/poor conditions in reality. Global measurements of distortion (bow, spring and twist) measured over a length of 2.5 m were made using the same method as described previously, (Perstorper et al. 2001, Kliger 1999).

2.2.4 Models

Models for predicting distortion can be divided into models for predicting twist and models for predicting bending distortion such as bow and spring. All these models can also be divided into three groups: i.e. statistical models, analytical models and numerical models. Statistical models are based on statistical correlations between various measured material parameters and twist, bow or spring. Analytical models are based on physical explanations of the phenomena (Stevens & Johnston 1960). Numerical models (Finite Element, for example) are usually complicated, and require very accurate input data (Ormarsson 1999, Persson 2000, Dahlblom 2000).

In this report, a few statistical models and one analytical model were used to predicting twist for industrial validation, as twist is very important for industry.

Statistical models

Multiple and stepwise regression analysis, together with forestry input data, which was simple to measure, was validated in this study. Four statistical models were applied here, see Section 8.4.

Analytical model

Stevens & Johnston (1960) presented an analytical model for twisting cylindrical shells of wood during adsorption. This model is based on a relationship between twist and shrinkage, grain angle and the radius of annular rings as shown in Eq. (2.1)

$$\alpha = \frac{l}{r} \cdot \frac{2s\theta}{1+s} \qquad \textbf{(2.1)}$$

where:

α	=	twist (°)
l	=	length of stud (m)
θ	=	spiral grain angle in centre of stud (GAstud) (°)
r	=	radius (m), distance from pith to centre of stud
s	=	tangential shrinkage

The model is only valid for small grain angles, and it is assumed that the longitudinal shrinkage is negligible.

On the condition that (θ/r) and tangential shrinkage are constant throughout the stud, and the pith is located in the centre of the stud Eq. (2.1) might predict the angle of twist in the stud sufficiently well for practical applications.

Balodis (1972) found that data obtained using his model correlated well with his experimental data. However, it did overestimate the magnitude of twist. He also presented three possible explanations for this difference: external restraint during seasoning, internal restraint, or mistakes produced during the measurements of grain angle. External restraints during drying and conditioning produce a substantial reduction in twist according to many studies, especially when combined with high-temperature drying (Arganbright et al. 1978).

3. Typical pattern for spiral grain formation

3.1 Introduction

This chapter presents the general results from the measurements of spiral grain. It shows the results from all measurements of the grain angle (GA) versus annual ring number (RN) numbered from the pith and GA versus distance from pith (Dist). These figures are based on 7023 observations, where each observation is a mean value of four measurements[10]. The relation between GA vs. RN illustrates grain angle formation as a pattern typical for a phenotype of a tree (genetic and environmental influence). This illustrates one certain species and the development of spiral grain within the sampled trees. It is considered important to present the results for both GA vs. RN and GA vs. Dist to enable a better explanation of the variation among trees regarding spiral grain, various forest and silvicultural parameters and their influence on engineering wood data. Grain angle versus distance from pith will give us the grain angle variation in a radial direction, which is of practical engineering and industrial interest.

In older times knowledge about ring width, orientation and grain angle was regarded as important and was used to achieve better quality in manufactured products. Today there is no practical method in use for online measurement of ring data or grain angle in the sawmill industry. For practical use, GA vs. Dist in radial direction is of importance for prediction of twist in sawn timber and to some extent for predicting the strength of wood in different products.

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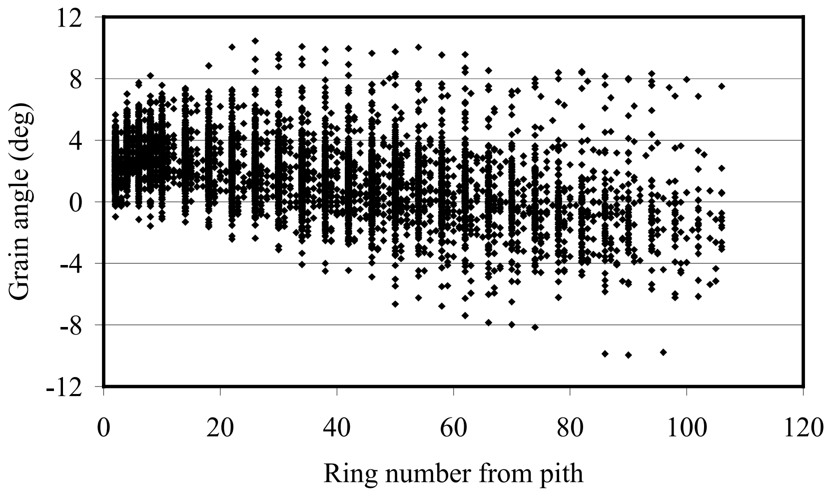
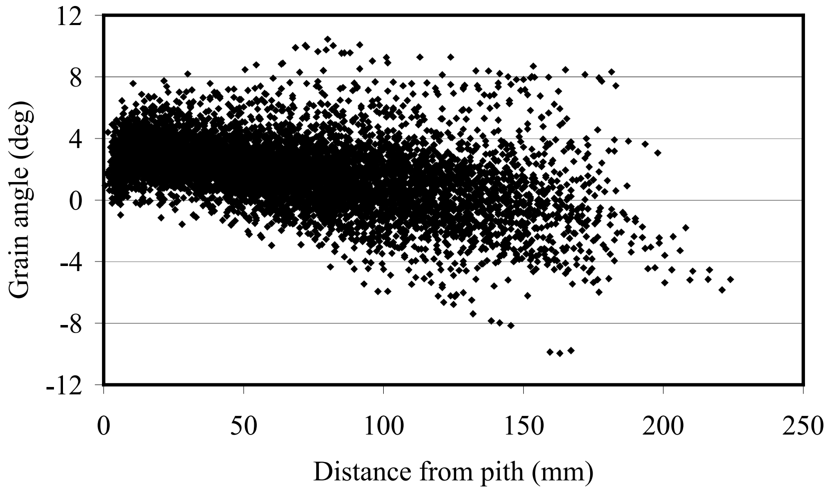
[10] One observation is an average value of two measurements in each radius, from one annual ring (north and south) see Subsection 2.1.3.

3.2 Spiral grain angle versus ring number or distance from pith

The results of the measurements are shown in Figure 3.1. The measurements were performed for every second annual ring up to ring number 10, and then for every fourth annual ring. Very few measurements (less than 1%) had a negative grain angle at ring number 2. These negative measurements could be correct, or could be due to error in measurement, which was ±0.6° in this study. Knots in, or close to, the sampled strip could also disturb the grain inclination. It was obvious from the results obtained that the grain angle is normally near zero close to the pith, and thereafter it increases and reaches a maximum value before ring number 10. After this culmination there is in most cases a slight decrease of the grain angle. Grain angle (GA) versus ring number from pith (RN) in Figure 3.1. (a) shows a similar pattern to GA versus distance from pith (Dist) in Figure 3.1. (b).



(a)



(b)

Figure 3.1.

(a) Relationship between grain angle and ring number from pith to bark.

(b) Relationship between grain angle and distance from pith to bark.
7023 observations based on 390 butt-, middle- and top logs from 21 stands.

In Figure 3.1. discs from all the 390 logs from 21 stands were included. If nine log discs with considerable disturbance from knots and other strange irregularities were excluded (from the total of 390 logs) there was a more assembled formation in the scatter plots, see Figure 3.2. To obtain a comparable and clear regression line, measurements from rings number 2 and 4, or closer than 15 mm from pith, were excluded. The reason for this is the large change of fibre inclination between each annual ring from pith to rings number 4 to 8.

In Figure 3.2. the predicted regression line and the 90% confidence intervals are drawn with straight lines.

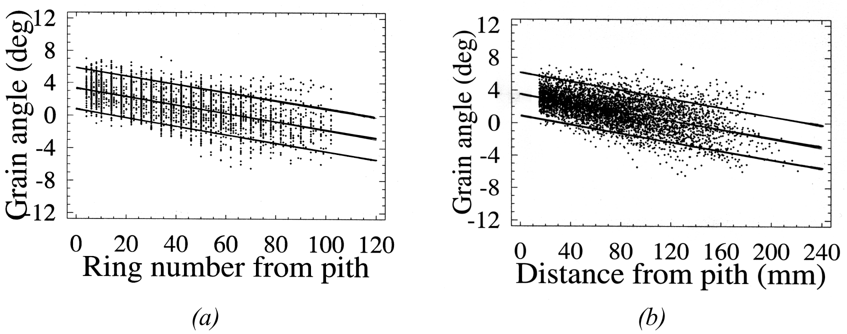


Figure 3.2.

(a) Relationship between grain angle and ring number from pith, from ring nr 4.

(b) Relationship between grain angle and distance from pith, from 15 mm from pit. 4988 observations based on 381 butt- middle- and top-logs. Prediction of regression line and 90 % confidence intervals.

3.3 Alternative models

Alternative statistical models have been tested when evaluating the results obtained from the measurements. Table 3.1 shows that the linear approach was better suited than alternative approaches to explain the relation between GA versus RN and GA versus Dist. R^2 increased from 0.25 to 0.36 for GA versus RN and from 0.21 to 0.31 for GA versus Dist, if 9 discs with irregularities in grain formation from knots were excluded, from the total of 390. The improvement of R^2 indicates the importance of knot free wood samples. R^2 was higher for GA versus RN (0.36) than for GA versus Dist (0.31). The value of correlation is higher for GA vs. RN compared to GA vs. Dist, see Table 3.1.

Table 3.1. *Comparison of alternative models for GA vs. RN and GA vs. Dist.*

Model	R-Squared RN	R-Squared Dist
Linear	36.3%	31.1%
Square root-X	36.2%	31.0%
Logarithmic-X	33.5%	29.4%

A linear model can describe the relationship between GA vs. RN and GA vs. Dist

$$GA_i = \alpha + \beta * RN_i + \varepsilon_i \qquad i = 1,2,......,4988$$

where ε denotes the random error with expectation $E(\varepsilon_i) = 0$ for all i and $V(\varepsilon_i) = \sigma^2$ for all i.

The estimated models are

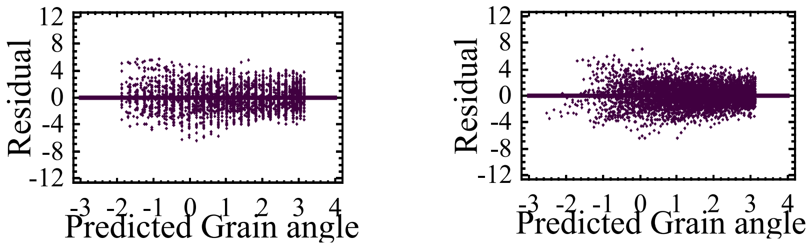
GA = 3.36 – 0.051*RN

GA = 3.53 – 0.027*Dist

where the parameter Dist should be given in mm.

The P-value in ANOVA is less than 0.01 for both models, which means statistically significant relationships at 0.01 significance level. The standard error of estimate and the standard deviation of residuals (in brackets) for both models were 0.00096 and (1.56) for GA vs. RN and for GA vs. Dist it was 0.00057 and (1.62).

The residual plots for the linear models above are expressed in Figure 3.3. The Figures show no heteroskedasticity, consequently the models can be considered stable with varying RN and Dist.



(a) *(b)*

Figure 3.3.

Residual plot for model in Figure 3.2 above.
(a) Residuals versus predicted grain angle for ring number from pith.
(b) Residuals versus predicted grain angle for distance from pith.

3.3.1 The model for individual logs

A linear regression can describe the relationship between GA vs. RN and GA vs. Dist for individual logs. R-Squared for both relations were 0.82 as an average for 57 individual butt-logs from stand 11-14. (Seven trees of 64 were rejected since the linear approaches were parallel with x-axis or spiral grain irregularities in the wood sample caused by knots). The linear approach is preferable for individual logs since it will give the easiest statistical estimation. The standard deviations of estimated mean value of R^2 (0.82) were 0.149 for GA vs. RN and 0.161 for the relation between GA vs. Dist.

3.4 Spiral grain angle versus ring number from pith

Figure 3.4 illustrates the average curve for spiral grain found in the same observations as in the scatter plot in Figure 3.1. The average grain angle reaches its maximum value at ring number 4. At this point the average grain angle is 3.15°. After this point the average grain angle decreases almost linearly. Between annual rings number 40 to 100 the grain angle reaches zero, on average at about annual ring number 70. This corresponds to a fibre direction parallel to the stem axis.

At ring number 100 the average grain angle is -1.2°. This means that in the normal case for older spruce trees, the fibre inclination forms a right handed helix around the stem under the bark. The gradual change of grain angle with increasing age will normally make the grain inclination more and more right handed as age increases.

The unbroken line above and the dashed line below the average line in Figure 3.4 show the upper and lower level for two standard deviations (standard deviation*2) in relation to ring number. Approximately 95% of the observations will be found between these standard deviation lines. Consequently, approximately 2.5% of the observations are over and 2.5% are below the standard deviation lines. Over and under these lines we can find most of the trees and logs that will cause the user of sawn timber the greatest problems with twist, when the moisture content in the wood is changed.

It is of great importance for the understanding of how the properties of wood are related to twist to observe that the variation of grain angle is smallest close to the pith, where the values lie between 1° and 6°, for 95% of the sampled trees, see Figure 3.4.

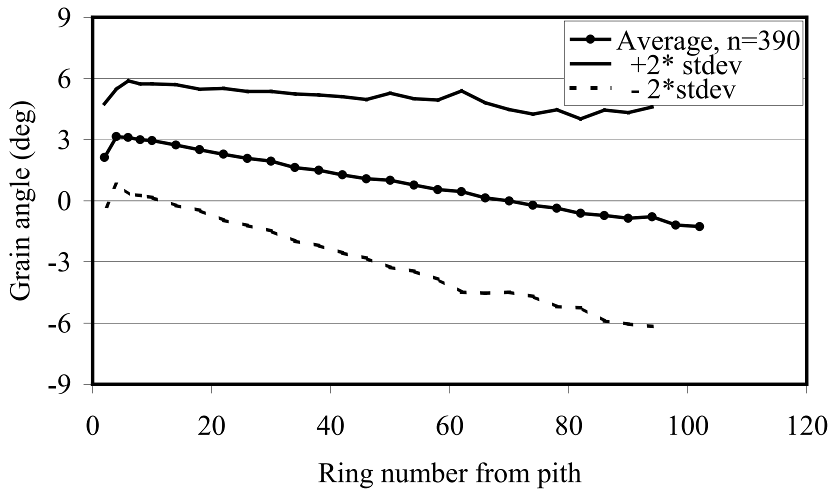


Figure 3.4. *Mean relationship between the average grain angle and ring number from pith to bark and ± 2 standard deviation. 7023 observations based on 390 logs.*

Figure 3.5 shows the standard deviation versus ring number and distance from pith. The standard deviation increases linearly from 1° close to pith to 3° at annual ring number 100, or 150 mm from pith.

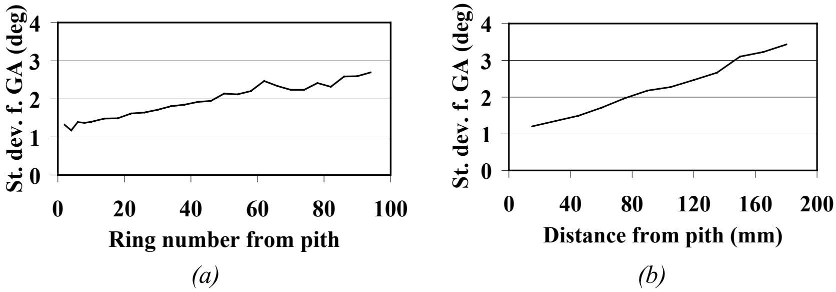


Figure 3.5.
Relationship between the standard deviation for:
(a) Grain angle and ring number from pith.
(b) Grain angle and distance from pith
7023 observations based on 390 butt to top logs.

3.5 Spiral grain angle versus distance from pith

Figure 3.6 shows the relation between average grain angle and distance from pith. The GA culmination occurs in this diagram at 15 mm from the pith. Butt-logs have a distinct point of culmination compared to top-logs, which have a flatter maximum, between 15 and 30 mm from pith. In average, the spiral grain is zero at about 135 mm from pith for the butt-logs and about 120 mm from pith for the top-logs.

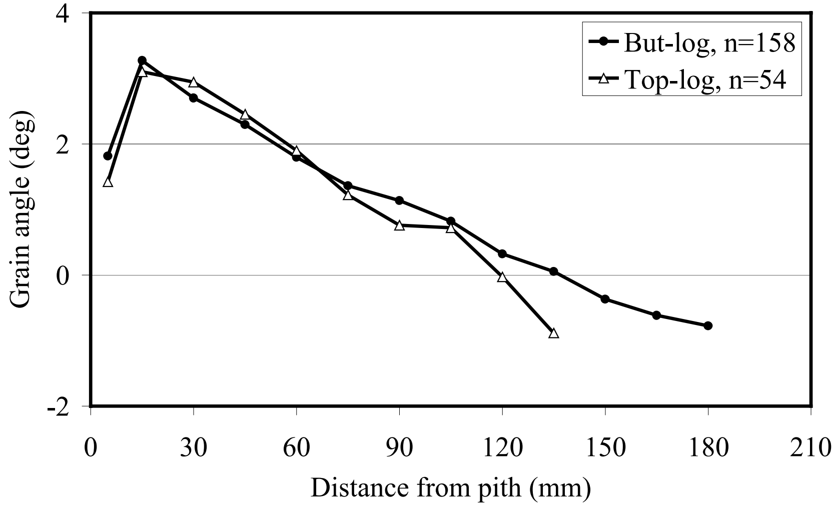


Figure 3.6. *Relationship between the average grain angle and distance from pith to bark. 2922 observations based on 158 butt-logs and 802 observations based on 54 top-logs.*

3.6 Spiral grain pattern in individual trees

All individual trees differ in appearance concerning spiral grain. Differences between species might be explained by the science of genetics, whilst differences between members of the same species can be explained by both inheritance and environment. As far as spiral grain in Norway spruce is concerned, there is a considerable difference between the way different grain angles arise and develop in different individuals.

In Figure 3.7 to 3.12 six different types of trees is shown. The trees clearly exhibit different characteristics for the grain angle with increasing annual ring numbers. Grain angle in butt-log, middle-log and top-log are shown in all six figures. The figures show that logs taken from different heights within the same tree have a tendency to exhibit similar patterns of spiral grain. This means that the grain angle is more or less identical in the same annual ring, counted from the pith, independent of height in the tree. This also shows that the special spiral grain characteristics exhibited by one individual are not a result of mere coincidence or fibre aberration close to a knot. As a result of this phenomenon one may be seduced into believing that the development of spiral grain is to a large degree governed by genetic factors. It has however been shown that the tree's growth environment influences the development of spiral grain, (Eklund & Säll 2000, Eklund, Säll & Linder 2002). To what degree genetics and environment work together is not taken up in this thesis, but it is indisputable that both of these factors have an influence on the spiral grain.

Figure 3.7 illustrates the grain angle in a right hand grained “**normal grained”** tree, or “anticlockwise warped” (“motvint”) as it is called in older Swedish literature. The curves shown in Figure 3.7 are in accordance with the average curves shown in Figure 3.4. The grain angle culminates in the 4th to the 6th annual rings, at around 3°, and then decreases successively until it is straight grained in the 40th to the 70th annual rings, and then progresses to show negative grain angles.

The development of the grain angle in the “**straight grained**” tree in Figure 3.8 does not differ much from the “normal” tree in Figure 3.7. The difference is that the grain angle in Figure 3.8 decreases rapidly after culmination, remains stable at approximately 1° to 2° after the 15th annual ring, and thereafter decreases gradually. It is not until the 80th annual ring that the “straight grained” tree exhibits a right handed grain angle.

Figure 3.9 shows a “**right hand grained**” tree, which as early as the 20th to the 40th annual ring changes to a right hand grain angle, and by the 80th annual ring the grain angle is -4°.

Figure 3.10 shows an “**extremely right hand grained**” tree. This tree changes from left to right handed at the 40th annual ring, and at the 80th annual ring exhibits a grain angle of -6°. This is a solitary tree that has grown on a sandy promontory in Helgasjön, a lake to the north of Växjö.

The opposite of the “right hand grained” tree is shown in figures 3.11 and 3.12. Both of these trees are “**left hand grained**”, or “clockwise warped” (“solvinda”) as they are called in the older Swedish literature. In the left hand grained tree in Figure 3.11 there are no changes in the grain angle after the 4th annual ring, which results in the grain angle remaining around 3° in the higher annual rings.

Figure 3.12 shows a tree with “**increasing left hand grain**”. In this tree the grain angle increases with the increasing age of the tree.

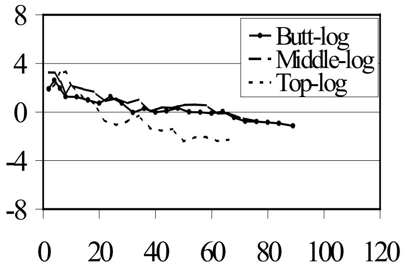


Figure 3.7. Grain angle vs. ring number for a ***normal grained*** *tree.*
Tree No 13:5.

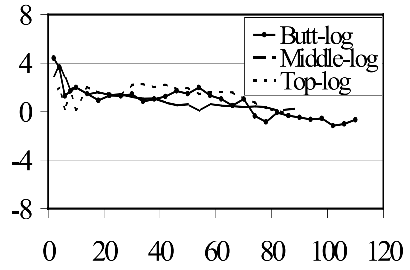


Figure 3.8. Grain angle vs. ring number for a ***straight grained*** *tree.*
Tree No 13:14.

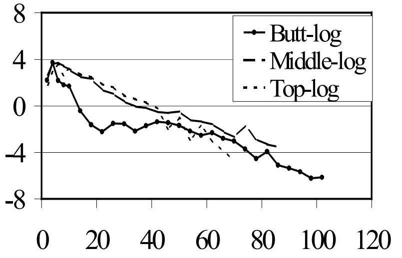


Figure 3.9. Grain angle vs. ring number for a ***right hand grained*** *tree.*
Tree No 13:23.

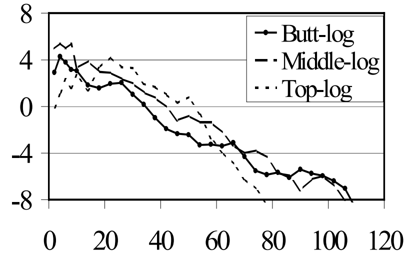


Figure 3.10. Grain angle vs. ring number for a ***extremely right hand grained*** *tree.*
Tree No 16:7.

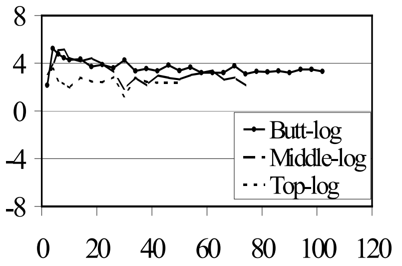


Figure 3.11. Grain angle vs. ring number for a ***left hand grained*** *tree.*
Tree No 26:4.

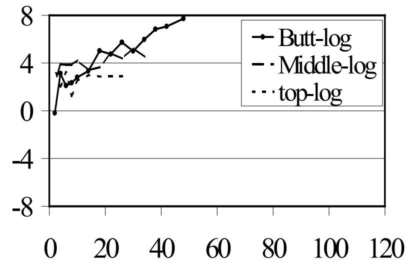


Figure 3.12. Grain angle vs. ring number for a ***increasing left hand grained*** *tree.*
Tree No 14:6.

3.7 Summary

As a summary of the results obtained from the measurements of the spiral grain angle, a practical conclusion may be stated.

" For the average log, the spiral grain angle culminates between the 4th and 8th annual rings, about 15 mm from pith, with a left handed helix and a grain angle of 3°. For the majority of logs, when the 50th annual ring is formed they are much more straight grained, with fibres nearly parallel to the stem axis. At the 100th annual ring, the helix is normally right handed with a grain angle of -1°. This linear ongoing change of grain angle with increasing annual ring number will continue for older trees".

This knowledge is of importance when estimating the grain angle variation in radial direction based on a measured grain angle under bark only. Normally such estimations might be based on the predetermined spiral grain angle of 3° at a 15-mm distance from pith.

All of the several types of trees described above in Section 3.6 can be found in one and the same stand. It is often sufficient to measure the grain angle at breast height or above in the first log to be able to judge the character or type of grain angle in the rest of the logs. This means that a tree with an abnormally large grain angle can be marked or allocated to a suitable assortment in the forest or when felling. To have access to an adequate and descriptive terminology for the different types of trees in the forest it may be suitable to use the terms right hand, left hand and normal grained trees.

4. Spiral grain pattern in different stands

4.1 Introduction

Previous studies have shown that spiral grain varies between different provenances and types of stands (Rault & Marsh 1952, Elliot 1958, Wellner & Lowery 1967, Danborg 1996). When stands are established, and during silvicultural activities such as cleaning and thinning, the goal is to achieve a high volume production and a high quality stand. The concepts and formulations used in forestry to describe the quality of a stand of Norway spruce differ from those used by a building constructor to describe the demands he makes for construction timber, whilst making structural calculations. A relevant question that arises in connection with this is: Are there stands that, from the point of view of spiral grain, deviate more and are likely to produce a greater proportion of twisted timber compared to the normal stand?

4.2 Description of sampled trees

Table 4.1. show data for sampled trees from respective stand. In stand 13, extra trees denoted as 13b were chosen to obtain the sub-sample of trees corresponding to the co-dominant and intermediate tree classes. 21 stands were studied.

The arithmetical mean value and standard deviation are shown in Table 4.1. Ten to fifteen sample trees have been selected from stands 11 to 14, while the number of trees chosen from the remaining stands are five or six. Significant differences can be observed between the stands, even though the number of sampled trees is low. These differences can to a certain degree be attributed to previous forest treatment, combined with site index, genetic differences between the trees and/or systematic differences when choosing sample trees.

Table 4.1. *Summary data for sampled trees from the selected stands. Number of sampled trees (n), diameter at breast height (DBHt), ratio between DBHt for sampled trees and the DBHst for stand (DBHt/DBHst), height of tree (H), ratio between height of tree and diameter at breast height (H/DBH), ratio between height to first green branch and height of tree (HGB/H), average ring-width at breast height (RW). Arithmetical mean values and standard deviation with brackets.*

Stand No	n	DBHt (mm)	DBHt/DBHst (mm/mm)	H (m)	0.1*H/DBH (dm/mm)	HGB/H (m/m)	RW (mm/y-ring)
11	13	391 (67)	1.25 (0.21)	29.1 (2.0)	0.76 (0.10)	0.26 (0.10)	1.5 (0.3)
12	15	415 (79)	1.43 (0.27)	29.2 (2.8)	0.72 (0.10)	0.23 (0.10)	1.8 (0.3)
13a	15	412 (86)	1.25 (0.26)	32.8 (2.8)	0.82 (0.14)	0.36 (0.10)	2.0 (0.4)
13b	10	237 (55)	0.72 (0.17)	25.1 (5.3)	1.07 (0.11)	0.53 (0.10)	1.1 (0.3)
14	14	380 (53)	1.12 (0.16)	27.8 (1.6)	0.74 (0.09)	0.44 (0.13)	3.5 (0.5)
21	6	367 (64)	0.82 (0.14)	30.0 (2.0)	0.84 (0.12)	0.44 (0.06)	2.0 (0.3)
22	6	325 (45)	0.98 (0.14)	28.6 (1.9)	0.89 (0.10)	0.56 (0.06)	2.4 (0.3)
23	6	255 (59)	1.27 (0.29)	21.7 (1.7)	0.88 (0.13)	0.43 (0.08)	1.7 (0.4)
24	6	271 (64)	1.03 (0.24)	21.5 (2.4)	0.81 (0.10)	0.31 (0.05)	1.8 (0.4)
25	6	248 (45)	0.99 (0.18)	20.3 (2.2)	0.83 (0.07)	0.42 (0.04)	1.7 (0.3)
26	6	270 (55)	1.23 (0.25)	21.6 (1.8)	0.82 (0.10)	0.24 (0.04)	1.0 (0.2)
27	6	233 (35)	1.05 (0.16)	19.8 (2.2)	0.85 (0.03)	0.26 (0.12)	0.8 (0.1)
28	6	228 (36)	1.27 (0.20)	19.5 (1.9)	0.86 (0.05)	0.38 (0.08)	0.8 (0.1)
51	6	327 (82)	1.09 (0.27)	22.5 (4.4)	0.70 (0.06)	0.28 (0.08)	2.0 (0.5)
52	6	306 (84)	1.02 (0.28)	24.2 (2.1)	0.83 (0.16)	0.33 (0.14)	1.7 (0.5)
53	6	322 (87)	1.07 (0.29)	26.2 (3.7)	0.84 (0.14)	0.38 (0.12)	1.8 (0.5)
54	6	307 (83)	1.02 (0.28)	25.3 (4.1)	0.85 (0.13)	0.50 (0.09)	1.9 (0.5)
55	5	330 (85)	1.18 (0.30)	26.8 (4.7)	0.83 (0.10)	0.32 (0.07)	1.8 (0.5)
56	6	286 (64)	1.30 (0.29)	21.8 (1.8)	0.79 (0.15)	0.28 (0.07)	3.4 (0.8)
57	5	325 (64)	1.16 (0.23)	26.8 (2.6)	0.84 (0.10)	0.33 (0.11)	1.9 (0.4)
58	6	256 (78)	1.02 (0.31)	19.7 (4.6)	0.78 (0.08)	0.39 (0.16)	1.4 (0.4)

Table 4.2. *Forest treatment for the different stands: Different methods of regeneration (natural or planting), and spacing (distance between seedlings). Programmes and number of thinnings. The stand age at first revision and number of stems/ha (st/ha), stand age when this study started (latest revision) and st/ha (in italic if estimated). Stand no 11 and 14 to 28 are managed by the Swedish University of Agricultural Sciences.*

Stand No	regeneration method and spacing (m)	thinning programme and number		first revision		latest revision	
			no	age	st/ha	age	st/ha
11	natural	free	1	100	730	135	340
12	natural	-[11]	-	-	-	120	680
13a	natural	-	-	-	-	110	430
13b	natural	-	-	-	-	110	430
14	plant, 1.5 x 1.5	free	5	23	4025	60	680
21	plant	free	-	33	3100	101	300
22	plant	strong low	6	31	3400	76	550
23	plant, 1.5 x 1.5	weak low	2	37	3600	82	950
24	plant, 2.0 x 2.0	weak low	2	37	1700	82	550
25	plant, 3.0 x 3.0	free	1	37	1000	82	580
26	natural	Ex. strong low[12]	1	77	7400	152	490
27	natural	strong low	7	77	8600	152	560
28	natural	strong crown	6	77	8500	152	1120
51	natural	low	-	-	-	90	*300*
52	natural	low	-	-	-	100	*300*
53	natural	untreated	-	-	-	100	*300*
54	natural	low	-	-	-	90	*350*
55	natural	low	-	-	-	100	*500*
56	natural	-	-	-	-	50	*550*
57	natural	low	-	-	-	95	*400*
58	natural	untreated	-	-	-	100	*600*

Mean diameter at breast height

Twelve stands had a mean diameter at breast height (DBH) that exceeded 300 mm. In two of these stands (12 and 13a) the sampled trees mean diameter was higher than 400 mm. The sample trees in stand 13a were all taken from the dominant tree class, while the sample trees in stand 13b were taken from the co-dominant and intermediate tree class. The mean

[11] - Data missing.
[12] One hard thinning, with a very large removal of standing volume.

diameter of the sample trees from stand 13a was 412 mm, whilst it was 237 mm in stand 13b, see Table 4.1.

Stands 26, 27 and 28 have the highest stand age (152 year) and the lowest DBH, 270 mm, 228 mm, and 233 mm respectively, see Table 4.1. This can be explained by the fact that these stands were grown on a site with low conditions, which explains by the site index H100 = 16m, see Table 2.1.

The relationship between the sample trees' mean diameter DBHt, and the mean diameter of the rest of the stand DBHst (DBHt/DBHst) reflect the relative size for sample trees. Seven stands (11, 12, 13a, 23, 26, 28 and 56) have a mean diameter of the sample trees more than 20% higher than the mean diameter for stands, see Table 4.1. In stand 12, the sample trees are 43% larger. For the material as a whole, the sample trees are 11% larger than the mean value of the DBH for all stands.

Stand 13b and 21 have a mean diameter of the sample trees substantially lower than the mean diameter of the rest of the stand; the relation DBHt/DBHst is 0.72 and 0.82 respectively. The selection of co-dominant and intermediate trees in stand 13b explains the low value for relative size of sampled trees. Regarding the choice of sample trees in stand 21, these have been taken from a very coarse stand whose mean diameter were 445 mm, see Table 2.1 and Table 4.1.

Mean height

The sample trees in stand 13a has the highest mean height, 32.8 m, while stand 28 has the lowest mean height, 19.5 m, see Table 4.1. The difference can mainly be explained by the fact that the site conditions for stand 13 was substantially better than for stand 28. Site index (H100) was 34m for stand 13 and 16m for stand 28, see Table 2.1 and Table 4.1.

Ratio between height and diameter at breast height (H/DBH)

Slenderness ratio, 0.1*H/DBHt, (dm/mm) is the relationship between height of sampled trees and the diameter at breast height. For the majority of stands, slenderness ratio varies between 0.80 and 0.90, which tells us that the trees had a relatively large taper, see Table 4.1. These ratios are typical for dominant trees in a stand. It is only the sample trees in stand 13b that deviate to any great degree from the others, and they have a slenderness ratio of 1.07. This shows that the sampled trees in stand 13b had small taper, or had a good stem shape.

Relative live crown height (HGB/H)

The relative live crown height, HGB/H, (m/m) is defined as the ratio between height to the first living branch, HGB, and the tree's height, H.

Table 4.1 shows that the majority of the sample trees have a value of relative crown height which varies between 0.25 and 0.40. Only three stands (13b, 22, 54) had a relative live crown height that was higher than 0.50. A low value for HGB/H tells that the tree has a low positioned crown base, which has an influence on the shape of the tree and its taper, and whether or not the trees stand sparsely. The value does not, however, tell us anything about whether the live crown starts at the same height on all sides of the trunk. Trees at the edges of stands and in uneven stands with many gaps often have an asymmetric positioned crown, where the crown begins at a low height on the side that faces the opening. This can affect both the qualities of the wood and the degree to which the stem is oval in form.

Annual ring width

The mean annual ring width at breast height, RW, (mm/y-ring) is a measure of how quickly the sample tree has grown, se Table 4.1. When calculating RW, the stand age has been reduced by the number of years it normally takes for the relevant site index (H100) to reach breast height (1.3 m). For stand 14, the stand age has thereby been reduced by six years, stands 12, 13a, 13b, 21 and 22 by seven years, stands 11, 23 to 25 and 51 to 58 by eight years, and stands 26 to 28 by ten years.

The majority of stands (16 of 21) had a RW that varied between 1 and 2 mm. Stands 26 to 28 had an average annual ring width that was 1 mm or less. This depended mainly on the very low site index, H100 = 16m, and the fact that the stand had approximately 8000 stems/ha when it was thinned for the first time, at the age of 77 years, see Table 4.2. It can be considered normal that the annual ring width varies between 1 to 3 mm. This level gives an indication of good timber quality according to prevalent opinions within the wood industry.

The annual ring width in stand 14 and 56 was 3.5 and 3.4 mm, respectively, see Table 4.1. The explanation for relatively wide annual rings in stand 14 and 56 is the low number of stems/ha in relationship to the stand age; 680 stems/ha for stand 14 (60 years) and ca. 550 stems/ha for stand 56 (50 years), see Table 2.1 and Table 4.2. These two stands were thinned from below, which means that the coarsest and the dominant trees were saved when thinned. The mean annual ring width for the remaining stands varied between 0.8 mm and 2.4 mm, with a mean value of 1.6 mm. The mean annual ring width for the dominant trees in stand 13a was 2.0 mm, and 1.1 mm for the smaller trees in stand 13b.

Standard deviation for RW in the sample trees in stand 56 was 0.8 mm, which indicated a large variation between the sample trees, while standard deviation for the remaining stands do not exceed 0.5 mm. This can be an indication that the chosen sample trees were relatively evenly coarse, see Table 4.1.

4.3 Mean values of spiral grain in stands

In this section, only the values for grain angle after the culmination at annual ring number six have been included. This simplifies calculation and makes it possible to clarify differences between the stands concerning grain angle development. The mean distance between the pith and the sixth annual ring was 19.5 mm.

Distribution of grain angle

Figure 4.1 shows the distribution of grain angle, GA, for the respective stands. Stand 12 has the greatest distribution (19°) and varies between -10° and 9°, while stand 23 has the smallest distribution (8°) and varies between -2° and 6°. The distribution of GA for stand 13a would have ranged from -6° to 5° (11°), if it had not been for the fact that two of the stems from the stand had a strong left hand grain in the higher annual ring numbers, see Figure 4.4 b. These two logs increase the distribution for stand 13b with a further 4°, up to 15°. The distribution of grain angle for the stands in Figure 4.1 shows that the stands differ, concerning both degree of distribution and expected mean value.

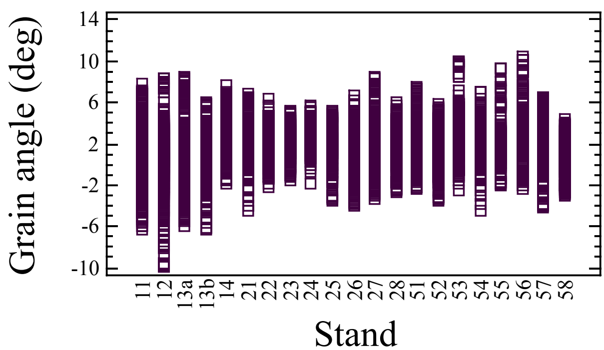


Figure 4.1. *Scatter plot for grain angle from ring number 6 to bark by stand. 6277 observations based on 21 stands.*

Mean values of measured grain angle values related to ring number or distance from pith

Regression analyses were carried out at each stand where the grain angle is the dependent variable. Two alternative model specifications are used for estimation: With ring number (RN) and the distance from pith (Dist), respectively, as explanatory variables. The prediction intervals, calculated at the mean are given in Figure 4.2 and 4.3 respectively. The length of the confidence interval depends on the chosen confidence level, on the size of the standard error of the residuals and the number of observations. The length of confidence interval also depends on the distance from mean in the independent variable and since it is calculated at its mean it is at its minimum (Aczel 1993).

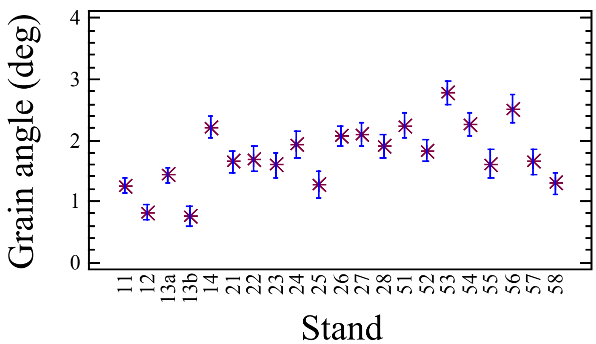


Figure 4.2. *Means of grain angle versus ring number and 90 % prediction confidence intervals for all stands. 6277 observations based on 21 stands.*

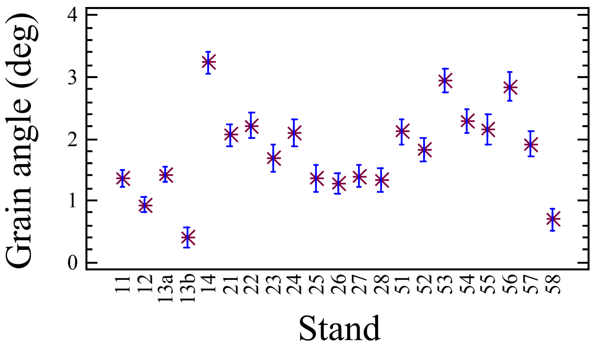


Figure 4.3. *Means of grain angle versus distance from pith and 90 % prediction confidence intervals for all stands. 6277 observations based on 21 stands.*

In Table 4.3, the numerical values are shown and the results are illustrated in Figure 4.2 and Figure 4.3. The total number of observations is 6277[13] for all stands. The number of observations per stand varies between the lowest number of 172 for stand 55, and 618 for stand 13a.

[13] One observation is an average value of two observations in each radius in one annual ring (north and south), see Chapter 2.1.3.

Table 4.3. *Data for mean values of grain angle versus ring number and grain angle versus distance from pith. Stand number (stand), number of observations (n).*

stand	n	mean values of grain angle vs. ring number	mean values of grain angle vs. distance from pith
All	6277	1.75	1.78
11	507	1.26	1.36
12	589	0.82	0.92
13a	618	1.43	1.42
13b	354	0.75	0.38
14	281	2.22	3.24
21	296	1.64	2.06
22	220	1.69	2.21
23	215	1.59	1.68
24	204	1.93	2.10
25	194	1.27	1.36
26	345	2.07	1.27
27	275	2.09	1.39
28	256	1.89	1.34
51	229	2.24	2.12
52	272	1.83	1.82
53	256	2.78	2.93
54	270	2.26	2.29
55	172	1.61	2.15
56	178	2.51	2.84
57	226	1.65	1.91
58	320	1.29	0.69

Interaction of results

Stand 13b has the lowest mean value of grain angle in the two specifications; against RN and against Dist. The highest mean values are found in stands 53 and 56, see Figure 4.2, Figure 4.3 and Table 4.3. Concerning the relation GA vs. RN, stand 14 has a mean value that does not deviate from the majority of the remaining stands, see Figure 4.2 and Table 4.3. If the mean value for GA and distance to pith is studied, stand 14 distinguishes itself by exhibiting the highest mean value, see Figure 4.3. Even stands 13b, 53 and 56 distinguish themselves when studying the mean value regarding distance to pith, see Figure 4.2 and 4.3. To some degree, this depends on differences in stand age (number of annual rings) and mean annual ring width.

The influence of annual ring width

The spread of GA and the mean value for GA in relation to RN or Dist gives an indication of differences between stands, and stand characteristics, regarding the development of spiral grain in different stands. This is caused by the fact that the mean value is to a certain degree affected by the age of the stand, since increasing age often leads to decreasing value for the grain angle, as GA generally decreases with increasing annual ring number from pith.

This leads to the indication that two trees of the same diameter with different ages (different annual ring width) will exhibit different mean values for GA, regarding GA vs. RN and GA vs. Dist, respectively. Broad annual rings in a log will in the normal case lead to a larger grain angle under bark for a given log diameter than in a log with narrow annual rings. This explains the fact that stands 14 and 56 have high mean values, since both of these stands have the highest mean annual ring widths, RW, and low values for slenderness ratio H/DBH, see Table 4.1. A low slenderness ratio (ca. 0.75) often indicates a large annual ring width.

The influence of individual trees

Stand 53 also exhibits a high mean value for grain angle. An explanation for this is that two of the 16 logs in stand 53 exhibit extreme left hand grain, which affects the mean value, see Table 4.3 and Figure 4.4.b. The stand and growth data for stand 53 do not indicate any abnormality.

Examples of other stands with individual logs that deviate from the spiral grain pattern in the remaining logs are 11, 12, 13a, 27, 53, 55, 56 and 57, see Figure 4.4.b for the respective stands.

Silvicultural effects on grain angle pattern

Stands 12, 13b and 58 exhibit low mean values for both GA vs. RN and GA vs. Dist, see Figure 4.2, 4.3 and Table 4.3. Stand 12 has, as mentioned earlier, the greatest distribution in grain angles (19°). The distribution in stand 13b is 13° and varies between -7° and 6°. The distribution for stand 58 is 8° with a variation between -3° and 5°. That the distribution of grain angle varies between stands 12, 13b and 58 does not depend on differences in age (100 to 120 years) or differences in number of registered annual rings, see Table 2.1. The distribution of grain angle can partly be explained by random factors or natural variation when choosing sample trees. The distribution between the stands probably tells us something about the evenness of the stands and their origins.

It is difficult to prove why stands 12, 13b and 58 have low mean values for GA, as previous forest treatment in the stands is not documented, see Table 4.2. According to the landowner Petersson (1998) stand 12 grew on what was previously grazing land. During the 1900:s grazing land was converted to forestland. The type of forest represented by stand 12 was, during its juvenile stage (5 to 40 years), mixed with deciduous trees, dominated by birch. Most of those trees were removed during the middle of the 1900:s. It is probable that the spruce grew under, and in competition with, birches and other deciduous trees. This type of forest, on former grazing land, can also be sparse and uneven during the first 50 years. Stand 12 also deviates by the fact that the mean diameter of the sample trees is 43% greater than the mean diameter of the stand, but despite this the mean annual ring width is only 1.8 mm, see Table 4.1. The sample trees in stand 12 also have a low slenderness ratio, 0.72, and a low live crown base, 0.23, which indicates that the stand had got high degree of stocking at a high age.

Stand 13b should in the first place be compared to 13a since they are sub samples from the same stand. As previously mentioned, 13b represents the smaller trees and 13a the coarser trees from the same area. The mean values of GA vs. RN and GA vs. Dist is 0.75 respectively 0.38 in stand 13b and lower than in stand 13a which corresponding values are 1.43 and 1.42, see Figure 4.2, 4.3 and Table 4.3. This indicates that the social status of the trees and their growth has an influence on spiral grain. The higher slenderness ratio (H/DBH), which is 1.07 for 13b compared to 0.82 for 13a, and the higher live crown height (HGB/H), 0.52 for 13b and 0.36 for 13a, show that the form of the trees differs within these two stands (tree classes), see Table 4.1. There is little knowledge regarding the past history of the stands 13a and 13b, see Table 4.2.

Stand 58 have no stand and growth data that deviates from the normal stand, see Table 2.1, Table 4.1 and Table 4.2. An explanation for the fact that stand 58 exhibits a low mean value and a low standard error of mean is probably that the number of annual rings is high (high age) and the number of observations is relatively large, see Table 4.3.

4.4 Spiral grain pattern in different stands

Figures for all stands are shown in Figure 4.4.a and Figure 4.4.b. Figure 4.4.a shows grain angle in butt-logs, plus standard deviation for the mean curve. The number of butt-logs included in 4.4.a varies between six and fifteen between the stands. The proportion of butt-logs in stand 11, 12, 13a and 14 were more than 50%, while the but-logs in the rest of stands were one-third.

All of the stands have, to the largest degree, a linear mean development after culmination at the 4^{th} to the 10^{th} annual ring. The figures show that the mean curve culminates in the higher annual rings, numbers six to ten, for the majority of the northerly stands (11, 23 to 28, and 51 to 58), while the southerly stands (12, 13, 14, 21 and 22) mainly culminate at annual ring number 4, see Figure 2.1 and Figure 4.4.a.

Variation of standard deviation

Standard deviation around the mean curve vary considerably between stands. Stands with relatively high standard deviations are 11, 12, 27, 53, 56 and 57, while stands 13a, 13b, 21, 22, 23, and 58 have a low standard deviation, see Figure 4.4.a. It is generally found that the standard deviation from the mean curve regarding grain angle in butt-logs agrees with the development and distribution of spiral grain when individual logs from the stands are shown, see Figure 4.4.a and 4.4.b.

Individual logs in stand

The number of logs shown per stand in the b-figures in Figure 4.4 varies between 15 and 27. The regression line in the b-figures shows the line for all of the grain angle observations that are included in the figure. In the majority of stands, there are individual logs where the development of grain angle deviates substantially from the regression line. Stand 12 can be taken as an example of those stands that include a number of logs whose grain angle development deviate from the regression line, see Figure 4.4.b, stand 12. In this figure it is obvious that two logs have a grain angle that increases with distance from pith, while two logs have a grain angle that decreases rapidly with distance from pith.

The proportion of logs that deviates from the prevalent pattern varies between the stands. Examples of stands with small variations around the regression line are 13b, 22, 23, 24, 25, 52 and 58, se Figure 4.4.b for respective stands. Among the stands with large variability around the regression line are 11, 12, 13a, 27, 53, 55, 56 and 57, see Figure 4.4a and Figure 4.4.b for the respective stand.

With a comparison between the mean curve for the combined material, see Figure 3.6, and the results for stands 14 and 56 in Figure 4.4.b, it can be concluded that a considerable number of logs in stands 14 and 56 are left hand grained. It is these deviating stands, which contain many individuals with extreme spiral grain, which cause serious problems for the wood users.

Figure 4.4. *Grain angle pattern in different stands. All of the registered measured values, from annual ring number 2 and outward to the cambium, are shown in the figures.*

(a) Grain angle versus ring number from pith for butt-logs. Mean and one standard deviation is shown.

(b) Grain angle versus distance from pith (mm) by log for butt-, middle-, and top logs.

(a) *(b)*

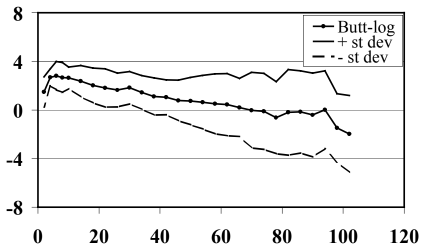


Figure 4.4. ***a***. ***Stand 11***. *13 butt-logs.*

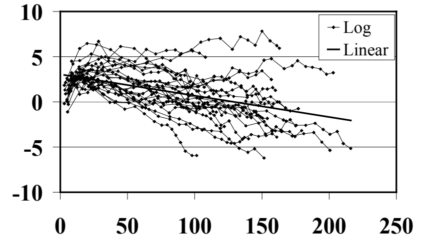


Figure 4.4. ***b***. ***Stand 11***. *24 individual logs.*

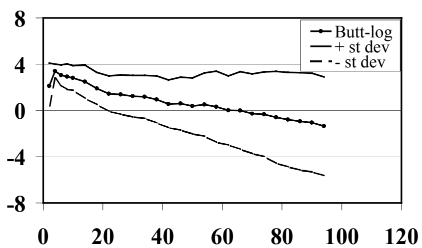


Figure 4.4. ***a***. ***Stand 12.*** *15 butt-logs.*

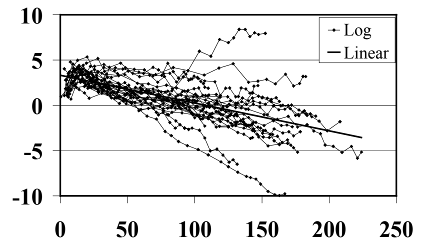


Figure 4.4. ***b***. ***Stand 12***. *27 individual logs.*

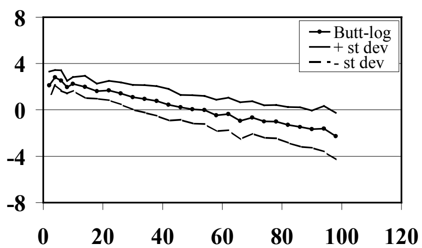


Figure 4.4. ***a. Stand 13 a***. *13 butt-logs.*

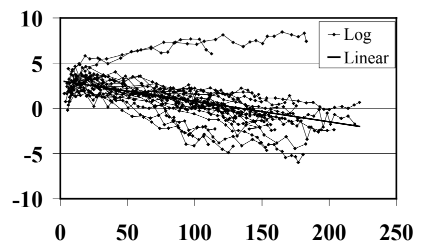


Figure 4.4. ***b***. ***Stand 13 a***. *25 individual logs.*

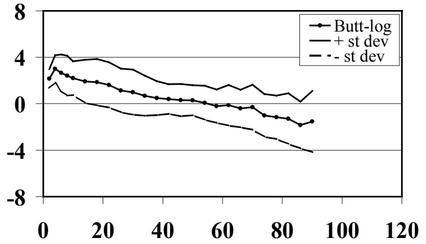


Figure 4.4. ***a***. ***Stand 13 b***. *9 butt-logs.*

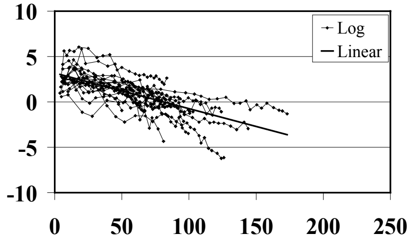


Figure 4.4. ***b***. ***Stand 13 b***. *19 individual logs.*

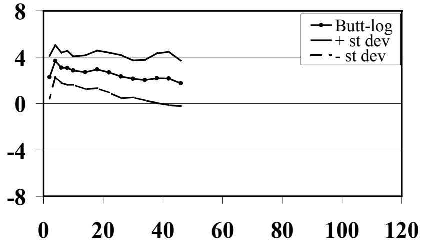


Figure 4.4. ***a***. ***Stand 14***. *14 butt-logs.*

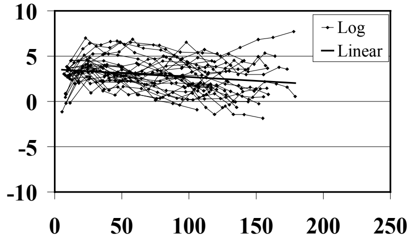


Figure 4.4. ***b***. ***Stand 14***. *26 individual logs.*

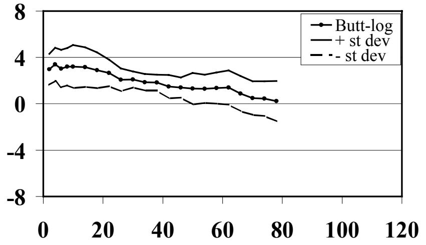


Figure 4.4. ***a***. ***Stand 21***. *6 butt- logs.*

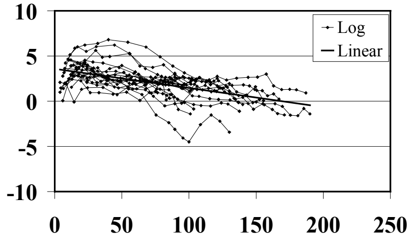


Figure 4.4. ***b***. ***Stand 21***. *19 individual logs.*

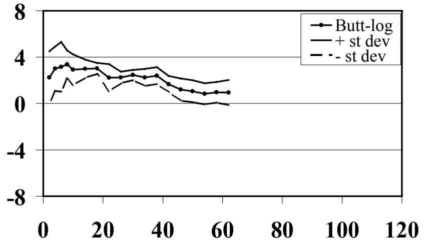


Figure 4.4. ***a***. ***Stand 22***. *6 butt- logs.*

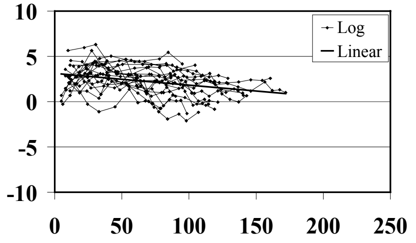


Figure 4.4. ***b***. ***Stand 22***. *18 individual logs*

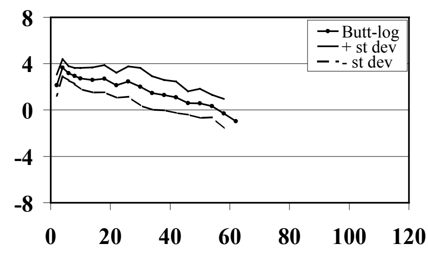


Figure 4.4. ***a***. ***Stand 23***. *6 butt- logs.*

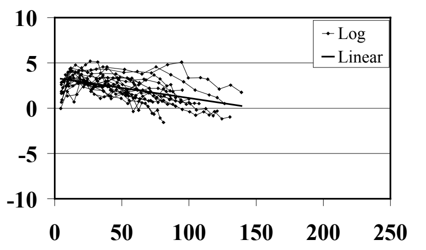


Figure 4.4. ***b***. ***Stand 23***. *18 individual logs.*

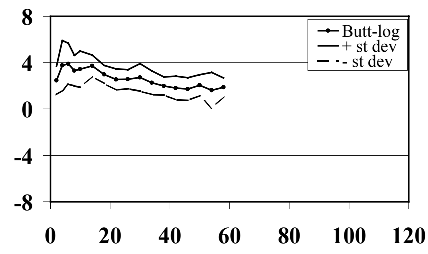


Figure 4.4. ***a***. ***Stand 24***. *6 butt- logs.*

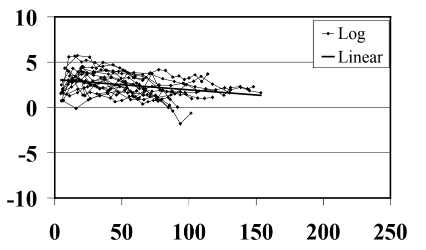


Figure 4.4. ***b***. ***Stand 24***. *17 individual logs.*

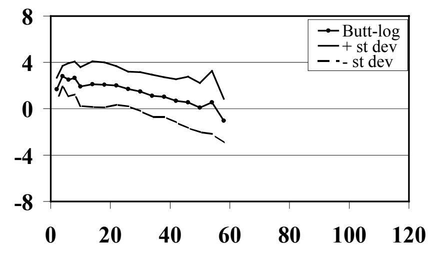


Figure 4.4. ***a***. ***Stand 25***. *6 butt- logs.*

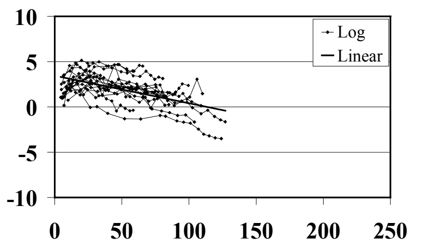


Figure 4.4. ***b***. ***Stand 25***. *16 individual logs.*

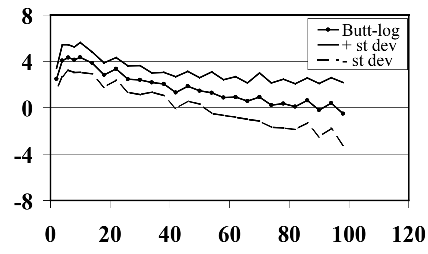


Figure 4.4. ***a***. ***Stand 26***. *6 butt- logs.*

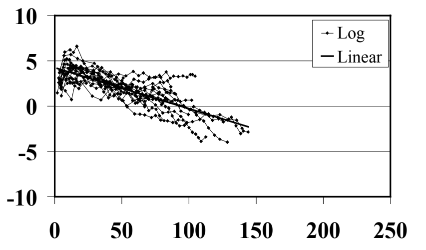


Figure 4.4. ***b***. ***Stand 26***. *17 individual logs.*

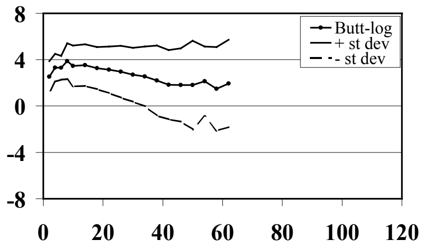


Figure 4.4. ***a***. ***Stand** 27. 6 butt- logs.*

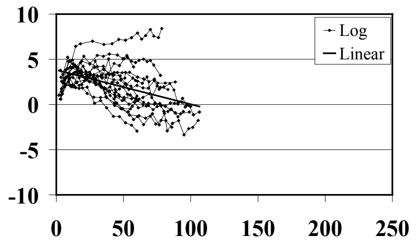


Figure 4.4. ***b***. ***Stand** 27. 16 individual logs.*

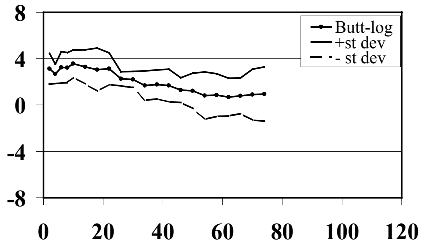


Figure 4.4. ***a***. ***Stand 28***. *6 butt- logs.*

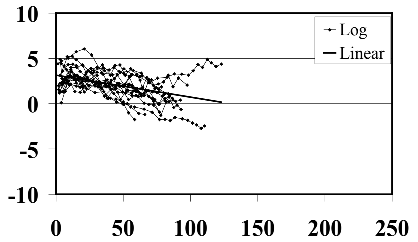


Figure 4.4. ***b***. ***Stand 28***. *16 individual logs.*

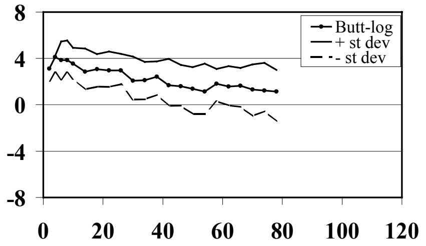


Figure 4.4. ***a***. ***Stand 51***. *6 butt- logs.*

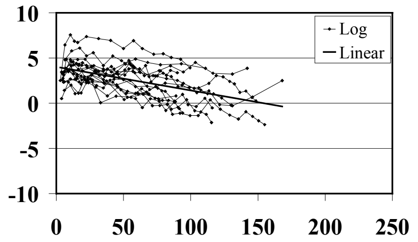


Figure 4.4. ***b***. ***Stand 51***. *15 individual logs.*

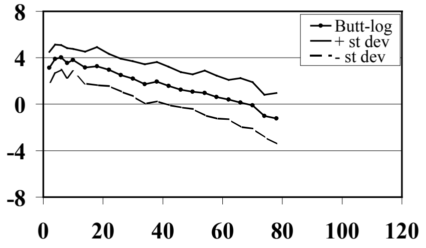


Figure 4.4. ***a***. ***Stand 52***. *6 butt- logs.*

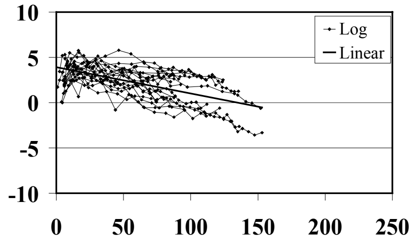


Figure 4.4. ***b***. ***Stand 52***. *18 individual logs.*

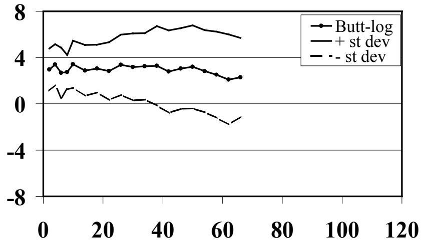


Figure 4.4. ***a***. ***Stand 53***. *6 butt- logs.*

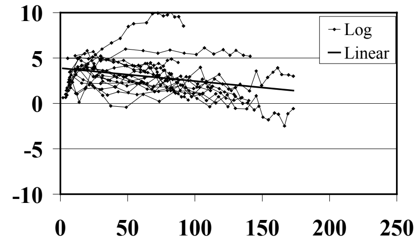


Figure 4.4. ***b***. ***Stand 53*** *16 individual logs.*

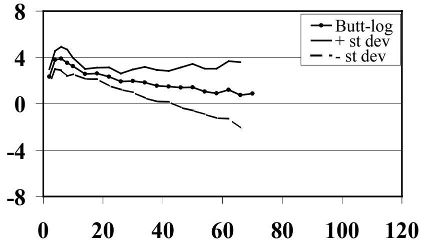


Figure 4.4. ***a. Stand 54.*** *6 butt- logs.*

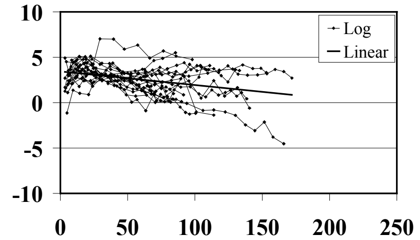


Figure 4.4. ***b***. ***Stand 54***. *18 individual logs.*

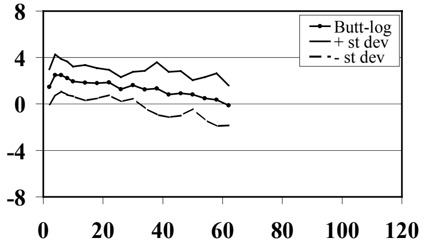


Figure 4.4. ***a***. ***Stand 55***. *5 butt- logs.*

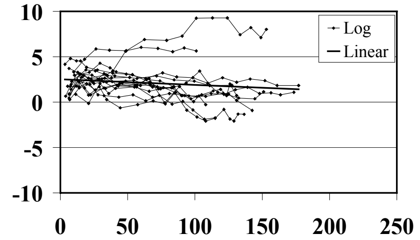


Figure 4.4. ***b***. ***Stand 55***. *15 individual logs.*

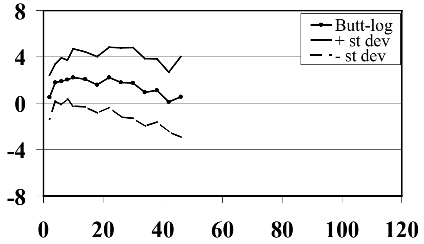


Figure 4.4. ***a***. ***Stand 56***. *6 butt- logs.*

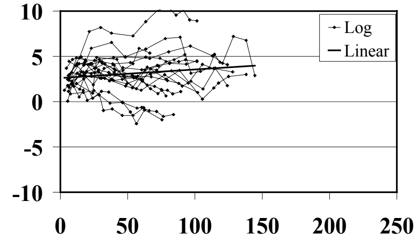


Figure 4.4. ***b***. ***Stand 56***. *18 individual logs.*

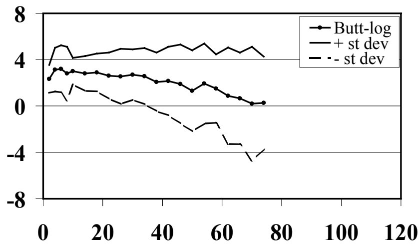


Figure 4.4. ***a***. ***Stand*** *57. 5 butt- logs.*

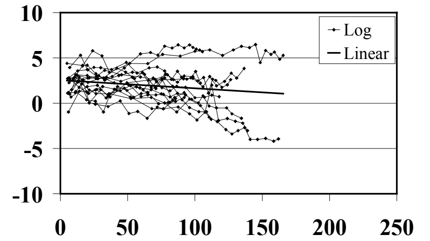


Figure 4.4. ***b***. ***Stand*** ***57***. *15 individual logs.*

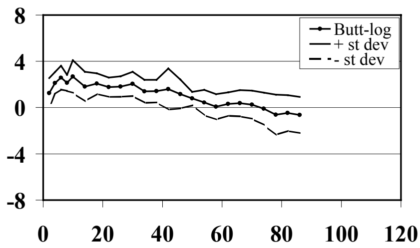


Figure 4.4. ***a***. ***Stand 58***. *6 butt- logs.*

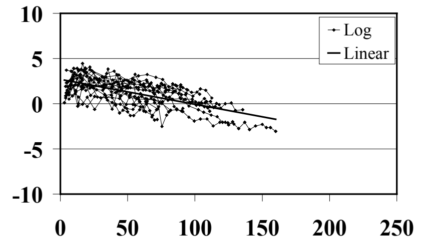


Figure 4.4. ***b***. ***Stand 58***. *16 individual logs.*

4.5 Regression analysis and linear models of stands

A linear model can describe the relationship between grain angle versus ring number and grain angle versus distance from pith for all observations. For the model with relation between grain angle and ring number from pith we will get:

$$GA_i = \alpha + \beta * RN_i + \varepsilon_i \qquad i = 1,2,......,6277 \qquad (1)$$

where ε denotes the random error with expectation $E(\varepsilon_i) = 0$ and variance $V(\varepsilon_i) = \sigma^2$ for all i.

However, considering each stand a covariance analysis model was applied:

$$GA_{ij} = \alpha + \sum_{j=1}^{21} D_j \alpha_j + \beta * RN_{ij} + \sum_{j=1}^{21} \beta_j D_j RN_{ij} + \varepsilon_{ij} \qquad (2)$$

i = *varies from 178 (stand no 56) to 618 (stand no 13a)*

$j = 1,.....,21$

D_j = *1 for stand j, 0 otherwise*

and ε_{ij} denotes a random variable with expection $E(\varepsilon_{ij}) = 0$ and variance $V(\varepsilon_i) = \sigma^2$ for all *i* and *j*.

The corresponding statistical model for relation between grain angle and distance, Dist, replaces ring number, RN.

The coefficients for the line calculated for all logs from all stands are presented in Table 4.4 and 4.5, beginning with the measurements of grain angle in the 6th annual ring. The intercept of the regression line, the α–value, is the GA-value for the regression line, where the line cuts the GA-axis. The β-value is the inclination of the regression line. The regression line clearly describe the character of spiral grain in the stands, independent of the age of the stands (number of annual rings) or the mean diameter of the stand (distance to pith).

4.6 Intercept and inclination for the relation between grain angle and ring number

In this section, a comparison will be made between the regression lines for the stands and the material as a whole, for the relation between GA and RN, see Table 4.4. For regression between GA and RN, the intercept is written as (α_{RN}) and the inclination is written as (β_{RN}).

Table 4.4 *Data for the coefficients of the fitted linear models grain angle (GA) versus ring number (RN) (GA= α.+β*RN) and comparison of regression line between mean values for all stands (All) and stand no j. Stand number (stand), number of observations (n), intercept (α_{RN}), inclination (β_{RN}, °/RN), standard error of model, significance of model (p), *** = p < 0.001, ** = p < 0.01, * = p < 0.05,*
- = no significance.

stand	n	Linear relation GA= $\alpha_{RN} + \beta_{RN}$ * RN				Comparison of regression line between All and stand no *j*.	
		α_{RN}	β_{RN} (°/RN)	st.error of model	p	α_{RN} p	β_{RN} p
All	6277	3.40	-0.0477	1.93	***		
11	507	3.08	-0.0486	2.35	***	-	-
12	589	2.41	-0.0436	2.44	***	***	-
13a	618	2.71	-0.0374	2.18	***	***	***
13b	354	2.79	-0.0547	1.44	***	**	-
14	281	3.60	-0.0338	1.82	***	-	-
21	296	3.28	-0.0446	1.46	***	-	-
22	220	3.42	-0.0484	1.37	***	-	-
23	215	3.75	-0.0652	1.00	***	-	*
24	204	3.34	-0.0362	1.11	***	-	-
25	194	3.42	-0.0646	1.49	***	-	-
26	345	4.20	-0.0553	1.26	***	***	*
27	275	3.92	-0.0497	2.04	***	*	-
28	256	3.12	-0.0330	1.44	***	-	**
51	229	3.89	-0.0453	1.73	***	*	-
52	272	4.03	-0.0619	1.41	***	**	*
53	256	3.65	-0.0220	2.15	***	-	***
54	270	3.84	-0.0431	1.51	***	-	-
55	172	3.10	-0.0394	2.10	***	-	-
56	178	3.38	-0.0094	2.42	-	-	***
57	226	2.56	-0.0219	2.29	**	***	***
58	320	2.76	-0.0404	1.11	***	**	-

The estimated model for the total number of observations from ring number 6 for relationship between GA and RN for the whole material is

GA=3.40 –0.0477*RN (1)

with standard error of estimate $s_e = 1.93°$ and R-squared $R^2 = 27.2$ %.

The equation is significant at one per cent significance level, see Table 4.4. The equations are significant for all individual stands except for stand 56, seeTable 4.4.

For the material as a whole, after culmination the grain angle is reduced by 0.0477° per annual ring, (which is equivalent to a reduction of ca. 1/20° per annual ring), see Eq. (1). This implies that a log with somewhat in excess of 100 annual rings is normally right hand grained under bark, with a grain angle of between -1° and -2°.

4.6.1 Differences between intercept (α_{RN}) and inclination (β_{RN})

The mean value for the whole material gives an intercept of 3.40°, see Table 4.4. Stand 12 has the lowest value (2.41°), while stand 26 has the highest (4.20°). For 9 of the 21 stands the intercept differs significantly from 3.40°, see Table 4.4. Five stands (12, 13a, 13b, 57, 58) have significantly lower value than 3.40°, whilst four stands (26, 27, 51, 52) have significantly higher intercept. The reason for the difference in intercept between the stands cannot be found in the measured forestry data for the stands, or in the partly known silvicultural background.

Since the observations in these calculations begin with the 6th annual ring, the intercept is affected by the inclination of the line (β-value). This claim can be supported by the fact that those stands (12, 13a, 13b, 57 and 58) that have a significantly lower value of intercept than 3.40° have, in four cases out of five, a higher value of inclination than the mean value for all logs (-0.0477°/RN), see Table 4.4. The opposite is also true: The four stands (26, 27, 51, 52) that have a significantly higher value of intercept than 3.40° have also a greater inclination for the line. These four stands have, in three cases out of four, a lower value of inclination than the mean value -0.0477°/RN, seeTable 4.4. This means that the point where the line cuts the y-axis (α–value) is mainly dependent on the inclination of the regression line (β-value).

4.6.2 Differences in inclination (β_{RN}) and its connection to silvicultural treatment

The inclination of the regression line, expressed by help of a β-value (β_{RN}) and its deviation from a mean value (-0.0477°/RN) for all stands, is of interest to enable separation of the stands, regarding the characteristics of spiral grain. The change in angle of spiral grain after culmination, in the 4th to 8th annual ring counted from pith, is often constant. In all stands, the inclination is negative, see Table 4.4. In eight stands (13a, 23, 26, 28, 52, 53, 56 and 57) the inclination differs significantly from the mean value, see Table 4.4.

Stands with small change of inclination

Four stands (13a, 53, 56, 57), have significantly higher value for inclination than -0.0477°/RN. Since there is a lack of data regarding silvicultural treatment for stands 51 to 58, it is not possible to draw too serious conclusions for these stands, see Table 4.2. Stand 13a and stand 56 are taken up here for special analysis. Stand 13a will be compared to stand 13b, and stand 56 will be compared to stand 14.

Stand 13a and 13b

Stand 13a has a high value for inclination and is interesting to compare with stand 13b, since they come from the same test area, see Table 2.1. Stands 13a and 13b show that trees from the same area, but with different sizes and growth patterns, differ significantly (p=0.0003) in terms of inclination. However the inclination for 13a is -0.0374°/RN and is significantly greater than -0.0477°/RN while inclination for 13b is -0.0547°/RN and is less than the mean value**,** although not significantly less, seeTable 4.4. The mean diameters of the sample trees in stands 13a and 13b are 412 mm and 237 mm respectively. 13a has a 74% higher DBH and is 31% taller that 13b. The trees in stand 13a belong to the dominant tree class[14], while the trees in 13b belong to the co-dominant and sub-dominant tree classes. This gives an indication that trees from different tree classes within in the same stand can have different spiral grain angle development, regarding the relationship between GA and RN.

Stand 14 and 56

Stand 56 has the highest value (least negative) for inclination (-0.0094°/RN), see Table 4.4. Note that the regression line for stand 56 is not significant. Stand 14 has also a relatively high value for inclination (-0338°/RN). In stands 14 and 56, the majority of logs are highly left hand grained, seeFigure 4.4.b.

Both stands have a similar history of silvicultural treatment. They have both been thinned extensively at a young age. It is probable that dominant trees with strong growth were not removed when the stands were thinned which gave large mean annual ring width (3.5 mm and 3.4 mm, respectively) see Table 4.1 and Table 4.2. Stands 14 and 56 were only 60 and 50 years old, respectively, when felled, and the sample trees' DBH

[14] Tree class: Dominant trees = at least 5/6 of the height, co dominant trees = between 4 and 5/6 of the height, intermediate trees = between 3 and 4/6 of the height, suppressed trees = less than 3/6 of the highest trees in stand.

was 380 mm and 286 mm respectively, which can be considered to be a high DBH value for such a low age.

It may be of interest to know that stand 14 grew 25 km from the west coast of Southern Sweden, at an altitude of 170 m above sea level. Stand 56 grew 30 km from the coast, at an altitude of 45 m above sea level, in south western Finland. The locality for stand 14 was exposed to strong westerly winds from the sea. Even stand 56 was exposed to westerly winds from the Baltic Sea. The present material is not sufficient to obtain a certain answer if spiral grain is affected of hard and prevailing winds. The question of wind influence can be an interesting part in a future project about which trees in a stand and which stands have more or less pronounced development of spiral grain.

Stands with high inclination, and comparison of stands with different thinning programmes

The other stands that deviate significantly from the mean value 0.0477°/RN are (23, 26, 28 and 52). These stands have a lower inclination than the mean value, see Table 4.4. Amongst these four stands, 23, 26 and 28 are worth studying more closely.

Stand 23, 24 and 25

Stand 23 is one of a three sample plots (23, 24, 25) which have been planted with different spacing and which have subject to thinning using different progammes, see Table 4.1 and Table 4.2. If the grain angle development for all logs within the stands (23, 24, 25) is studied, it can be seen that stand 24 has a tendency towards all logs being left hand grained, see Figure 4.4.b. The consequences is a high value for inclination. The inclination for the regression line for stand 24 is significantly higher and differs from stands 23 and 25 ($p = 0.0002$). The inclinations for stands 23 and 25 are almost identical, see Table 4.4.

The explanation for the difference in stand 24 compared to 23 and 25, regarding spiral grain, is probably the following stands history and selection of sample trees. Stand 23 was established with 4440 seedlings/ha and has been low thinned[15] twice. Stand 24 was established with 2500 seedlings/ha and has also been low thinned twice, while stand 25 was planted with 1110 seedlings/ha and has been thinned once using so called free thinning[16], see Table 4.2. Despite the differing spacing when planting and thereby different numbers of seedlings/ha, the

[15] Low thinning: Smaller trees are removed.
[16] Free thinning: Trees with low quality are removed.

mean annual ring width is the same for all three stands (1.7 to 1.8 mm), see Table 4.1.

DBH for the sample trees in stand 23 is 27% higher than the average of the stand, see Table 4.1, while the sample trees in stand 23 and stand 25 in general have the same DBH as the average of the stand's, see Table 4.1.

In general it can be said that low thinning in stands 23 and 24, and free thinning in stand 25 results in a reduction of the difference in DBH for the remainder of the stand after thinning. Free thinning in stand 25 reduces the proportion of large dominant trees, while the same types of trees have been left intact in stands 23 and 24, in the process of low thinning. The number of stems/ha at time of clear cut was 950 stems/ha in stand 23, 550 stems/ha in stand 24, and lastly 580 stems/ha in stand 25, see Table 4.2. The volume in the three stands was to a great degree equal, 280, 300 and 290 m^3sk/ha respectively, see Table 2.1.

Low thinning in stand 23, where a large number of stems were left, led to a situation where there was hard competition between the dominant trees. The strong low thinning in stand 24 has concentrated growth to a smaller number of dominant trees. The free thinning programme in stand 25 has reduced the number of stems to 580 stems/ha, which is largely the same as stand 24. This favouring of strongly dominant trees in stand 24 may be an explanation of the fact that the selected trees in this stand show lower inclination in grain angle (a higher value for inclination) than stands 23 and 25.

The treatment of stand 24 can be compared to the treatment which leads to high values for inclination in stands 14 and 56, (see section "Stands with small change of inclination"), while the treatment of stands 23 and 25 results in the fact that stems are left that have a larger change in grain angle with increasing age. These two stands can be compared to the trees represented by stand 13b. The three stands 23, 24 and 25 suggest that the establishment of stands and thinning programmes affect the development of spiral grain, regarding the value of inclination.

Stand 26, 27 and 28

Stands 26, 27 and 28 also form a group of stands that have been thinned in different ways and which stem from the same test locality. The stands have grown on a low productive soil with a site index of H100 = 16m. The three stands, or test areas, were established when the stands were 77 years old. The density of the stems was then very high, around 8000 stems/ha, see Table 4.2. Stand 26 has been low thinned once, down to ca. 500 stems/ha. Stand 27 has been low thinned seven times, and had 560 stems/ha at the time of selecting trees, while stand 28 has been crown thinned[17] six times, and contained 1120 stems/ha, see Table 4.2. When the stands were selected and felled, the stand age was 152 years. The stands had largely the same annual ring width (0.8 to 1.0 mm). The DBH for the sample trees in stands 26 and 28 was respectively 23% and 27% greater then the average of the stand, while stand 27 had 5% coarser sample trees than the average of the stand, see Table 4.1.

The sample trees in stand 26 have significantly lower values for inclination than 0.0477°/RN while the sample trees in stand 28 exhibit significantly higher values for inclination than the mean value, see Table 4.4. There are no significant differences within stands 26 or 27, for either intercept or inclination. Stand 28 deviates thereby significantly, compared to the other two stands.

The extremely intense low thinning (from 7400 down to 500 stems/ha) that stand 26 was subjected to, when the stand was 77 years old, does not seem to have affected the development of spiral grain. During the 7 low thinnings of stand 27, it is reasonable to assume that the same types of dominant trees have been saved, which ought to result in similar values for intercept and inclination for stands 26 and 27, which also is the case, see Table 4.4. During the crown thinning in stand 28, the dominant trees have to a certain degree been removed. When the choice of sample trees was made for this project, trees were chosen within stand 28 that differ from the original stand's dominant tree class, and to an even greater degree from the sample trees chosen in stands 26 and 27, where dominant trees were saved during thinning. Crown thinning in stand 28 has resulted in the fact that those trees that have been saved have been subjected to relatively large thinning operations, when the larger trees were removed. The sample trees in stand 28 consist mainly of trees that previously grew in the co-dominant tree class, in a stand with abundant stems.

The different thinning programmes, and especially crown thinning, appear to have affected the development of grain angle in the stands. This can explain why the value for inclination for stand 28 differs significantly from stands 26 and 27, see Table 4.4. The treatment of stand 28 can be compared to the treatment that leads to high values for inclination in stands 14, 24 and 56. Subjecting stands to extreme thinning leads even in this case to a higher value for inclination.

[17] Crown thinning: Removal of large trees of low quality.

4.7 Intercept and inclination for the relation between grain angle and distance from pith

This section presents a comparison between the stand's regression lines and the material as a whole, for the connection between spiral grain angle and distance from pith, see Table 4.5. For the regression line between GA and Dist, the intercept is written (α_{Dist}) and the inclination is written (β_{Dist}).

The model for the relationship between spiral grain angle (GA) versus distance from pith (Dist) for observations measured more than 20 mm from pith is

GA=3.53 –0.025*Dist (2)

with standard error of estimate $s_e = 2.00°$ and R-squared $R^2 = 21.6$ %.
The linear equation for all stands Eq. (2) shows that spiral grain angle, as a mean value decreases with 0.0250°/mm, calculated from the 6^{th} annual ring, which has a mean distance from pith of 20 mm. If distance from pith is instead expressed in dm, the change in grain angle becomes -2.5°/dm, which is easier to memorise in practical applications.

The following example shows how large the grain angle under bark is calculated to be when Eq. (2) is applied: For a log with a diameter of 440 mm under bark, it is assumed that grain angle in the normal case culminates 20 mm from the pith, when the grain angle is 3°. This gives the following result: 3°- (440 mm/2 – 20mm)*0.0250° = -2°.

Table 4.5. *Data for the coefficients of the fitted linear models grain angle (GA) versus distance from pith (Dist) (GA= α.+β*Dist) and comparison of regression line between mean values for all stands (All) and stand no j. Stand number (stand), number of observations (n), intercept (α_{Dist}), inclination (β_{Dist}, °/mm), standard error of model, significance of model (p), ***=p<0.001, **=p<0.01, *=p<0.05, - =no significance.*

stand	n	Linear relation GA= $\alpha_{Dist} + \beta_{Dist}$ * Dist				Comparison of regression line between All and stand no *j*.	
		α_{Dist}	β_{Dist} (°/mm)	st.error of model	p	α_{Dist} p	β_{Dist} p
All	6277	3.53	-0.0250	2.00	***		
11	507	3.35	-0.0262	2.37	***	-	-
12	589	3.44	-0.0318	2.24	***	-	***
13a	618	3.14	-0.0233	2.18	***	*	-
13b	354	3.37	-0.0415	1.45	***	-	***
14	281	3.94	-0.0122	1.81	***	-	***
21	296	3.74	-0.0226	1.43	***	-	-
22	220	3.35	-0.0155	1.47	***	-	*
23	215	3.64	-0.0262	1.16	***	-	-
24	204	3.30	-0.0141	1.15	***	-	*
25	194	4.11	-0.0394	1.39	***	-	**
26	345	4.60	-0.0497	1.20	***	***	***
27	275	4.33	-0.0460	2.08	***	*	***
28	256	3.35	-0.0273	1.44	***	-	-
51	229	4.22	-0.0284	1.68	***	**	-
52	272	4.23	-0.0328	1.50	***	**	*
53	256	4.33	-0.0187	2.06	***	**	*
54	270	3.67	-0.0175	1.59	***	-	*
55	172	2.68	-0.0078	2.17	-	**	***
56	178	2.56	0.0100	2.41	-	**	***
57	226	2.61	-0.0097	2.30	*	**	***
58	320	2.88	-0.0299	1.17	***	**	-

Regarding the relationship GA vs. Dist, equations for all stands are significant except for stands 55 and 56, see Table 4.5. One of the reasons for lack of significance is that these stands have several logs with large differences for spiral grain pattern, see Figure 4.4. b. It could also be the case that the stands themselves are uneven and contain a large variation between trees, concerning spiral grain. Stand 56 is described in Section 4.2, and distinguishes itself regarding silvicultural background and growth.

4.7.1 Differences between intercept (α_{Dist})

Ten stands (13a, 26, 27, 51, 52, 53, 55, 56, 57 and 58) differ significantly from the mean value for intercept (3.53°), see Table 4.5. Five of these ten stands (13a, 55, 56, 57 and 58) have significantly lower intercept than the mean value whilst five stands (26, 27,51,52 and 53) have a significantly higher intercept. In a similar way to the correlation between GA and RN, see Subsection 4.6.1, it is not possible to see any correlation between the intercept's variation between the stands, and the silvicultural data that are available. There is, on the other hand, a correlation between low values for intercept and high values for inclination, for four of the five stands. The opposite is also true for four of the five stands that have high values for intercept and low values for inclination. The reason for this is primarily the fact that when the equation of the line is calculated, it does not begin until the 6th annual ring, which has a mean distance of 20 mm from pith.

4.7.2 Differences between inclination (β_{Dist})

Changes in grain angle for inclination are, for 14 stands (12, 13b, 14, 22, 24, 25, 26, 27, 52, 53, 54, 55, 56 and 57), significantly different from the mean value for the whole material, which is –0.0250°/mm, see Table 4.5. Of these 14 stands, six stands (12, 13b, 25, 26, 27 and 52) have a lower inclination than the mean value whilst the remaining eight stands (14, 22, 24, 53, 54, 55, 56 and 57) have a higher inclination than –0.0250°/mm. Of these stands, no significance for linear regression is found in stands 55 and 56, see Table 4.5.

Stands with small change of inclination

Of all stands, it is stand 56 that exhibits the highest value for inclination (0.0100°/mm), see Table 4.5. Observe that this is the only stand that has a positive value for inclination, however this is not significant as a model, see Table 4.5. The remaining stands with high values for inclination are 14, 22, 24, 54, and 57. These stands have a value for inclination that varies between -0.010°/mm and -0.0175°/mm. The primary explanation for a small change in grain angle with increasing distance from pith (high value for β_{Dist}) is either; high values for β_{RN} (small changes in grain angle per annual ring) and/or large mean annual ring width, see Table 4.1, 4.4 and 4.5.

For stands 14 and 22 it is above all the large mean annual ring width, 3.5 mm and 2.4 mm respectively, that explains a high value for inclination. For stands 24 and 54, it is a connection between a somewhat higher value for inclination in regard to GA vs. RN and a normal annual ring width (1.8 and 1.9 mm respectively) that suffices to give a significant deviation from the mean value (0.0250°/mm). The fact that stand 57 shows a small change in grain angle with increasing distance from pith (-0.0097°/mm) depends largely on a high value for inclination in regard to ring number, seeTable 4.4. Regarding the connection between high values for β_{RN} and β_{Dist} the correspondence is clear. Amongst the eight stands with the highest values for inclination in regard to ring number (β_{RN}) (13a, 14, 24, 28, 53, 55, 56 and 57) it is seen that seven of these stands (13a, 14, 24, 53, 55, 56 and 57) also have high values for inclination in regard to distance from pith (β_{Dist}), see Table 4.4 and Table 4.5.

Stands with large change of inclination

The four stands that have the lowest values for inclination are 13b, 25, 26 and 27, see Table 4.5. The reason why stands 13b, 26 and 27 exhibit low values for inclination is that the annual ring width is small, 0.8 to 1.0 mm. Stands with normal development regarding changes in grain angle with increasing age have a large change in grain angle in relation to distance from pith if the ring width is small. This shows that the mean annual ring width is of consequence for changes in grain angle regarding the relation between spiral grain angle and distance from pith.
This indicates also that if the annual ring width is under 1.0 mm, this can lead to wood with large changes in grain angle regarding distance from pith. This can result in timber that has a tendency to twist.

The reason stand 25 has a low value for inclination is largely connected to the history of the stand, which differs considerably from the other stands. Many of the dominant trees, which often have a higher value of inclination regarding ring number and also distance from pith, were removed when stand 25 was subjected to free thinning, see equivalent results for stands 13a and 13b in Subsection 4.6.2.
Amongst the six stands (13b, 23, 25, 26, 27 and 52) that have the lowest values for inclination regarding ring number from pith (GA vs. RN) there are five of the stands (13b, 25, 26, 27 and 52) that also have low values for inclination for the relation between grain angle and distance from pith, see Table 4.4 and Table 4.5.

4.8 Summary

The results in this chapter show that there are large differences in the development of spiral grain between different stands. The fact that a stand has a large or small inclination in grain angle in relation to distance from pith, a high or a low value for inclination, can be explained partly by the annual ring width, but also by the characteristics of the stand regarding changes in grain angle between annual rings. Differences concerning spiral grain can arise from silvicultural operations such as thinning programmes, see Sections 4.6.

In stands 13a and 13b there is an indication that trees from different tree classes (different heights) in the same stand can have different inclination for the spiral grain angle, see Table 4.4.

As a mean value, grain angle decreases after culmination (20 mm from pith) with approximately 0.05° per annual ring. The equivalent value for reductions in grain angle with increased distance from pith is 0.025° per mm (2.5°/dm).

Certain stands (13b, 26, 52 and 58) have no logs that deviate from the pattern, while other stands (11, 12, 27, 53 and 56) have large variations for development of spiral grain between logs taken within the same stand, see Figure 4.4.b. In an otherwise uniform stand such as 13a, with high quality timber, and small variations in spiral grain between the majority of logs, there can be a couple of logs that deviate from the remainder of the stand, see Figure 4.4.b. It is spiral grain in individual stands, such as stands 14 and 56, and individual trees, as in stand 13a, that lead to the greatest proportion of the twisted timber that causes problems for the user.

It can be seen that thinning methods and thinning strength affect the development of spiral grain. Examples of stands that have been subjected to heavy thinning are 14, 24, 28 and 56. Heavy thinning results in the fact that grain angle does not decrease at the same pace, as annual ring numbers or distance from pith increase.

5. Spiral grain pattern and change with tree size

5.1 Introduction

In Chapter 4, the results from stand 13a and 13b indicate that trees with different sizes from the same stand (stand 13) have different grain angle inclinations. In this chapter, the influence of tree size is in focus, to determine if the pattern of spiral grain is affected by the size of the tree in a stand.
The relationship between GA versus RN and GA versus Dist can be described by a linear model

$$GA_i = \alpha + \beta * RN_i + \varepsilon_i \qquad i = 1,2,......,4988$$

where ε denotes the random error with expectation $\mathrm{E}(\varepsilon_i) = 0$ for all i and $V(\varepsilon_i) = \sigma^2$ for all i.

When processing the data in this chapter, only values of measurement from annual ring number 4, from pith to cambium in the butt-logs, are taken into account in the statistical calculations. The material was divided into two groups, corresponding to diameter in breast height (DBH). If the DBH exceeds the average DBH for the sampled trees in the stand, the group is named the highest of dominant trees (HD). The complementary part, that has a smaller diameter than the mean value of DBH, is named dominant trees (D).

The term dominant trees correspond to the tree classes. Tree class is a classification of trees of the same age in a stand, in regard to the relative height of trees in the stand. Dominant trees (D) correspond to the group of trees in the stand that are at least 5/6 of the height of the highest trees (100 highest trees/ha) in the stand. Evidently, in this report, the HD trees are a sub sample of extremely large trees taken from the class of dominant trees.

5.2 Data for sampled trees

Table 5.1 shows the number of sampled trees, average DBH, height (H) and standard deviation for DBH and tree height for HD and D trees in each group of stands or stand.

Table 5.1. *Data for sampled trees from different tree classes in different groups of selected stands or in stand. Tree class: Highest of dominant trees (HD), dominant trees (D), number of sampled trees (n), diameter at breast height (DBH), height, mean values and standard deviation in brackets ( ).*

Stand and tree class (HD) (D)	n	DBH (mm) Stand. dev.	Height (m) Stand. dev.
11-58 HD	76	380 (78)	27.4 (4.3)
11-58 D	77	280 (71)	24.4 (4.9)
11-14 HD	28	450 (49)	31.0 (2.7)
11-14 D	27	350 (52)	28.7 (2.9)
11 HD	7	438 (43)	30.1 (1.6)
11 D	6	337 (45)	27.8 (1.7)
12 HD	7	466 (47)	30.7 (2.2)
12 D	7	355 (73)	27.8 (2.7)
13a HD	7	480 (56)	34.6 (1.2)
13a D	7	362 (40)	32.0 (2.5)
14 HD	7	412 (20)	28.5 (0.8)
14 D	7	349 (58)	27.1 (1.9)

5.3 Relation between grain angle and ring number

When all butt-logs from stands 11 to 58 are taken into consideration for statistical comparison of regression lines between HD and D trees, there is no statistical difference between the tree classes for the relation between GA and RN. For the intercept there were no significant differences between HD and D trees. Likewise, the inclination of regression-line is almost the same for the HD and D trees, -0.050 and -0.048, respectively. R-square for the regression line is 0.38 and 0.35 respectively, for HD and D trees, with standard deviation of residuals of 1.7° for both lines.

One problem with dividing stands 21 to 58 into two groups is that there are just 5 to 6 trees in each stand, which makes the two groups of HD and D trees from these stands quite similar. The mean DBH for HD trees for stands 21 to 58 is 339 mm, and for D trees the mean DBH is 245 mm. If these DBH values are compared to the mean values of DBH for stands 11 to 14, the D trees in stands 11 to 14 have a higher DBH than the HD trees in stands 21 to 58. Stands 11, 12, 13a and 14 have the largest mean DBH values of all stands, see Table 4.1.

Figure 5.1 shows a combined value for the regression lines for HD and D trees in stands 11 to 14 (11, 12, 13a, 14). The HD trees have a grain angle inclination of 0° at ring number 70 from pith (RN 70) and the D trees have 0° at RN 50 from pith. Table 5.2 shows the result of fitting a linear regression model to describe the relationship between GA versus RN and tree classes (HD and D trees).

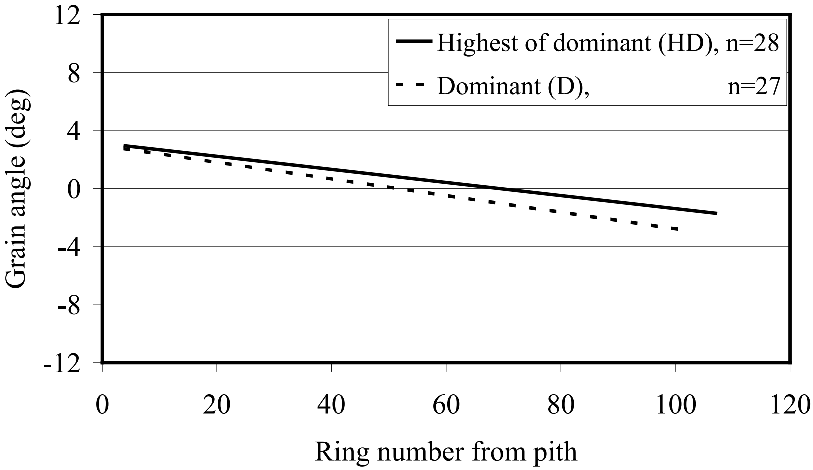


Figure 5.1. *Regression lines for grain angle versus ring number from pith for the highest of dominant trees and dominant tees in stand 11-14.*

Table 5.2. *Comparison of regression lines for the highest of dominant trees (HD) and dominant trees (D) in stand 11-14. Dependent variable is spiral grain angle (GA) and independent is ring number from pith (RN).*

Parameter	Estimate	Standard Error	T Statistic	P-value
intercept (α_{RN}) for (HD)	3.14	0.1403	22.4	0.0000
inclination (β_{RN}) for (HD)	-0.045	0.0026	-17.0	0.0000
difference for α_{RN} (D-HD)	-0.16	0.2041	-0.8	0.4279
difference for β_{RN} (D-HD)	-0.012	0.0039	-3.2	0.0016

This corresponds to two separate lines, one for each tree class, and the model for the relation between GA and RN for HD and D trees in Table 5.2 reduces to:

Highest of dominant trees: **GA = 3.14 – 0.045*RN**

Dominant trees: **GA = 2.98 – 0.057*RN**

For intercept there is no significant difference between the tree classes, see Table 5.2. More of interest is if there is any significant difference in inclination for GA versus RN for the different height classes. There is a significant difference, P-value = 0.0016, between HD and D trees in stands 11 to 14, see Table 5.2. R-square for the regression line is 0.31 and 0.41 respectively, for HD and D trees, with a standard deviation of residuals of 1.9° for both lines.

Table 5.3 shows the coefficients of the fitted linear model (GA= $\alpha_{RN} + \beta_{RN}$ *RN) for the tree class (HD and D) of each stand (11, 12, 13a, and 14). Table 5.3 also shows if there is any significant difference between tree classes in each stand (11 to 14). There is no significant difference between the intercept for HD and D trees in any one of the four stands (11 to 14), see Table 5.3. The coefficient of inclination for D trees is lower in all stands compared to the same coefficient for HD trees in each of the stands (11 to 14), see Table 5.3. Notice that there is no significant difference between HD and D trees in stand 11, for the relation between GA vs. RN.

Table 5.3. *Comparison of regression line between the tree classes, highest of dominant trees (HD) and dominant trees (D) in each stand. Data for mean values of spiral grain angle (GA) versus ring number from pith (RN) and the coefficients of the fitted linear model (GA=* $\alpha_{RN} + \beta_{RN}$ **RN). Stand number and tree class (stand) and (HD) or (D), intercept (*α_{RN}*), inclination (*β_{RN}*), significance of difference between HD and D trees in each stand (significance), ***=p<0.001, **=p<0.01, *=p<0.05, - = no significance.*

Stand/ tree class (HD) (D)	Comparison of regression line between: Highest of dominant trees and smaller dominant trees GA= $\alpha_{RN} + \beta_{RN}$ *RN			
	intercept α_{RN}	significance	inclination β_{RN}	significance
11 HD	2.65		-0.033	
11 D	2.80	-	-0.040	-
12 HD	2.80		-0.046	
12 D	3.41	-	-0.064	*
13a HD	2.68		-0.042	
13a D	2.33	-	-0.060	***
14 HD	3.51		-0.009	
14 D	3.14	-	-0.052	**

Table 5.1 shows that there is not more than 2.9 m difference in height between HD and D trees in stand 11, 12, 13a. In stand 14 there is just 1.4 m in difference of height between the HD and D trees. It is evident that it is difficult to explain the significant difference between inclination (β_{RN}) with the rather small differences of height between the tree classes HD and D, see Table 5.1 and Table 5.3. For a forester, the difference in DBH between HD and D trees in stand 11 to 14 seems of more significance, to explain that there has been a more favourable growth for the HD trees. The HD trees in stand 11, 12 and 13a have approximately 30% larger DBH compared to the D trees, in stand 14 the same relation is 20%. The difference regarding height between HD and D trees in stands 11 to 14 is approximately 8 %.

5.4 Relation between grain angle and distance from pith

Figure 5.2 shows a combined value for the regression lines for HD and D trees in stands 11 to 14 (11, 12, 13a, 14). The HD trees have a grain angle inclination of 0° when the distance from pith (Dist) is 150 mm and the D trees have 0° at Dist 100 mm from pith, see Figure 5.2. Table 5.4 shows the result of fitting a linear regression model to describe the relationship between spiral grain angle, distance from pith and tree classes (HD and D trees).

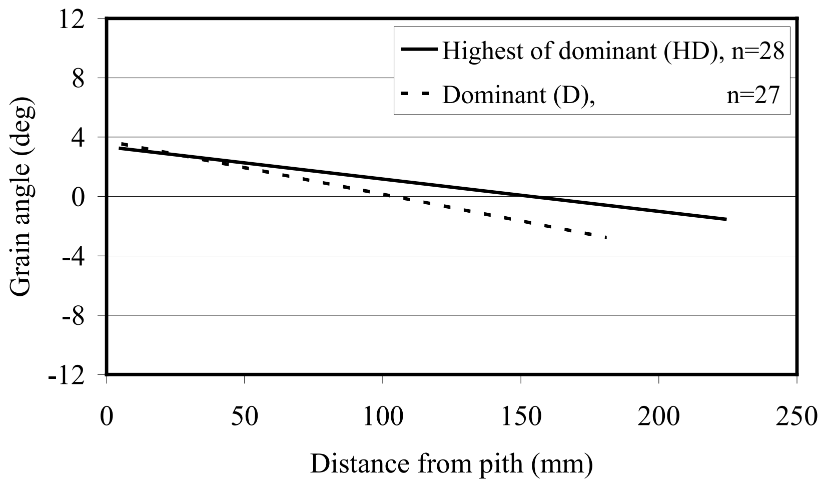


Figure 5.2. *Regression lines for grain angle versus distance from pith for the highest of dominant (HD) and dominant (D) tees in stand 11-14.*

Table 5.4. *Comparison of regression lines for the highest of dominant trees (HD) and dominant trees (D) in stand 11-14. Dependent variable is spiral grain angle and independent is distance from pith.*

Parameter	Estimate	Standard error	T Statistic	P-value
intercept (α_{Dist}) for (HD)	3.36	0.1647	20.4	0.0000
inclination (β_{Dist}) for (HD)	-0.022	0.0014	-15.3	0.0000
difference for α_{Dist} (D-HD)	0.41	0.2516	1.6	0.1009
difference for β_{Dist} (D-HD)	-0.014	0.0024	-6.1	0.0000

This corresponds to two separate lines, one for each tree class, and the model for relation between GA and Dist for HD and D trees in Table 5.4 reduces to:

Highest of dominant trees: **GA = 3.36 – 0.022*Dist**

Dominant trees: **GA = 3.77 – 0.036*Dist**

For intercept (stands 11 to 14) there is no significant difference between the tree classes (HD and D trees), see Table 5.4.
There is a high significance, p-value = 0.0000, for difference in inclination between HD and D trees in stands 11 to 14. R-square for the regression line is 0.26 and 0.40 respectively, for HD and D trees in stands 11 to 14, with a standard deviation of residuals of 2.0° for both lines.

The significant difference in inclination between HD and D trees for the relation GA versus RN in Table 5.1 will become more pronounced when the relation GA versus Dist is taken into consideration. The reason for this is that the mean annual ring width in the D trees is smaller, compared to ring width in HD trees.
The difference of the coefficients for inclination is about 20% for HD and D trees, for the relation between GA versus RN. The corresponding value for the relation between GA versus Dist, for HD and D trees, is about 40%, see Table 5.2 and Table 5.4.

A separate study of the relation between GA versus Dist for comparison between HD and D trees in each stand (11, 12, 13a and 14) shows the same pattern as is shown in Table 5.3. There is a weak or no significant difference between HD and D trees for the intercept in any one of the four stands 11, 12, 13a and 14. The coefficient of inclination for D trees is in all stands lower, compared to the same coefficient for HD trees in each of the stands 11 to 14. Observe that there is no significant difference between HD and D trees in stand 11 for the relation between GA versus Dist.

5.5 Summary

There is a difference in spiral grain angle inclination between different sizes of trees in the tree class of dominant trees in the same stand. In all stands studied in this chapter there is a tendency or a significant difference between the largest of the sampled trees, highest of dominant trees, and the smaller trees in tree class dominant trees in the same stand. The change in spiral grain angle for the smaller trees in the dominant tree class is more obvious than for the largest trees in the dominant tree class. The difference of inclination between tree sizes is more pronounced, when the relation between grain angle and distance from pith is taken into account compared to the relation between grain angle and ring number from pith.

6. Spiral grain pattern in butt-, middle- and top-logs

6.1 Butt-, middle- and top-logs in general

In the following chapter the focus is on the influence of tree height, to determine whether increases in height change the pattern of spiral grain. The influential point, when the spiral grain angle reaches the maximum grain angle, occurs at ring number 4 in butt-logs, se Figure 6.1. The GA maximum at ring number 4 is distinct; if expressed in distance from pith it occurs approximately 15 mm from pith with a grain angle of 3.2° and with standard deviation of 1.3°, se Figure 3.6 and Figure 3.5 b.

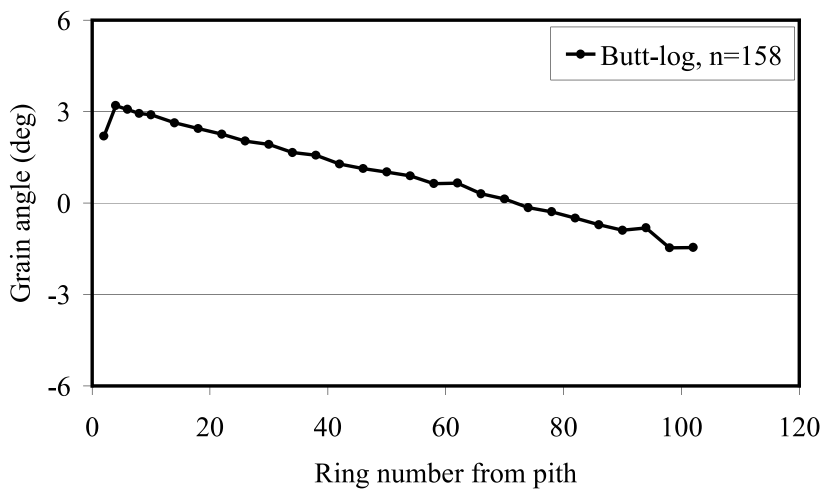


Figure 6.1. *Mean relationship between the average grain angle and ring number from pith for butt-logs. 3362 observations based on 158 butt-logs from 21 stands.*

Discs for measuring grain angle in butt-logs were taken at a sampling height of 4 meters above stump, in middle- 13 meters and in top-logs 22 meters above stump. Figure 6.2 shows the grain angle pattern for middle and top-logs. The formation of spiral grain pattern higher up in the tree

(13 m and 22 m) displayed an even culmination between rings number 4 and number 8 from pith. The average grain angle at this culmination point will be reached at ring number 6, where the grain angle is 3.1°, with standard deviation 1.4°, se Figure 6.2.

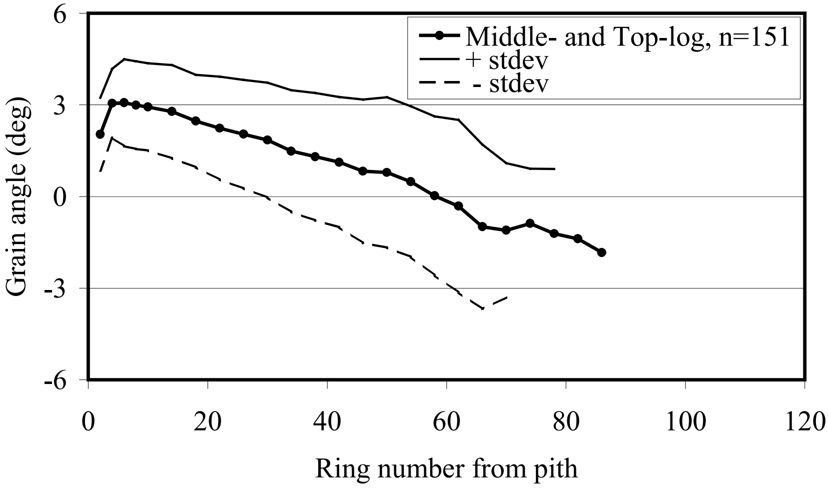


Figure 6.2. *Mean relationship between the average grain angle and ring number from pith to bark and ± standard deviation. 2321 observations based on 151 middle- and top-logs from 21 stands.*

On average, the grain angle is zero at lower cambial age (RN) with increasing height within the tree, see Figure 6.3. For middle- and top logs, the grain angle is zero when the cambial age reaches approximately 60 years, see Figure 6.2. In butt-logs, grain angle is zero when the cambial age rises to approximately 70 years, se Figure 6.1. The pattern of an increasing standard deviation with increasing ring number for the middle- and top-logs in Figure 6.2 is in agreement with all logs shown in Figure 3.5 (a) and (b). The standard deviation is 1.1° at ring number 4 and increases to 2.8° at ring number 60, for middle- and top-logs.

6.2 Influence of height in trees

A linear model can describe the relationship between spiral grain angle versus ring number from pith for different heights in tree (butt-, middle- and top-logs)

$$GA_i = \alpha + \beta * RN_i + \varepsilon_i \qquad i = 1,2,......,1944$$

where ε denotes the random error with expectation $E(\varepsilon_i) = 0$ for all i and $V(\varepsilon_i) = \sigma^2$ for all i.

Regression analysis for the linear model is calculated from logs taken from the same trees. There are only 37 trees that contained logs from the three different heights. In general these trees were the biggest ones in the sampled stands and most of them were taken in stands 11, 12, 13a, 13b and 14.

In Figure 6.3 the spiral grain angle versus ring number from pith is displayed for butt- middle- and top-logs. Butt-logs show the same pattern as we can see in Figure 6.1. The influential culmination point at ring number 4 for the 37 butt-logs is distinct, with an angle of 3.2° and standard deviation of 1.3°. The separated curves for middle- and top-logs in Figure 6.3 show a similar pattern in the juvenile wood as the 151 middle- and top-logs do in the merged diagram in Figure 6.2.

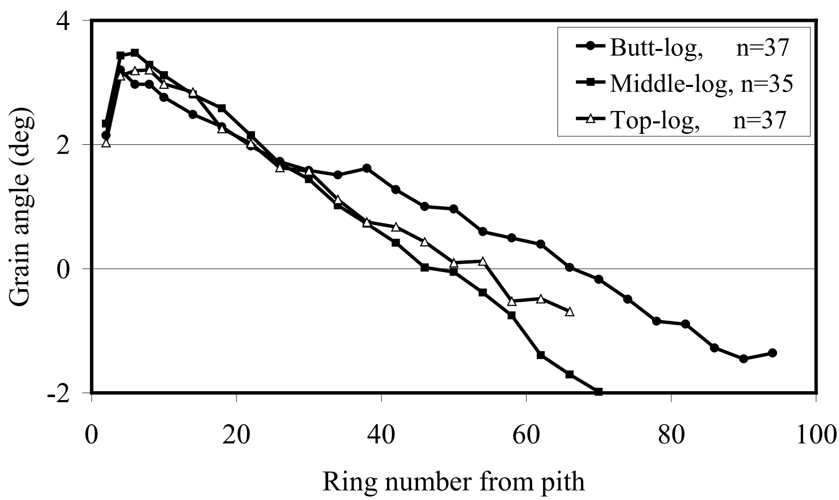
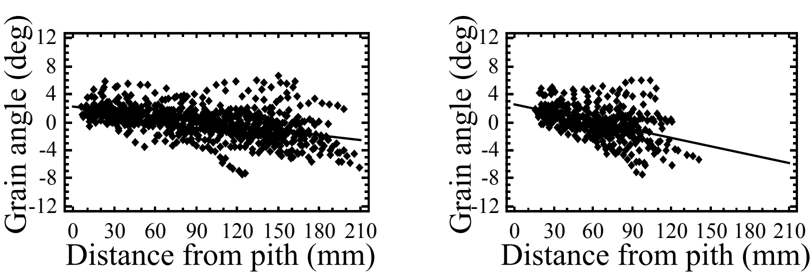


Figure 6.3. *Relationship between the average grain angle and ring number from pith. 1944 observations based on 109 butt- middle- and top-logs from 37 trees.*

The pattern of a flat culmination between ring number 4 and 8 is evident for the top-logs, see Figure 6.3. Grain angle reaches the maximum at ring number 6 for middle logs and at ring number 8 for top-logs, see Figure 6.3. The maximal grain angle for middle- and top-logs is 3.5° and 3.2° respectively, with the standard deviation of 1.4° and 1.2° respectively, at the culmination point.

The grain angle is zero when the cambial age reaches approximately 60 years. In the restricted material of 37 trees, grain angle is zero for butt-logs at annual ring number 66, which is nearly the same as for the complete material, where it is zero at RN 72, see Figure 6.1 and Figure 6.3. For middle- and top logs in the restricted material, the grain angle is zero when the cambial age reaches 50 years, compared to 60 years in the complete material, see Figure 6.2 and Figure 6.3.

Figure 6.4. (a) and (b) shows scatter-plots for GA versus Distance from pith for the butt- and top-logs in Figure 6.3. The figures indicate that the inclination is greater for top-logs compared to butt-logs. It also shows that top-logs seem to have larger standard deviation at the same distance from pith compared to butt-logs.



(a) Butt-logs

(b) Top-logs

Figure 6.4. *Grain angle versus distance from pith.*
(a) For butt-logs from 37 trees.
(b) For top-logs from 37 trees.

6.2.1 Differences of grain angle inclination with height

The results of regression analysis presented gives the coefficients for the linear model:

$y = \alpha + \beta x + \beta' xD + \gamma' D$

(D= dummy variable)

Based on 1860 observations, the resulting model estimation gives the regression line for a specific log and the comparisons of regression lines between butt-, middle- and top-log. The regression lines begin from ring number 6 for all logs. The number of observations for the logs is 784, 593 and 483 for butt-, middle- and top-logs respectively. The comparison of regression lines, where the dependent variable is spiral grain angle (GA), and independents are ring number (RN) or distance from pith (Dist), and level code is type of log, gives 3 regression lines for GA versus RN and GA versus Dist, respectively.

Difference of inclination for the relation GA versus RN with increasing height

Table 6.1 shows the results of fitting a linear regression model to describe the relationship between GA, ring number from pith (RN) and heights in tree expressed as butt-, middle- and top-logs.

Table 6.1. *Comparison of regression lines for butt-, middle- and top-logs. Dependent variable is spiral grain angle (GA) and independent is ring number from pith (RN).*

Parameter	Estimate	Standard Error	T Statistic	P-Value
intercept (α_{RN}) for butt-log	3.26	0.1400	23.3	0.0000
inclination (β_{RN}) for butt-log	-0.050	0.0027	-18.7	0.0000
difference, α_{RN} (middle – butt)	0.47	0.2133	2.2	0.0261
difference, α_{RN} (top – butt)	0.33	0.2269	1.4	0.1493
difference, β_{RN} (middle – butt)	-0.023	0.0047	-4.9	0.0000
difference, β_{RN} (top – butt)	-0.020	0.0061	-3.4	0.0008

This corresponds to three linear relations, one for each log type. For example, when Log = butt-, middle- or top-log, the model reduces to:

Butt-log: GA = 3.26 - 0.050*RN

Middle-log: GA = 3.74 - 0.073*RN

Top-log: GA = 3.59 - 0.070*RN

R-Squared statistic indicates that the model as fitted explains 32% of the variability in GA and the standard error of the estimate shows the standard deviation of the residuals to be 2.0°. For intercept there was a weak or no significance between the log types. More of interest is if there was a significant difference in inclination for GA versus RN with increasing height in tree. The P-value is less than 0.001 for inclination, which shows a strong significant difference between butt- and middle- and top-logs, see Table 6.1. There was no significant difference between middle- and top-logs, neither for intercept nor inclination.

Difference of inclination for the relation GA versus Dist with increasing height

Table 6.2 shows the results of fitting a linear regression model to describe the relationship between GA, distance from pith (Dist) and heights in tree expressed as butt-, middle- and top-logs.

Table 6.2. *Comparison of regression lines for butt-, middle- and top-logs. Dependent variable is spiral grain angle (GA) and independent is distance from pith (Dist).*

Parameter	Estimate	Standard Error	T Statistic	P-Value
intercept (α_{Dist}) for butt-log	3.32	0.1770	18.8	0.0000
inclination (β_{RN}) for butt-log	-0.023	0.0013	-14.5	0.0000
difference, α_{Dist} (middle – butt)	0.67	0.2790	2.4	0.0163
difference, α_{Dist} (top – butt)	0.79	0.2916	2.7	0.0065
difference, β_{Dist} (middle – butt)	-0.011	0.0028	-3.8	0.0001
difference, β_{Dist} (top – butt)	-0.016	0.0036	-4.5	0.0000

This corresponds to three linear relations, one for each log type. For example, when Log = butt-, middle- or top-log the model reduces to:

Butt-log: GA = 3.32 - 0.023*Dist

Middle-log: GA = 3.99 - 0.033*Dist

Top-log: GA = 4.12 - 0.039*Dist

R-Squared statistic indicates that the model as fitted explains 24% of the variations in GA, and the standard error of the estimate shows the standard deviation of the residuals to be 2.2°. For intercept there was a significant difference between the log types. More of interest is if there was a significant difference between inclinations at increasing height, and if there was any similarity to relation between GA-RN and GA-Dist respectively. The P-value is less than 0.001 for differences of inclination of grain angle which shows a strong significant difference between butt-logs and logs from higher level in tree for GA versus Dist, se Table 6.2. On the other hand there were no significant differences between middle- and top-logs, neither of intercept nor inclination. The P-value of 0.18 for difference of inclination between middle- and top-logs for the relation between GA and Dist indicates a tendency to increasing inclination with increasing height between 13 and 22 meters height in tree.

6.3 Summary

The culmination point for spiral grain angle in the core wood occurs at somewhat higher ring number from pith with increasing height in tree. In Butt-logs the grain angle culminates at ring number four from pith and in top-logs from 20 meters height the culmination for grain angle occurs at ring number eight. Observe that the value of spiral grain angle at the culmination point in the core wood does not seem to be influenced by increasing height in tree.

After culmination, the grain angle with increasing ring number or distance from pith decreases more rapidly, with increasing height in tree. The increasing inclination of grain angle is more significant and pronounced for the relation between grain angle and distance than between grain angle and ring number, with increasing height in tree. Notice: There is a just significant increasing inclination, or slope of grain angle, between butt-logs, measured 4 meter above stump, and middle logs, which were measured 13 meter above stump.

7. Grain angle under bark at first thinning and clear cutting

7.1 Introduction

The size and direction of the grain angle under bark, in logs and standing trees, is something that was often taken into account in earlier centuries, when working with wood. Grain angle under bark told the user whether the tree or log was useable or suitable for a certain purpose. In instructions from The Swedish Timber Measurement Council (Virkesmätningsrådet) (VMR 1/99), regulations governing grain angle are based on the relation between the diameter of the log and its grain angle under bark. This relation affects twist in the sawn timber when it is dried (Kliger & Säll 2000). It follows from this that it may be interesting to know the distribution of grain angle under bark at the first thinning and at clear cutting, and the relation between these points of time in the history of the stand.

Description of figures and material

The following tables and figures illustrate grain angle 50 mm from pith (GA50), plus grain angle under bark (GAub). The reason for showing grain angle 50 mm from pith is that it is of interest to know if a young stand, approaching the first thinning, can be judged to be a more or less probable quality stand, regarding spiral grain.

Figure 7.2 and the figures in appendix A show the relative distribution of logs as a percentage, at 2° intervals. Figure 7.2 shows only butt-logs for stands 11 to 14, whilst the figures in Appendix A show all logs for respective stands. The figures marked as (a) in Figure 7.2 and Appendix A show grain angle 50 mm from pith (GA50), whilst figures marked as (b) show the distribution of grain angle under bark (GAub) within the respective stands.

7.2 Differences between grain angle 50 mm from pith and grain angle under bark

The results show that the distribution of GA50 is considerably less than GAub, see figures (a) and (b) in Appendix A, as well as Table 7.1 and 7.2.

The mean value for GA50 for all 390 logs is 2.4° and the standard deviation is 1.6°, see Table 7.1. The equivalent mean value for GAub for all logs is 0.6°, with a standard deviation of 2.6°, see Table 7.2. That the results show a decrease in grain angle and an increase in standard deviation is completely in accordance with the results in Chapter 3.

7.3 Grain angle 50 mm from pith

When we study only grain angle 50 mm from pith (GA50) for all logs, it is shown that five stands (12, 13b, 14, 53 and 58), differ significantly ($p < 0.05$ = *) from the material as a whole, see Table 7.1. Three of these five stands (12, 13b and 58) have a lower mean value than 2.4° (the mean value for all logs), whilst stands 14 and 53 deviate by exhibiting a higher mean value for the whole stand, regarding GA50.

Table 7.1. *Results for grain angle 50 mm from pith (GA50) for logs from stand 11-58. Stand number (stand), (*)=significant different from All logs, number of logs (n), average ring number for 50 mm from pith, average grain angle in degrees 50 mm from pith (GA50) and the standard deviation in brackets (stdev), relative frequency (%) of logs in intervals of 4°.*

stand	n	ring number 50 mm from pith	grain angle 50 mm from pith	grain angle 50 mm from pith (deg) for all logs, relative frequency (%)					
			mean (stdev)	< -8	-8 - -4	-4 - 0	0 - 4	4 - 8	> 8
All	390	21	2.4 (1.6)	0	0	5.6	80.0	14.1	0.3
11	24	20	2.1 (1.9)	0	0	13	62	25	0
* 12	27	20	1.7 (1.3)	0	0	0	93	7	0
13a	26	20	2.1 (1.5)	0	0	4	88	8	0
*13b	18	26	1.4 (1.1)	0	0	11	89	0	0
* 14	26	9	3.4 (1.5)	0	0	0	77	23	0
21	19	15	2.9 (1.5)	0	0	0	84	16	0
22	18	13	3.0 (1.2)	0	0	0	67	33	0
23	18	20	2.4 (1.0)	0	0	0	94	6	0
24	17	19	2.9 (1.0)	0	0	0	82	18	0
25	16	20	2.3 (1.6)	0	0	6	81	13	0
26	17	37	1.9 (0.9)	0	0	0	100	0	0
27	16	36	1.9 (2.4)	0	0	25	56	19	0
28	16	32	1.8 (1.2)	0	0	6	94	0	0
51	15	24	2.8 (1.6)	0	0	0	73	27	0
52	18	20	2.8 (1.3)	0	0	0	89	11	0
* 53	16	18	3.2 (2.1)	0	0	6	56	31	6
54	18	22	2.6 (1.1)	0	0	0	94	6	0
55	15	15	2.4 (1.6)	0	0	7	80	13	0
56	18	16	2.6 (2.2)	0	0	17	61	22	0
57	15	17	2.6 (1.8)	0	0	7	73	20	0
* 58	16	33	1.3 (1.2)	0	0	25	75	0	0

7.3.1 Relation between ring width and grain angle 50 mm from pith

Seven stands (14, 21, 22, 53, 55, 56 and 57) also distinguish themselves by having a relatively low number of annual rings (less than 18) within the first 50 mm from pith, see Table 7.1. A wide annual ring should lead to the fact that grain angle will be somewhat higher at a given distance from pith. In all of these stands (14, 21, 22, 53, 55, 56 and 57), the mean annual ring width is 3 mm to 5 mm in the interval 0 mm to 50 mm from pith. Within this interval, stand 14 has the lowest number of annual rings (nine), and has thereby the largest mean annual ring width (5.5 mm). Stand 14 also exhibits the highest value for GAub (3.4°) 50 mm from pith. For all of the seven stands with wide annual rings, the value for GA50 is equal to or larger than 2.4°, the mean value for all logs, se Table 7.1.

7.3.2 Relative frequency of logs in different classes of grain angle

The relative frequency in Table 7.1 shows that no logs have a value for GA50 that is less than -4°. Table 7.1 also shows that a small proportion of logs (5.6%) are below 0°, whilst the majority of logs (80%) have a grain angle that varies between 0° and 4°, whilst 14.1% of the logs have values between 4° and 8°. Note that amongst the logs that have a value for GA50 that is less than 0°, there is only one log from all 390 that has a value below -2°. Four logs from a total of sixteen logs (25%) in stand 27 exhibit values for GA50 that are below 0°, see Table 7.1. This can be explained to a great degree by the fact that stand 27 is one of those stands that have the greatest number of annual rings in the interval 0 mm to 50 mm from pith. Stands 26, 27 and 28 have in excess of 30 annual rings in the interval 0 mm to 50 mm from pith, see Table 7.1. Stand 27 has been low thinned seven times, which means that the stand has not been subjected to any strong thinning and has retained a high number of stems under a large proportion of the rotation period, see Table 4.2.

Stands and individual trees that show a smaller ring width seem to develop a tendency whereby changes in grain angle per annual ring decrease more rapidly, compare stands 13a and 13b in Table 4.3 and Table 4.4. This can explain the fact that almost all logs in stands 26 and 27 exhibit values in the interval 0° to 4°, unlike the logs in stand 27, see Table 7.1.

7.4 Relation between grain angle 50 mm from pith and grain angle under bark

From a silvicultural point of view, it is interesting to know whether there is a relation between the relative distribution for grain angle 50 mm from pith within the stand and the relative distribution for grain angle under bark. If there is a relation, this information can be used in the choice of thinning regime.

7.4.1 Stands grained to the right

The following five stands (11, 13b, 27, 56 and 58) have a large proportion (≥11%) "right handed" logs, with grain angles under 0° for GA50, see Table 7.1. The relation between GA50 for the logs from these stands and GAub for the same stands gives a coefficient of correlation of 0.69, which suggests a somewhat close relation. Of the five stands containing a large proportion of logs with low values for GA50, we find the two stands 11 and 13b, which also exhibit a significantly lower value for GAub, see Table 7.2. Furthermore, 21% of the logs in stand 11, and 10% of the logs in stand 13b, have values for GAub that are lower than -4°, which shows that in both of these stands there is a tendency towards finding trees and logs with extreme right hand grain angle.

Table 7.2. *Results for grain angle under bark for logs from stand 11-58. Stand number (stand), (*)=significant different from All logs, number of logs (n), number of year rings in average between pith and bark, average grain angle in degrees under bark (GAub) and the standard deviation in brackets (stdev), relative frequency (%) of logs in intervals of 4°.*

stand	n	ring number under bark	grain angle under bark	grain angle under bark (deg) for all logs, relative frequency (%)					
			mean (stdev)	< -8	-8 - -4	-4 - 0	0 - 4	4 - 8	> 8
All	391	62	0.6 (2.6)	0.3	4.4	36.3	50.9	7.2	1.0
* 11	24	83	-0.9(3.4)	0	21	46	25	8	0
* 12	27	83	-1.7 (3.4)	4	18	48	26	4	0
*13a	27	96	-0.6 (2.9)	0	15	58	30	7	0
*13b	19	78	-1.1 (2.0)	0	10	69	21	0	0
* 14	26	40	2.0 (2.3)	0	0	23	58	19	0
21	19	61	0.3 (1.7)	0	0	37	63	0	0
22	18	47	0.7 (1.7)	0	0	39	50	11	0
23	18	46	0.8 (1.2)	0	0	22	88	0	0
24	17	46	1.5 (1.3)	0	0	18	82	0	0
25	16	46	1.0 (2.1)	0	0	25	69	6	0
26	17	82	-0.3 (2.3)	0	0	53	47	0	0
27	16	67	0.9 (2.8)	0	0	50	36	6	6
28	16	62	0.7 (1.9)	0	0	31	63	6	0
51	15	59	1.2 (2.3)	0	0	33	67	0	0
52	18	58	0.7 (1.8)	0	0	39	61	0	0
* 53	16	62	2.3 (2.4)	0	0	12	69	13	6
54	18	58	1.4 (2.5)	0	6	17	61	17	0
55	15	43	1.5 (2.5)	0	0	26	60	7	7
* 56	18	37	2.7 (2.7)	0	0	17	50	28	5
57	15	59	1.0 (2.8)	0	0	27	60	13	0
58	16	80	-0.3 (1.4)	0	0	69	31	0	0

If we confine ourselves to studying GAub in the figures in Appendix A (b) and the compilation in Table 7.2, for those stands that contain a large proportion of logs with grain angles under 0°, we find that stands 11, 12, 13a, 13b and 58 distinguish themselves. The relative proportion of logs within these stands with grain angles below 0° is ca. 70%, which must be compared with the material as a whole, which has a proportion of 41% for logs with grain angles below 0° regarding GAub, see Table 7.2. Three of the stands that exhibit the highest values for right hand grain are 11, 13b and 58. These three stands are also found amongst the stands that exhibit the highest values for right hand grain regarding GA50, see Table 7.1 and 7.2. It is reasonable to assume that extreme right hand grain in a stand will be apparent as early as the point in time for the first thinning.

7.4.2 Stands grained to the left

"Left hand grained" stands are those stands that contain a large proportion of logs with grain angles higher than 4°. Seven stands (11, 14, 22, 51, 53, 56 and 57) have a high proportion of logs (>20%) with values for GA50 that are higher than 4°, see Appendix A (a) and Table 7.1. Five of these seven stands (14, 22, 53, 56, 57) also contain a high proportion of logs with high values for GAub, see Appendix A (b) and Table 7.2. For the logs in these seven stands, the relation between values for GA50 and the values for GAub for the same logs gives a coefficient of correlation of 0.63. This suggests that there is a relatively strong connection between high values for grain angle 50 mm from pith and high values for grain angle under bark. Stands 14 and 53 deviate significantly ($p<0.05$), exhibiting high values for both GA50 and GAub, see Table 7.1 and Table 7.2.

Eight stands (14, 22, 27, 53, 54, 55, 56 and 57) have a large proportion of logs, (higher than 8.2%, which is the value for the material as a whole), where GAub exceeds 4°, see Table 7.2. Concerning logs whose GAub exceeds 4°, the proportion in stands 14 and 53 is 19%, and stand 56 contains 33%, see Table 7.2. Amongst these extremely left hand grained stands, there are two logs, in stand 53 and stand 56, with a value for GAub higher than 8°. The three stands 14, 52 and 56 will produce a large proportion of sawn timber that is inferior because of twist.

7.4.3 Effect of ring width and inclination for grain angle under bark

Stands 14 and 56, when they were clear cut, had only 40 annual rings and 37 annual rings respectively, at the top end of the butt-log, with a mean annual ring width at breast height of 3.5 mm and 3.4 mm respectively, see Table 4.1 and Table 7.2. The width and the low number of the annual rings are a contributory factor to the fact that many of the logs have a high value for GAub.

Another important factor to take into account is how changes in grain angle with increasing annual ring number, β_{RN}, acts together with wide annual rings, see Section 4.6. For the eight stands (14, 22, 27, 53, 54, 55, 56 and 57) in Table 7.2, which contain a large proportion of logs with values for GAub higher than 4°, it is seen that four of these stands (14, 53, 56 and 57) exhibit small changes in grain angle (high value for β_{RN})

with increasing annual ring number from pith, see Table 4.4. Since both a relatively wide annual ring and small reduction in grain angle with increasing annual ring number from pith acts together, this will lead to the fact that relatively many logs will exhibit left hand grain under bark, despite their large dimensions.

For all logs, the relation between grain angle 50 mm from pith (GA50) and grain angle under bark (GAub) has a coefficient of correlation 0.62 (R^2= 0.39), see Figure 7.1. Both of these values for the material as a whole are in accordance with what has been shown above for stands with a large proportion of both high and low values for grain angle.

The relation between grain angle under bark (GAub) and annual ring width (RW) for the combined material is low or non-existent, as the coefficient of correlation is 0.24 (R^2= 0.06). It follows that it is not possible to utilise the annual ring width to predict grain angle under bark. There is a slightly stronger relation between grain angle under bark (GAub) and the number of annual rings between pith and bark (RNub). The coefficient of correlation is –0.40 (R^2=0.16), which indicates a weak relation between GAub and RNub. In multiple regressionanalyse using both RNub and annual ring width (RW), the relation between GAub and RN+RW is not strengthened, since RNub and RW are strongly multi collinear.

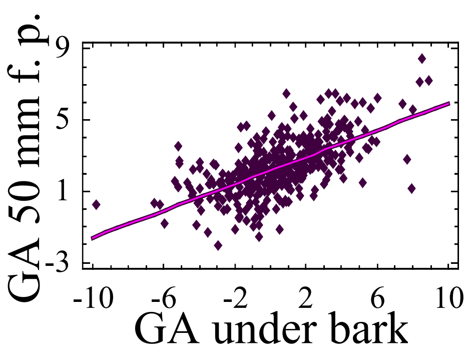


Figure 7.1. *Grain angle 50 mm from pith versus grain angle under bark for 390 logs.*

7.5 Standard deviation for mean values of grain angle under bark

The standard deviation for the mean value for the stand regarding GAub tells us something about the risk for finding logs with grain angles below -4° or higher than 4°. There is no absolute limit for how high or low grain angle under bark may be, for rejecting a log as being unsuitable for sawing. However, when the grain angle under bark is below -4° or higher than 4°, a large proportion of logs begin to produce considerable quantities of sawn timber with low shape stability because of spiral grain.

The eight stands (11, 12, 13a, 27, 54, 55, 56 and 57) that have a standard deviation greater than 2.5° have in all cases logs whose GAub is below -4° and/or higher than 4°, see Table 7.2. Stands 11 and 12 exhibit the highest standard deviation for GAub (3.4°). In stand 11, 29% of the logs have a value for GAub that is below -4° or higher than 4°. In stand 12, 26% of the logs have values for GAub that are above or below the limit of -4° or 4°, see Table 7.2. Other stands that contain a relatively large proportion of logs (more than 20%) with values for GAub that are below -4° or higher than 4° are stand 54, which contains 23%, and stand 56, which contains 32%. The four stands 11, 12, 54 and 56 will in all probability produce a large amount of extremely twisted timber, as between 23% and 32% of the logs in these stands have values for grain angle under bark which are below -4° or higher than 4°.

7.6 Relation between grain angle 50 mm from pith and grain angle under bark in butt logs

7.6.1 Results for all butt-logs

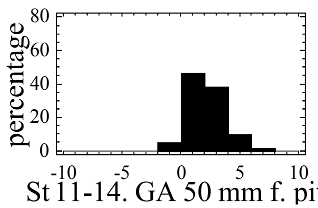
The relation between grain angle 50 mm from pith (GA50) and grain angle under bark (GAub) for all butt-logs (157 logs) is relatively strong, with a coefficient of correlation, 0.61 (R^2= 0.38). Note that for butt-logs, there is no relation between GAub and annual ring width, either for ring width in the whole cross section or in the interval 0 mm to 50 mm from pith. Neither is there, for butt-logs, any relation between GA50 and annual ring width in the interval 0 mm to 50 mm from pith.

7.6.2 Results for butt-logs from stand 11 - 14

For butt-logs, grain angle 50 mm from pith, and grain angle under bark, for stands 11 to 14, is shown in Figure 7.2.a and Figure 7.2.b, as well as in Table 7.3 and Table 7.4.

Figure 7.2. *Relative frequency for grain angle 50 mm from pith(GA50) and grain angle under bark (GAub) for butt-logs in stand 11-14.*
(a) Grain angle 50 mm from pith
(b) Grain angle under bark

(a) *(b)*



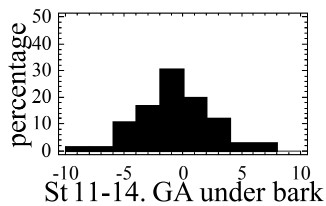
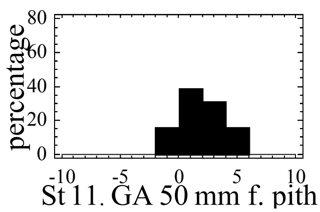


Figure 7.2. (a) ***Stand 11-14.*** *Relative frequency for GA50 mm from pith for 63 butt-logs.*

Figure 7.2. (b) ***Stand 11-14****. Relative frequency for GA under bark for 65 butt-logs.*



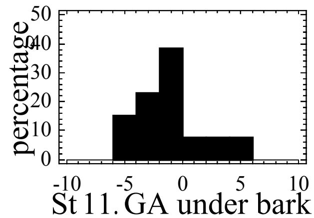
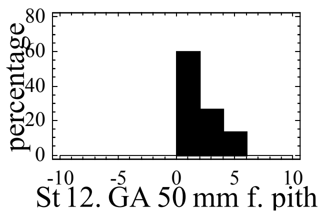


Figure 7.2. (a) ***Stand 11****. Relative frequency for GA50 mm from pith for 13 butt-logs.*

Figure 7.2. (b) ***Stand 11****. Relative frequency for GA under bark for 13 butt-logs.*



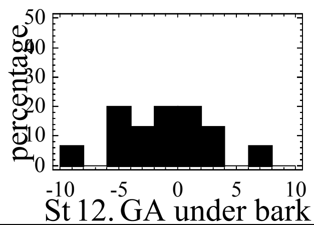


Figure 7.2. (a) ***Stand 12.*** *Relative frequency for GA50 mm from pith for 15 butt-logs.*

Figure 7.2. (b) ***Stand 12****. Relative frequency for GA under bark for 15 butt-logs.*

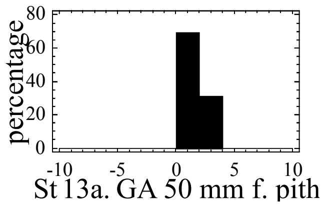


Figure 7.2. (a) ***Stand 13a****. Relative frequency for GA50 mm from pith for 13 butt-logs.*

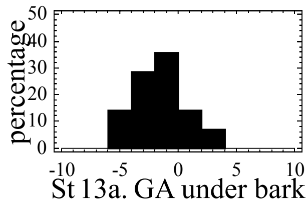


Figure 7.2. (b) ***Stand 13a****. Relative frequency for GA under bark for 14 butt-logs.*

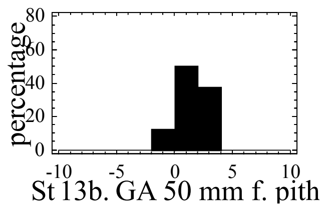


Figure 7.2. (a) ***Stand 13b.*** *Relative frequency for GA50 mm from pith for 8 butt-logs.*

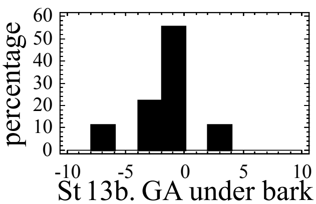


Figure 7.2. (b) ***Stand 13b****. Relative frequency for GA under bark for 9 butt-logs.*

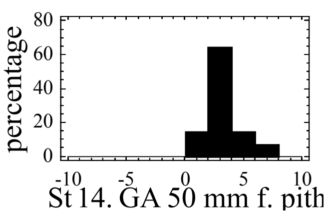


Figure 7.2. (a) ***Stand 14****. Relative frequency for GA50 mm from pith for 14 butt-logs.*

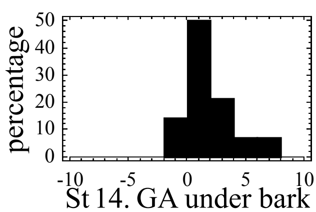


Figure 7.2. (b) ***Stand 14.*** *Relative frequency for GA under bark for 14 butt-logs.*

The number of sample trees in stands 11 to 14 varies between 10 and 15, whilst the number of sample trees in stands 21 to 58 is only 5 or 6. The larger number of butt-logs in stands 11 to 14 enables a separate study, to observe differences between the stands. Stands 11 to 14 also differ from the other stands in that the proportion of butt-logs is ca. 50% of the total number of logs per stand, whilst the relation between butt-logs and the remainder of the logs in stands 21 to 58 is 35% butt-logs. This brings about the fact that the mean value for GAub is lower in stands 11 to 14, as butt-logs have considerably more annual rings than middle- and top-logs from the same tree (the grain angle diminishes with increasing number of annual ring from pith). It must also be taken into account that stands 11, 12, 13a and 14 have ca. 50% more observations than stands 13b and 21 to 58, which results in the confidence interval being reduced for the four stands with more observations, and it is therefore more probable that these stands will differ significantly from the mean value for GA50 and GAub.

Relation between GA50 and GAub

The relation between GA50 and GAub for butt-logs (63 logs) in stands 11 to 14 is relatively weak; the coefficient of correlation is 0.51 (R^2= 0.26). This result can depend on the fact that the sample material consists solely of 63 logs. The equivalent relation for all butt-logs is somewhat stronger, (R^2= 0.38), see Subsection 7.6.1.

7.6.3 Silvicultural influences and relations between stands

Taking into consideration the fact that grain angle decreases with increasing annual ring number, GAub should be lower when only butt-logs are shown, when compared to the results for all logs, see Section 7.4. This is not the case for all stands from stand 11 to stand 14. Stands 11, 13a and 13b have a lower mean value for GAub, whilst GAub for stands 12 and 14 is somewhat higher, when only the figures for butt-logs are shown, see Table 7.2 and Table 7.4. That stand 12 exhibits a higher value can be explained by the fact that the standard deviation is 4.2°, which makes the mean value for the stand somewhat uncertain, see Table 7.2. Stand 12 is the only stand of the total of 21 stands, containing logs where GAub varies between -10° and 8°, see Figure 7.2. (b) and Appendix A (b). Stand 12 contains both extremely right hand grained logs and extremely left hand grained logs. The proportion of butt-logs under -4° in the stand is 27%, and the proportion butt-logs over 4° is 7%. This means that 34% of the butt-logs from the stand can be regarded as more or less unsuitable as sawn timber, see Table 7.4.

Table 7.3. *Results for grain angle 50 mm from pith for butt-logs from stand 11-14. Stand number (stand, (*)=significant difference from All, number of logs (n), average ring number for 50 mm from pith, average grain angle in degrees 50 mm from pith and the standard deviation in brackets (stdev), relative frequency (%) of butt-logs in intervals of 4°.*

stand	n	ring number 50 mm from pith	grain angle 50 mm from pith mean (stdev)	grain angle 50 mm from pith (deg) for butt-logs, relative frequency (%) < -8	-8 - -4	-4 - 0	0 - 4	4 - 8	> 8
All	63	19	2.1(1.4)	0	0	5	84	11	0
11	13	21	1.9(1.6)	0	0	15	69	15	0
12	15	20	1.8(1.4)	0	0	0	87	13	0
13a	13	22	1.7(0.9)	0	0	0	100	0	0
13b	8	22	1.8 1.2)	0	0	12	88	0	0
* 14	14	9	3.0 1.4)	0	0	0	79	21	0

Table 7.4. *Results for grain ange under bark for butt-logs from stand 11-14. Stand number (stand), (*)= significant difference from All, number of logs (n), number year rings in average between pith and bark, average grain angle in degrees under bark and the standard deviation in brackets (stdev), relative frequency (%) of butt-logs in intervals of 4°.*

stand	n	ring number under bark	grain angle under bark mean (stdev)	grain angle under bark (deg) for butt-logs, relative frequency (%) < -8	-8 - -4	-4 - 0	0 - 4	4 - 8	> 8
All	65	87	-0.6(3.2)	2	12	48	32	6	0
11	13	95	-1.2(3.2)	0	15	62	15	8	0
12	15	97	-1.1(4.2)	7	20	33	33	7	0
13a	14	110	-1.6(2.1)	0	14	65	21	0	0
13b	9	90	-1.4(2.4)	0	11	78	11	0	0
* 14	14	46	2.1(2.4)	0	0	14	71	15	0

Stand 12 has a low distribution for GA50, see Figure 7.2. (a) and Table 7.3, and up to the stage of 40 to 50 years appears normal in comparison with the other stands. During the period of first 50 years, the stand has growth equivalent to that in stands 11, 13a and 13b, and has the same number of annual rings, from pith to 50 mm from pith, see Table 7.1. Subsequently, silvicultural actions such as removal of deciduous trees and ordinary thinning has influenced the development of the remaining trees in stand 12, resulting in the fact that spiral grain has been affected in such a way that the distribution of GAub at the stage of clear cutting has become extremely large, see Figure 7.2. (b) and Table 7.4. The development of grain angle in stand 12 points towards the fact that a normal distribution of spiral grain angle in a young stand can de influenced in different directions through silvicultural operations. Thus, GAub at the time of clear cutting can be influenced through silvicultural operations during the whole growth period of the tree.

Stand 14 differs significantly ($p < 0.05$) from the other stands, regarding mean value for both GAub and GA50, see Table 7.3 and Table 7.4. The mean value for GAub in stand 14 is more than 3° higher than in stands 11 to 13b, see Table 7.4. The reasons for differences in stand 14 have been taken up previously, and have been explained by, amongst other things, a low number of annual rings from pith (46 rings) plus the fact that changes in spiral grain angle are small (the value for *β-RN* is larger than in the other stands). 15% of butt-logs in stand 14 have a GAub in excess of 4°, see Figure 7.2. (b) and Table 7.4.

In Table 7.4, it can be seen that stand 13a has 110 annual rings. This is because of the fact that 4 of the 14 butt-logs have 133 to 161 annual rings at their top ends, which means that the total age of these trees is 150 to 180 years. In a stand that is naturally regenerated it is not unusual that certain trees or parts of the stand have a divergent age in comparison to the age shown in the rest of the stand. In stand 13a, there is only one of the four trees with higher age that exhibits a different grain angle development regarding the relation between GA and RN. This tree is left hand grained (*β-RN* is positive). If we remove the four trees with high numbers of annual rings from the samples from stand 13a, the value for RN under bark decreases from 110 to 97. The other values in Table 7.4 are affected in the following fashion if those four trees are removed and the number of trees is reduced to 10. The mean value for GA under bark becomes -2.2 (-1.6), standard deviation becomes 1.7 (2.1) The proportion of logs in the interval -8° to -4° becomes 20% (14%), in the interval -4° to 0° becomes 70% (65%) and in the interval 0° to 4° it becomes 10% (21%). The difference is mainly dependent upon the fact that a relatively left hand grained tree has been excluded, which means that the mean value is reduced and the standard deviation is reduced.

7.7 Summary

Many logs begin to produce considerable amounts of sawn timber with low shape stability, caused by a too large degree of spiral grain, when grain angle under bark is lower than -4° or higher than 4°. In certain stands, in excess of 20% of logs can exceed the values of -4° or 4° grain angle under bark. If standard deviation for spiral grain angle under bark exceeds 3°, there is also a tendency towards increased risk that the stand will contain a large proportion of logs that are unsuitable as sawn timber.
The variation of grain angle 50 mm from pith is considerably less than it is for grain angle under bark for mature and larger dimensions of timber. When diameter at breast height (DBH) is about 15 cm in a stand, there are in general no butt-logs that exhibit negative grain angles (right hand grained) under bark. The diameter at the top end of the butt-log is ca. 10 cm under bark when DBH is 15 cm on bark.

There is a certain relation between grain angle under bark in a tree where the top end of the butt-log is 10 cm, and the grain angle found when the tree is mature for cutting. The degree of explanation is 38% for the relation between grain angle 50 mm from pith and grain angle under bark at the time of clear cutting. It is thus possible to say with a degree of certainty whether or not a tree should be removed because of too large grain angle, as early as the first thinning. There is not however any relation between grain angle under bark and the mean annual ring width in any individual log.

8. Prediction of twist

8.1 Introduction

Being able to grade trees in a forest or logs prior to conversion and to avoid using raw material with a large propensity to distortion as twist, spring and bow could be very important for sawmill industries. In this thesis only one dimension of sawn timber, 50 by 100 mm, were studied. Smaller or larger dimensions will have other dispositions to twist. However, the sawing patterns have also an effect on twist, which was not taken into account in estimations of twist in this study.

It has been shown that the proportion of straight sawn timber after drying can easily be increased by avoiding converting logs with large spiral grain angle measured under bark (Northcott 1965, Danborg 1994, Perstorper et al.1995, Ormarsson 1999, Forsberg, 1999, Woxblom 1999, Kliger & Säll 2000, Kliger 2001).

8.2 Relation between moisture content and twist

Spiral grain is an important parameter in any model aiming to describe distortion in sawn timber after drying and subsequent moisture changes in use. There is no significant correlation between twist in green condition and twist after drying, i.e. twist directly after sawing can not be used as a criterion for sorting out twist-prone studs before drying (Forsberg 1999, Woxblom 1999). Figure 8.1 shows the relationship between twist in studs at a moisture content of 18% (TW18%) and at 10% (TW10%).

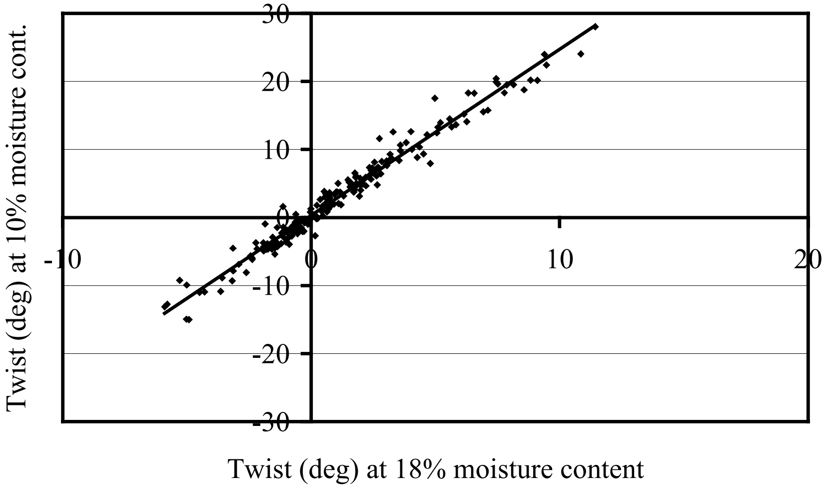


Figure 8.1. *Relationship between twist measured at 18% and 10% moisture content. Based on 209 planed studs from butt-, middle- and top-logs.*

The studs were sawn with the centre of the stud at different distances from the pith. The studs shown in Figure 8.1 represents material from stands 11 to 14, which is the same material as is shown in Chapters 3 to 7. Materials and methods for measuring distortion of these studs are reported in the EC-project [17] "STUD" (Kliger 1999, Perstorper et al. 2001). These studs were planed when the moisture content was 18% and conditioned without restraints.

A linear model can describe the relationship between twist at 10% and twist at 18% moisture content

$$TW10\%_i = \alpha + \beta * TW18\%_i + \varepsilon_i \qquad i = 1,2,......,209$$

where ε denotes the random error with expectation $\mathrm{E}(\varepsilon_i) = 0$ for all i and $V(\varepsilon_i) = \sigma^2$ for all i.

The estimated model for the total number of observations for the relation between TW10% and TW18% is

TW10%= 0.30 + 2.44*TW18% (8.1)

[17] EC-project: FAIR CT 96-1915, Improved Spruce Timber Utilisation.

with standard error of estimate $s_e = 1.31°$ and R-squared $R^2 = 97.1\%$.

This result shows that twist in planed studs increases with a factor close to 2.5 when moisture content decreases from 18% to 10%. There is a strong correlation between twist at the different moisture levels under the fibre saturation point (which is about 28% for spruce). Twist did not seem to change direction during drying. Johansson et al. (1999) and Woxblom (1999) report equally strong correlations between twist at different moisture content levels.

8.3 Relation between distance from pith and twist

The distance to pith is also a very important parameter when it comes to the magnitude of twist. Figure 8.2 show that there is an evident relation between twist and distance to pith when distance is under 50 mm. Further away from the pith twist normally becomes smaller and is not so much related to distance. The studs shown in Figure 8.2 represent the material described in Subsection 2.2.

The curvature (denoted by ARC) is also an expression of distance to pith and is calculated as 1 divided by the distance from the pith to the centre of each stud. Very close to the pith, the curvature of the annual rings is large. Ormarsson (1999) and Woxblom (1999) show similar results. Studs with the pith in centre display the largest twist.

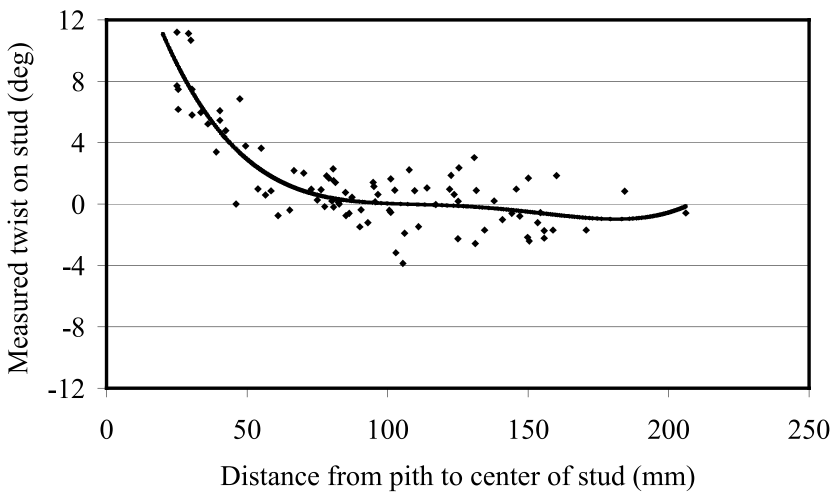


Figure 8.2. *Relationship between measured twist on studs and distance from pith to centre of the stud. Based on 89 studs dried to 11% moisture content.*

8.4 Twist, spring and bow

Regarding spring and bow in studs, the amount and direction of change between green and dry condition, has a weak correlation (Forsberg 1999, Woxblom 1999). In sawn wood the direction of spring and bow changes when the surrounding climate changes (Mishiro & Booker 1988, Woxblom 1999).

Depending on the sawing pattern, spring and bow change more or less when the moisture content changes. Quarter sawn[18] studs have significantly larger total movement for spring, compared to flat sawn[19]. The change for bow is more pronounced for flat sawn studs compared to quarter sawn when the surrounding climate changes (Woxblom 1999).

The result in Figure 8.3 shows grain angle under bark (GAub), twist, spring and bow for the studs from stands 1 and 2 (described in Section 2.2). The material was divided into trees with normal GAub and studs from tree no 5 in stand 2 (tagged 2B) with an extremely high level of GAub.

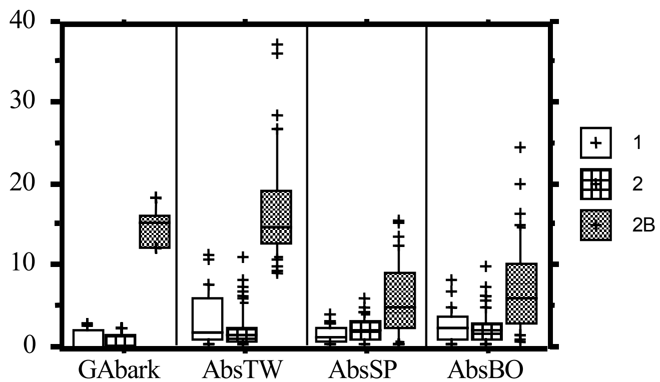


Figure 8.3. *Box plot representing studs from stands 1, 2 and 2B= (tree no. 5 in stand 2) for the spiral grain (degrees) measured under bark (GAbark), absolute values in degrees of twist (Abs TW), spring (Abs SP) and bow (Abs BO) in mm for studs at moisture content 11%. (Box plot showing 10th , 25th ,50th ,75th and 90th percentile)*

The growing conditions in stands 1 and 2 were completely different. Stand 1 represents a site with normal growing conditions (G26) compared to stand no 2, which was grown on a site with an extremely

[18] Quarter sawn: Sawn timber in which the annual rings form an angle of 45 to 90° with the flat side.

[19] Flat sawn: Sawn timber is considered flat-sawn when the annual rings make an angle of less than 45° with the flat side.

high site index (G38), see Table 2.2. Both stands have had ordinary silvicultural system. Tree data and number of logs and studs are shown in Table 2.3. The average annual ring width at breast height was about 2 mm in stand 1, and over 3 mm in stand 2, see Table 2.3. Even though there was a great difference between stands 1 and 2 in site index there were small differences in twist, spring and bow for the studs sawn from logs with normal GAub, see Figure 8.3. If there were any tendencies it seems that the studs from stand 1 (site index G26) are more twisted.

Tree no 2B, with a high GAub, showed, as expected, an extremely high level of twist; nearly all studs had a twist in excess of 10°. There were two studs from the highest top-log that had a twist about 35° over a length of 2.5 m. These studs were flat sawn with the pith on the wide side. Twist should not exceed 3° over a length of 2.5 m to be acceptable for the building requirements, see (Johansson et al. 1990 and 1994, Bergman et al. 1997). For several of the studs sawn from tree 2B, strength and stiffness will certainly be reduced by more than 50%, dependent on a high level of grain angle in the studs, see Table 1.1. Spring and bow were also much more pronounced for the studs sawn from tree 2B. The reason for this was probably compression wood in the logs.

8.5 Statistical models

8.5.1 Twist in studs sawn more than 50 mm from pith

To estimate spiral grain angle calculated for the centre of the stud (GAstud) there have to be some assumptions made regarding grain angle close to pith and measurements of the log. The assumption is that the maximum grain angle is 3°, at a distance of 15 mm from pith, see Section 3.5. After this maximum the grain angle usually changes linearly (decrease or increase) as the distance from pith increases, see Figure 4.4. b and (Gjerdrum, Säll & StorØ 2000). This linear change of grain angle in a radial direction is called the slope of grain angle (GAslope). Slope of grain angle is based on the difference between measured grain angle under bark and the presumed spiral grain angle of 3°, 15 mm from pith. GAslope is here expressed in the unit degrees/m.

The necessary measurements of the log to obtain data for calculation of twist are log diameter and grain angle under bark at the middle of the log. When the position of the centre of stud in relation to the pith is known, it is possible to calculate GAstud with regard to the slope of grain angle in the same log.

The following equations are used to calculate GAslope and GAstud in a certain log where GAub, diameter of log under bark and distance from pith to centre of stud (stud dist) are known.

GAslope = (GAub - 3°) / ((log diameter/2) – 0.015 m)

GAstud = 3° + (stud dist – 0.015 m) * GAslope

The relationships between measured twist (TW) of studs in degrees, at moisture content 10-11% (10%), and spiral grain angle calculated for the centre of the stud (GAstud), grain angle under bark (GAub), or the slope of grain angle (GAslope) are shown in the following. Only studs with a centre more than 50 mm from the pith are included in Figure 8.4 to Figure 8.6.

8.5.2 Relation between twist and grain angle in centre of stud

Spiral grain angle in the centre of the stud is probably a prime factor for understanding which studs will remain straight when moisture content changes.

Two linear models describe the relationship between TW and GAstud, see Figure 8.4. One model for 92 studs from stands 1 and 2 and the second model for 102 studs from stands 11 to 14.

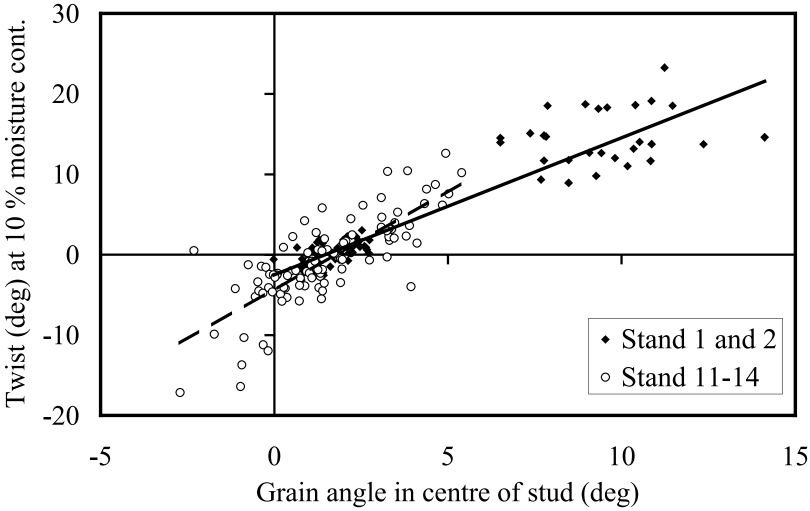


Figure 8.4. *Relationship between measured twist at 10% moisture content and grain angle in centre of stud. Only studs further than 50 mm from the pith are included. Observations based on 92 studs from stand 1 and 2 and 102 studs from stands 11-14.*

Linear model used for statistical evaluation for the two groups of stands:

$$TW_i = \alpha + \beta * GAstud_i + \varepsilon_i \qquad i = 1,2,......, n$$

where ε denotes the random error with expectation $\mathrm{E}(\varepsilon_i) = 0$ for all i and $V(\varepsilon_i) = \sigma^2$ for all i.

The estimated model for the observations from stands 1 and 2 is

TW=-2.50 + 1.70*GAstud **(** 8.2)

with standard error of estimate s_e =2.60° and R-squared R^2 =87.0%.

Similar results are obtained for 102 studs from the EC-project "STUD", see Subsection 8.1.1. These studs were dried to 10% mc without restrain. Consideration was taken to the reduction of twist that occurred when the studs were planed when moisture content was 18%. This made its possible to compere the not planed studs from stand 1 and 2.

The model corresponding to Eq. 8.2, for studs from stand 11 to 14 is

TW= -4.35 + 2.46*GAstud (8.3)

with standard error of estimate s_e =3.27° and R-squared R^2 = 62.0%.

Figure 8.4 and Eq. 8.2 and 8.3 shows that there is a statistically significant relationship between TW and GAstud with a p-value less than 0.001 for both equations, which indicates a relatively strong relationship between the variables. There is no significant difference in intercept and inclination between Eq. 8.2 and 8.3.

The result in Eq. 8.2 shows that straight studs will be obtained if GAstud is 1.47° (TW =0° when GAstud =1.47°) and Eq. 8.3 gives TW= 0° when GAstud is 1.77°. This result shows us that studs that have a grain angle of about 1.5° in the centre of the stud remain straight, in the meaning of twist, when moisture content changes. This result also shows that studs would be twisted to the right (negative value of twist) when GAstud is less than 1.5°.

8.5.3 Relation between twist and grain angle under bark

Two linear models describe the relationship between TW and GAub, see Figure 8.5. One model is for 92 studs from stands 1 and 2 and the second model is for 102 studs from stands 11 to 14.

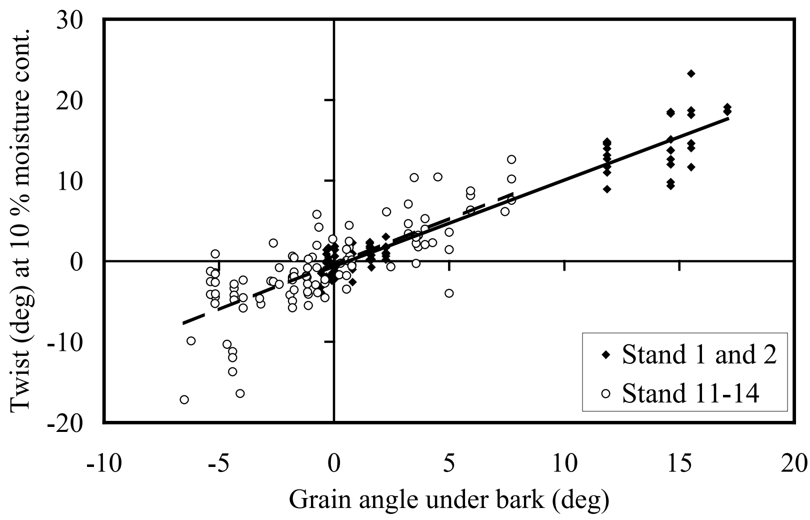


Figure 8.5. *Relationship between measured twist at 10% moisture content in studs and grain angle under bark on logs. Only studs further than 50 mm from the pith are included. Observations based on 92 studs from stand 1 and 2 and 102 studs from stand 11-14.*

Linear models used for statistical evaluation are the same as for the relation between TW and GAstud above.
The estimated model for the observations from stands 1 and 2 is

TW=-0.62 + 1.07*GAub **(** 8.4)

with standard error of estimate s_e =1.93° and R-squared R^2 =92.8%.

Similar results are obtained for 102 studs from the EC-project "STUD". The equation corresponding to Eq. 8.4, for studs from stands 11 to 14 is

TW= -0.35 + 1.13*GAub (8.5)

with standard error of estimate s_e =3.40° and R-squared R^2 = 58.8%.

Figure 8.5 and Eq. 8.4 and 8.5 show that there is a statistically significant relationship between TW and GAub with a p-value less than 0.001 for both equations, which indicates a relatively strong relationship between the variables. There is no significant difference in intercept and inclination between Eq. 8.4 and 8.5.

The result in Eq. 8.4 shows that straight studs will be obtained if GAub is 0.58° (TW =0° when GAub = 0.58°) and Eq. 8.5 gives TW= 0° when GAub is 0.31°. This result show us that logs that have a grain angle under bark (GAub) of about 0.5° give studs that remain straight, in the meaning of twist, when moisture content changes. This result also shows that studs would be twisted to the right (negative value of twist) when GAub is less than 0.5°.

8.5.4 Relation between twist and slope of grain angle

Two linear models describe the relationship between TW and GAslope, see Figure 8.6. (Explanation for GAslope, see Subsection 8.5.1) One model is for 92 studs from stands 1 and 2 and the second model is for 102 studs from stands 11 to 14.

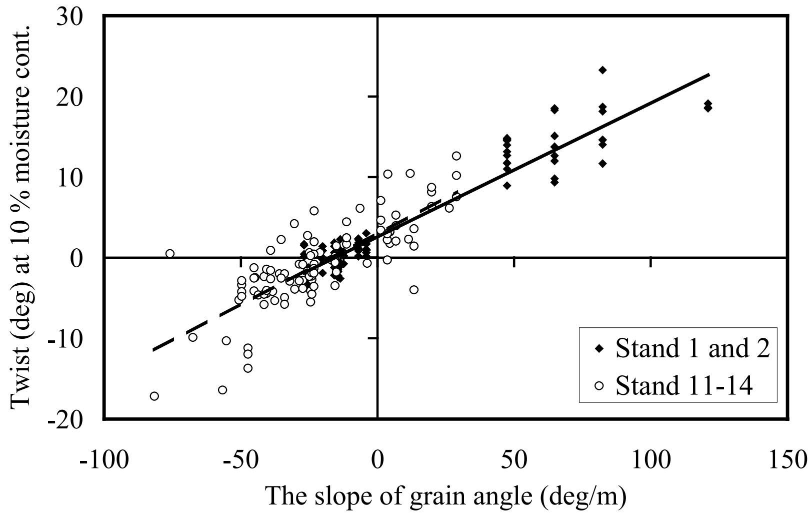


Figure 8.6. *Relationship between measured twist at 10% moisture content in studs and the slope of grain angle in logs. Only studs further than 50 mm from the pith are included. Observations based on 92 studs from stands 1 and 2 and 102 studs from stands 11-14.*

The linear models used for statistical evaluation are the same as for the relation between TW and GAstud above.
The estimated model for the observations from stands 1 and 2 is

TW= 2.58+0.17*GAslope **(** 8.6)

with standard error of estimate s_e =2.22° and R-squared R^2 =90.6%.

Similar results are obtained for 102 studs from the EC-project "STUD". The equation corresponding to Eq. 8.6, for studs from stands 11 to 14 is

TW= 3.01 + 0.17*GAslope (8.7)

with standard error of estimate s_e =3.28° and R-squared R^2 = 61.9%.

Figure 8.5 and Eq. 8.6 and 8.7 show that there is a statistically significant relationship between TW and GAslope with a p-value less than 0.001 for both equations, which indicates a relatively strong relationship between the variables. There is no significant difference in intercept and inclination between Eq. 8.6 and 8.7.

The result in Eq. 8.6 shows that straight studs will be obtained if GAslope is -15.2°/meter (TW =0° when GAslope =-15.2°/m) and Eq. 8.7

gives TW= 0° when GAslope is -17.7°/meter. The results show us that logs that have a slope of grain angle (GAslope) of about -16°/meter produce studs that remain straight, in the meaning of twist, when moisture content changes. The result also shows that studs may be twisted to the right (negative value of twist) when GAslope is less than -16°/meter.

It is interesting to note that the average slope of grain angle in all logs, proven in Section 4.7, is -0.025°/mm (-25°/m), which is approximately the same value of GAslope that gives straight studs. A normal change of grain angle from left to right will be a requirement for sawn timber that does not twist.

The model including GAslope is the most interesting model for practical use, when a decision will be taken without knowing the sawing pattern of logs. The reason is that GAslope includes both diameter of log and grain angle under bark. Whether a log is suitable for sawing is dependent on the relation between GAub and log diameter. Large log diameters tolerate a higher GAub when GAslope is taken into account.

A multiple regression model including both GAub and GAslope must be excluded since there is a high multicollinearity of –0,97 between GAub and GAslope.

8.5.5 Relation between twist, slope of grain angle and log taper

A multiple linear regression model describes the relationship between TW and the two independent variables GAslope and Taper. Taper is the conical shape of the log expressed in diminution in mm per meter of log length (mm/m).

The multiple linear regression model used for statistical evaluation of the 92 studs from stands 1 and 2 is

$$TW_i = \alpha + \beta_1 * GAslope_i + \beta_2 * Taper_i + \varepsilon_i \qquad i = 1,2,......,92$$

where ε denotes the random error with expectation $\mathrm{E}(\varepsilon_i) = 0$ for all i and $V(\varepsilon_i) = \sigma^2$ for all i.

The estimated multiple linear regression model for the observations from stands 1 and 2 is

TW= 4.27 + 0.17*GAslope – 0.18*Taper (8.8)

with standard error of estimate $s_e = 2.14°$ and R-squared $R^2 = 91.3\%$.

Equation 8.8 shows that there is a statistically significant relationship between TW and the two variables GAslope and Taper with a p-value less than 0.001 for the model.

8.5.6 Statistical models including distance from pith

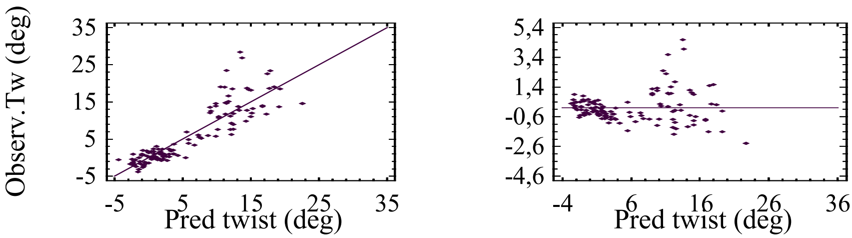
There are clear relationships between measured twist and calculated twist for studs, using statistical models without regard to distance from pith, see Equation 8.2 to 8.8. In models 1a to 4a, Table 8.1 and Figure 8.7, all studs sawn at different distance from pith are included. Distances to pith in models 1a to 4a in Table 8.1 are expressed as the inverse of distance in meters from pith to centre of stud, 1/r, (ARC). This variable can be used in practice, at sawmill industries, where the dimensions of sawing yield are known.

Table 8.1. *Statistical models for estimation of twist valid for studs sawn at different distance from pith. Predicted twist (TW), annual ring curvature 1/r(m) (ARC), standard error of estimate (s_e), R-squared (R^2). The models are based on 129 studs from stand 1 and 2.*

Model	Equation	s_e	R^2
1a	TW=-5.97 + 0.32*ARC + 1.87*GAstud	3.56	78.5
2a	TW=-3.22 + 0.27*ARC + 1.09*GAub	2.15	92.1
3a	TW= 0.01 + 0.28*ARC + 0.17*GAslope	2.19	91.8
4a	TW= 1.41 + 0.28*ARC + 0.17*GAslope - 0.15*Taper	2.14	92.3

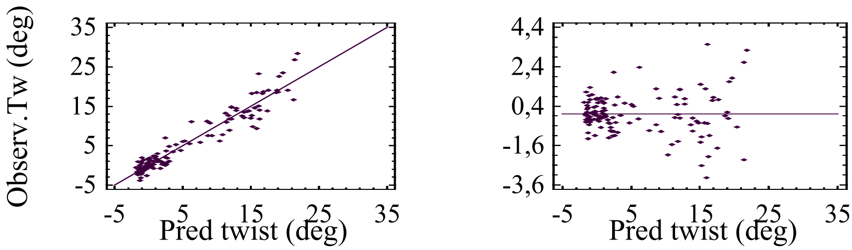
Figure 8.7. (a) Statistical model

Figure 8.7. (b) Studentized residual



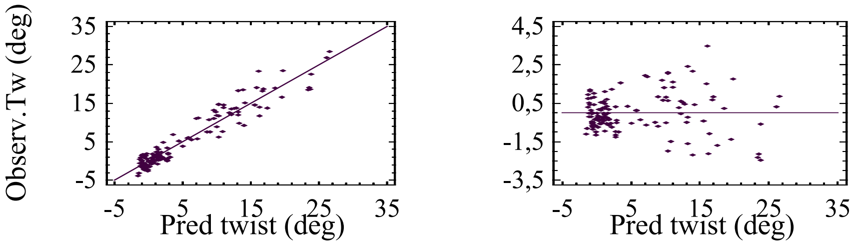
Model 1a

TW=α + β_1*ARC + β_2*GAstud



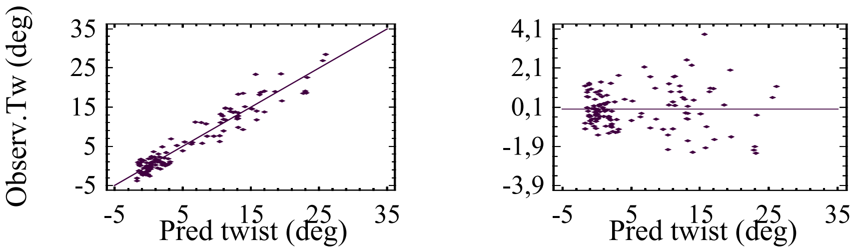
Model 2a

TW=α + β_1*ARC + β_2*GAub



Model 3a

$TW = \alpha + \beta_1 * ARC + \beta_2 * GAslope$



Model 4a

$TW = \alpha + \beta_1 * ARC + \beta_2 * GAslope + \beta_3 * Taper$

Figure 8.7 *Statistical models with regard to distance from pith and residual plots for the models.*
(a) Observed twist versus predicted twist for models 1a to 4a.
(b) Studentized residual versus predicted twist for models 1a to 4a.
Observations based on 129 studs sawn at different distances from pith from stands 1 and 2.

However, the models are different in prediction of twist based on different independent variables.

The first model, 1a, has the highest value of (s_e) and the lowest R-squared value and the residual plot in Figure 8.7 (b) shows us that the model has increasing differences in variance when predicted twist increases. Also Figure 8.7 (a) shows that model 1a is not so uniform when the predicted twist increases. Models 2a, 3a and 4a have similar values for s_e and R^2. Model 4a gives the best value in Table 8.1 and appears to be good in terms of a high correlation value between predicted and measured twist in Figure 8.7 (a) and (b). This model is also of practical use, since the value of the independent variable taper of logs is available when measuring logs at sawmill industries.

8.5.7 The best model on a future harvester

In the forest, on a harvester, it is hard to know the sawing pattern of logs. The harvester normally measures log diameter for every decimetre of log length when crosscutting the trees in the forest. The diameter of logs is also measured very accurately when the logs are measured and classified by the Swedish Timber Measurement Council at the measurement station at sawmills. Diameter measurement by the harvester or at the sawmill also gives the taper of the log. This is also of practical use, since taper is used on the harvester, to calculate the price and volume of logs, to optimise the value of the tree when crosscutting it to logs. Taper is also an independent variable to GAslope; the correlation between GAslope and taper is -0.28.

Table 8.2 summarises the models proven in Section 8.5 for stands 1 and 2. In Table 8.2 the value of R-square is high for all models. The lowest value of R-square is represented by model 1b, where GAstud is the variable used to predict twist. Model 1b is not suitable on a harvester since GAstud is dependent on knowing distance from pith for a certain stud for estimation of twist.

Models 2b to 4b in Table 8.2 estimate twist of studs without taking distance from pith into account. These three models will be more suitable on harvesters where you want to know if logs will be suitable for sawing or for more suitable for use in other connections. It is of importance to know that the studs in this material are sawn from logs with a top diameter between 200 mm and 430 mm under bark, with an average diameter of 315 mm.

Table 8.2. *Statistical models for estimation of twist, valid for studs sawn > 50 mm from pith. Predicted twist (TW), R-squared (R^2). The models are based on 92 studs from stands 1 and 2.*

Model	Model	R^2
1b	TW= -2,50 + 1,70*GAstud	0,87
2b	TW= -0,62 + 1,07*GAub	0,93
3b	TW= 2,58 + 0,17*GAslope	0,91
4b	TW= 4,27 + 0,17*GAslope - 0,18*Taper	0,91

However, the models differ in prediction of twist based on different independent variables. For deciding the best model, the studs from stands 1 and 2 are used, since these studs were dried in an ordinary kiln, with restrain, to 12% mc and then conditioned to 11% mc. Planing has not influenced the distortion of the studs from stands 1 and 2.

To predict the best model out of 2b to 4b, it is useful to study the residual plot with studentized residuals related to predicted twist for each model, see Figure 8.8. The best model out of 2b, 3b and 4b for estimating twist whilst in the forest seems to be model 4b, which has a low value for s_e, a high level for R^2 and the shape of the plotted residuals is the most uniform (there are small differences in variance when predicted twist increases). In this material there are small differences between models 2b to 4b, see Figure 8.8.

Since there is a good correlation between twist and GAslope, where diameter of log is incorporated, the models 3b or 4b seem to be the most suitable on the harvester.

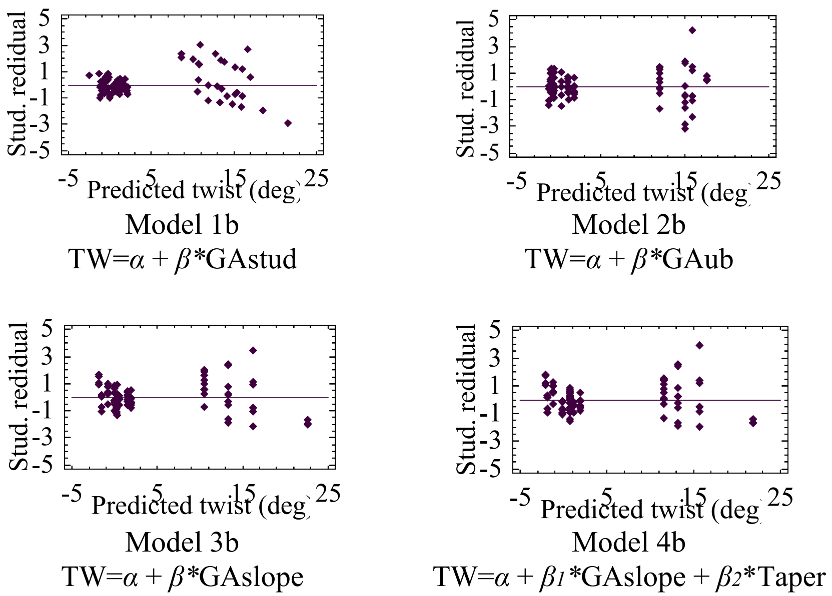


Figure 8.8. *Relation between studentized residual and predicted twist for model 1b to 4b. Observations based on 92 studs from stand 1 and 2.*

8.6 Analytical model

Stevens and Johnston's model of twist is treated in Section 2.2. The model might be a simple tool for predicting twist in sawn timber. It might appliy to timber sawn from large-diameter logs and for studs sawn further than 50 mm from the pith and with the same spiral grain angle in radial direction through the stud.

Eq. (2.1) is recalled.

$$\alpha = \frac{l}{r} \cdot \frac{2s\theta}{1+s} \qquad (2.1)$$

where:

α	=	twist of stud (°)
l	=	length of stud (2.5 m)
θ	=	spiral grain angle in centre of stud (GAstud) (°)
r	=	radius (m), distance from pith to centre of stud
s	=	tangential shrinkage

However, to improve the accuracy of this model, it is important either to measure or calculate the spiral grain angle in the centre of the stud (GAstud) and estimate a reliable value for tangential shrinkage. Length (l) and radius (r) are easy to know if log length and sawing patterns are known.

In the EC-project[20] "STUD", sticks (200x12x12 mm³) were sawn from each log from stands 11 to 14. In total, 1614 sticks were studied, for measurement of distortion and shrinkage coefficients. These studies were made at Lund University, Division of Structural mechanics. The tangential shrinkage coefficient in these sticks was in average 0.26 (% change of tangential shrinkage per %-unit of mc under fibre saturation point). The moisture content in studs from stands 1 and 2 was 11%. This give a difference of mc of 17 units of per cent (28% - 11%) if mc at the fibre saturation point is 28%. In Stevens and Johnston's model the constant for tangential shrinkage (s) will then be 0.04 = 0.0026x17, when the results above are taken into account.

A linear model used for statistical evaluation for Stevens and Johnston's model (S&J) for studs from stands 1 and 2 with centre more than 50 mm from the pith is

$$TW_i = \alpha + \beta * S\&J_i + \varepsilon_i \qquad i = 1,2,......,92$$

where ε denotes the random error with expectation $\mathrm{E}(\varepsilon_i) = 0$ for all i and $V(\varepsilon_i) = \sigma^2$ for all i.

[20] EC-project: FAIR CT 96-1915, Improved Spruce Timber Utilisation.

The estimated model for the observations from stands 1 and 2 is

TW=-2.66 + 0.99*S&J **(**8.9)

with standard error of estimate s_e =2.30° and R-squared R^2 =89.9%.

The predicted twist given by S&J:s model overestimates twist with 2.66°, see Eq. (8.9) and Figure 8.9.

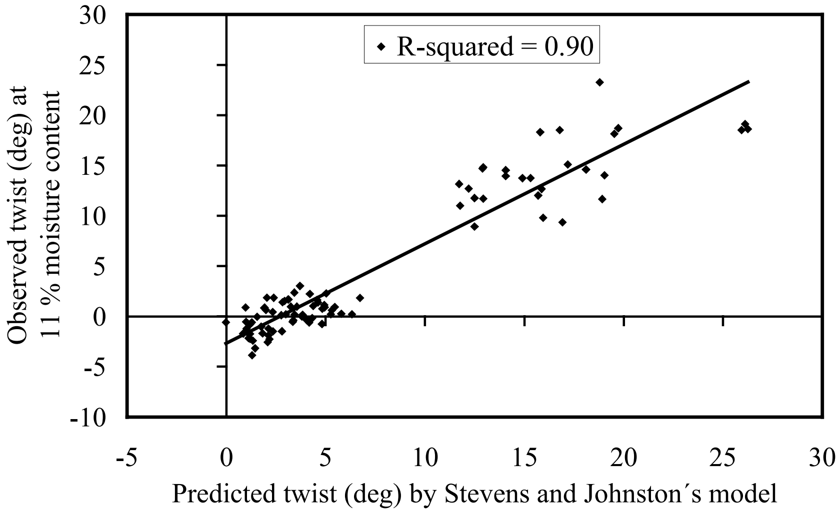


Figure 8.9. *Relationship between measured twist at 10% moisture content in stud and Stevens and Johnston's model. Only studs further than 50 mm from the pith are included. Observations based on 92 studs from stands 1 and 2.*

It is of some interest to know how well S&J:s model will predict twist if studs closer than 50 mm from pith are included in the estimation.
The estimated model for all studs (n=129) from stands 1 and 2 is

TW=-2.73 + 0.88*S&J **(**8.10)

with standard error of estimate s_e =3.21° and R-squared R^2 =82.3%.

The predicted twist given by S&J:s model overestimates twist more, if studs close to pith are included, see Eq. (8.9) and (8.10). Also, the statistical values of s_e and R^2 tell us that twist is not estimated well for studs from close to the pith, see Eq. (8.10) and Figure 8.10.

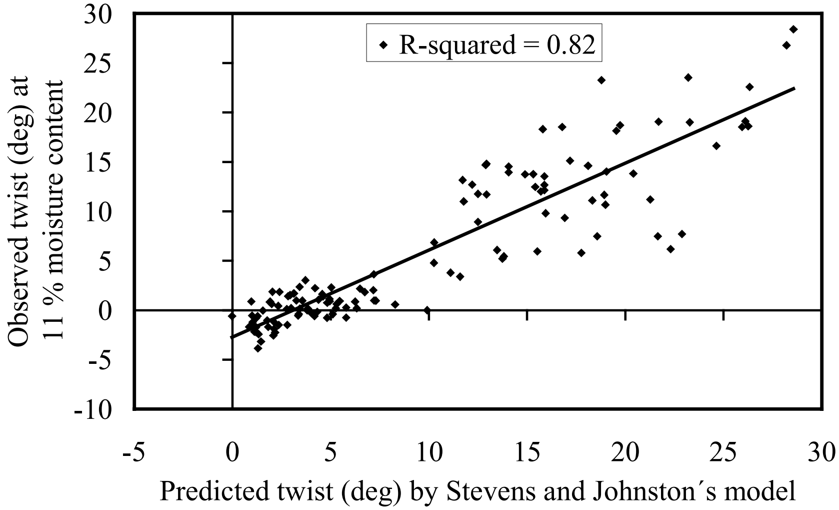


Figure 8.10. *Relationship between measured twist at 10% moisture content in stud and Stevens and Johnston's model. Studs with different distances from the pith are included. Observations based on 129 studs from stand 1 and 2.*

The residual plots in Figure 8.11 (a) for studs sawn more than 50 mm from pith prove that the residuals are fairly uniform when the predicted twist changes. Figure 8.11 (b) shows the studentized residuals for all studs sawn with different distances from pith.

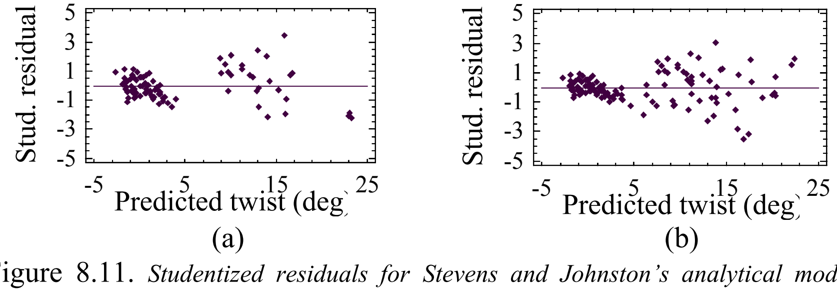


Figure 8.11. *Studentized residuals for Stevens and Johnston's analytical model model.*

(a) *Residuals for studs sawn further than 50 mm from the pith. Observations based on 92 studs from stands 1 and 2.*

(b) Residuals for studs sawn at different distance from pith. Observations based on 129 studs from stands 1 and 2.

This figure shows obvious signs of heteroskedasticity (there are large differences in variance when predicted twist increases). In conclusion, these results show us that Stevens and Johnston's analytical model of twist appears to be generally applicable for industrial use, for studs sawn more than 50 mm from pith, but that the analytical model overestimates prediction of twist.

8.7 Number of rejected /accepted studs

All the studs from stands 1 and 2 and 11 to 14 were graded according to end-user requirements (Johansson et al. 1990 and Bergman et al. 1997). According to these requirements, the limit for twist is 5 mm, measured over a length of 2.5 metres (or, when expressed in degrees, twist must not exceed 3°), when dried to the final moisture content of 10% to 11% (10%). As a result, all the studs exceeding 3° were classified as rejects. The limits for bow and spring are 6 mm and 4 mm respectively when the above-mentioned requirements apply.

Studs sawn close to the pith; i.e. distance less than 50 mm

Table 8.3 shows the number and percentage of rejected studs. The measured and observed twist at 10% mc is compared to calculated twist, using the statistical multiple regression model 4a (TW= 1.41 + 0.28*ARC + 0.17*GAslope - 0.15*Taper) in Section 8.5.

Table 8.3. *Number and percent of rejected studs sawn close to pith (< 50 mm), in total (All) and for each stand at 10% moisture content. Observed twist (TW) compared to twist calculated by the statistical model (TW= 1.41 + 0.28*ARC + 0.17*GAslope - 0.15*Taper).*

stand	total number of studs	Rejected			
		observed		model 4a	
		no	%	no	%
All	114	*100*	88	*77*	68
1	9	*9*	100	*7*	78
2	8	*7*	87	*7*	87
2B	6	*6*	100	*6*	100
11	20	*15*	75	*12*	60
12	20	*15*	75	*9*	45
13	32	*29*	90	*19*	59
14	19	*19*	100	*17*	89

The result is very clear. 100 studs of 114 (88%) with a nominal distance from the pith under 50 mm were rejected at 10 % mc. If the degree of twist at 10% mc is reduced to the level of twist at 18% mc, with the constants in Eq. (8.1), the relative amount of rejected studs will be reduced from 88% to 52%.

The number of studs in stands 1 and 2 is too low to draw any deeper conclusions regarding relevance. Stands 11 and 12 had 75% rejected studs and stand 14 had 100% rejected studs. Stand 14 is one of the fastest grown stands, see Chapters 2 and 4. The statistical model 4a seems to be reliable but it underestimates twist for the studs sawn close to pith.

Studs sawn more than 50 mm from the pith

Table 8.4 shows the number and percentage of rejected studs sawn more than 50 mm from the pith. Twist is measured on studs at 10% mc or calculated using the statistical multiple regression model 4a (TW= 1.41 + 0.28*ARC + 0.17*GAslope - 0.15*Taper) in Section 8.5.

Table 8.4. *Number and percent of rejected studs sawn more than 50 mm from the pith, in total (All) and for each stand at 10% moisture content. Observed twist (TW) compared to twist calculated by the statistical model (TW= 1.41 + 0.28*ARC + 0.17*GAslope - 0.15*Taper).*

stand	total number of studs	Rejected			
		observed		model 4a	
		no	%	no	%
All	208	*87*	42	*97*	47
1	17	*3*	18	*0*	0
2	55	*0*	0	*2*	4
2B	34	*34*	100	*34*	100
11	22	*13*	59	*14*	64
12	24	*12*	50	*21*	88
13	29	*12*	41	*16*	55
14	27	*13*	48	*10*	37

As seen in Table 8.4, 42% of studs are rejected. The results are very clear. If the degree of twist at 10% mc is reduced to the level of twist at 18% mc, with the constants in Eq. (8.1), the relative amount of rejected studs will be reduced from 42% to 18%.

The results in Section 8.5, Eq. (8.6) and (8.7), show that logs which have a slope of grain angle (GAslope) of about -16°/meter produce studs which remain straight, in the meaning of twist, when moisture content changes. Figure 8.6 shows that a value for GAslope between approximately -35°/m and 5°/m, which is equivalent to approximately -16°/m ± 20°/m, results in studs which remain sufficiently straight, with a degree of twist under 3° at mc 10%. If logs with GAslope under -36°/m and over 5°/m are rejected, the relative amount of rejected studs is reduced to 18% (42%) at 10% mc and to 1% (18%) at mc 18%.

Stand 2, with a very high site index of G38, had no rejected studs and represents a stand with a large ring width of 3.4 mm and a normal GAub. Stand 1, with a site index of G26 and a ring width of approximately 2 mm, had 18 % rejected studs. These two stands show that ring width and site index are not related to the production of twisted sawn timber. Even stands 11 to 14 show similar relative amounts of twisted studs, even though ring width and site index are very different, see Table 8.4 and Chapters 2 and 4.

The statistical model 4a seems to be reliable and quite effective for predicting twist in studs sawn at different distances from pith, for large logs, with a diameter of more than 200 mm. The model 4a overestimates twist for stand 12.

Observations of studs from tree no 2B, with a large left-hand spiral grain angle under bark, show that not a single stud was straight enough to be accepted, applying the criterion of 3°. In total 40 studs were sawn, and 34 of these studs were sawn more than 50 mm from the pith. After being dried in a package in the industrial kiln, to 11% mc, all these studs displayed a very large degree of twist. In fact, the lowest twist value was 9°. Logs from this tree were about to be delivered to a sawmill to be sawn in normal production. This illustrates very clearly that sawmills must set requirements in terms of the magnitude of spiral grain limits measured on logs, and not convert these logs to sawn products, if they display too much spiral grain.

8.8 Summary

The degree of twist is highly correlated to the moisture content in wood. The amount of twist, measured in degrees, is more than doubled when the moisture content decreases from 18% to 10%.

88% of Studs sawn close to pith (< 50 mm) were rejected when dried to 10% moisture content, as exceeding 3° twist. The corresponding proportion of rejects was 52% of studs when dried to 18%. The rejection rate for studs sawn more than 50 mm from pith was 42% when moisture content was 10%, compared to an 18% rejection rate at 18% moisture content.

Studs sawn closer than 50 mm from pith are greatly predisposed to twist, and there are several explanations for this, including juvenile wood, annual ring curvature and probably ring width. The presence of twist in studs sawn more than 50 mm from pith can be explained by spiral grain. The relationship between grain angle under bark related to log diameter, and twist of studs, was strong, stronger than when grain angle was calculated for centre in the individual stud.

If it were feasible to measure the spiral grain angle under bark (GAub) on a harvester and/or at the sawmill it would be possible to calculate whether or not a log is suitable as a saw log.

In conclusion, the statistical models including GAslope (change of grain angle in degrees from pith to bark, measured in °/meter) and taper of log will provide a sufficient basis for decisions regarding whether a log is suitable for the purpose of sawing or should be used for other purposes. Statistical models can also take into account sawing patterns, for calculation and prediction of twist. The distance from pith to centre of stud will make the relation between log data (GAub, diameter and taper of log) and the twist of sawn wood stronger.

The results show that if logs with GAslope under -36°/m and over 5°/m were rejected the relative amount of rejected studs was reduced by 60% at 10% moisture content and by much more at a moisture content of 18%.

9. Discussion and concluding remarks

9.1 Discussion and conclusions

In the present study the main focus was on the formation of spiral grain in Norway spruce (*Picea abies*) and the effect of twist in sawn timber. The relation between spiral grain angle and ring number from pith was used to explain how spiral grain was related to different biological factors. The same analysis was made for grain angle and distance from pith to explain how spiral grain was related to the timber quality factor twist.

The correlation between grain angle and ring number from pith was used to study the influence of silvicultural treatment, height in tree and size of tree in the stand. The relation between grain angle and distance from pith is of importance for practical use of wood in building constructions. This can be used to decide whether a log is suitable for further processing.

Linear regression and linear multiple regression analysis were used to describe and analyse these relations for spiral grain angle. The study also indicate that it is possible to improve wood quality removing trees with severe grain angle already at the time of first thinning, if the age and diameter of the trees are known.

Typical pattern for spiral grain formation.

The spiral grain angle culminated between the 4^{th} and 8^{th} annual rings, about 15 to 20 mm from pith, with a left handed helix and a mean grain angle of 3°. After the culmination point there was an almost linear change. This was formed in most of every individual tree in regard to increasing ring number as well as increasing distance from pith. For the relation between grain angle and increasing ring number from pith this is in a accordance with Danborg (1994) and Jensen (1994) who showed similar results for stands of Norway spruce younger than 50 years. This linear change (Gjerdrum, Säll & StorØ 2000) was as a mean a slight

decrease of about –0.05° per annual year ring or 0.025° per mm in radial direction.
For the majority of logs the helix was right handed in the 100th annual ring. The grain angle inclination according to the log axis was at that time –1°.

The standard deviation for the grain angle increased from 1° close to pith to 3° at the 100th annual ring (150 mm from pith), showing that the variation increased with tree age. Two thirds of the trees had a grain angle under bark between -4° and 2° at the 100th annual ring. The fact that two thirds of the trees exhibit the general pattern is in accordance with Danborg (1994). Every tree has its own spiral grain pattern (Champion 1924, Northcott 1957, Krempl 1970, Danborg 1994, Pape 1999 a).

One reason for the individual spiral grain pattern in a certain tree is due to genetic variation. However it is also evident that the environments close to the tree are of importance for spiral grain pattern (Subsection 1.6.2). In comparison to even stands, uneven stands seems to have more of trees that have a left-handed helix (Rault & Marsh 1952, Elliot 1958, Lowery 1967, Wellner & Lowery 1967, Sjömar 1988). Thus, silviculture is very important for the formation of spiral grain.

The knowledge that these left-handed helix trees are inappropriate in building constructions has been well known for centuries (Polhem 1739 and 1740, Sjömar 1988). Today there is a trend in European silviculture against using more uneven and uneven aged stands. Since this might be detrimental for the wood quality further studies concerning this is urgent.

Spiral grain pattern in different stands.
There was a significant effect of the stand on grain angle. In some stands there was a large variation between trees (Figure 4.4). There was interplay between large or small changes in grain angle per annual ring, and the width of the annual rings. This results in sharp or low decreases in grain angle for every distance unit in a radial direction if the annual rings are narrow or wide. If the annual ring width is small (< 0.5 mm) the decrease of the grain angle in radial direction (°/mm) can be marked negative. This can be seen in co-dominant and particularly in intermediate trees. These trees are predisposed to produce sawn wood of poor quality since they will twist to the right.

Thinning regimes and thinning strength seems to affect the development of spiral grain. Grain angle decreased more slowly from pith and outwards in stands that have been subjected to strong thinning. This might be an effect of increased radial growth since Danborg (1994) and Pape (1999 a) found similar results for Norway spruce when diameter growth increased. Thinned trees get better supply of water and nutrients than unthinned. Rudinsky & Vité (1959) showed that release of suppressed trees in thinning operations improved supplies of water and this resulted in increasing spiral grain angle. Thus, improved water supply might explain why thinned trees in the present study increased their spiral grain angles.

Spiral grain pattern and change with tree size.
Within the same stand there was a tendency that the grain angle decreased more from pith to bark for small trees than large ones. This was more pronounced, when looking at the distance from pith rather than for increasing ring number. Vité (1959) found similar results between poorly growing trees and fast growing trees with wide growth rings for *Pinus ponderosa* and *Abies concolor*.

The highest trees in the dominant tree class are also the largest trees. These trees have the largest annual ring width. In the present study there was no clear relation between ring width and grain angle (Subsection 7.4.3) in accordance with Krempl (1970) and Jensen (1994).

Water availability can been shown to affect both growth rates and grain angles (Elliot 1958, Rudinsky & Vité 1959). The supply for uptake of water and nutrients is also affected by the size and position of a tree. The reason why the grain angle was affected might be the fact that such trees often are growing close to the forest border or an open area. Such trees are for example more exposed to wind and snow which might affect properties (e.g. grain angle). The canopy of the border trees will also be directed towards the open area. This will probably also give these asymmetric trees more compression wood which result in that these trees give more spring and bow in sawn wood.

There seems to be a number of trees in all sizes that have undesired grain angle. However, from this study it was not possible to find any tree parameter that could be used to identify and subsequently remove these trees.

In a future project it will be of great interest to study why some trees deviate from the normal spiral grain pattern. It would also be favourable if methods could be developed so that these trees could be removed.

Spiral grain pattern in butt-, middle- and top-logs.

There was a tendency that the culmination point for spiral grain occurred at a higher ring number from pith with increasing height in tree. Danborg (1994) showed similar results. This culmination occurred in the present study as a mean at ring number four, 4 m above stump, and at ring number eight 20 meter above stump.

After its culmination the grain angle decreased more rapidly higher up in the tree. For example the mean decrease of grain angle was – 0.023°/mm in butt-logs and – 0.039°/mm in top-logs. Based on the results obtained in this thesis (Section 8.5) butt-logs will on average produce only smaller amounts of twist prone sawn wood, while sawn wood from top-logs is more disposed to twist. If increasing slope of grain angle is even more pronounced in the very top-log in mature trees, this will result in large amounts of wood that is predisposed to twist. However, more studies are needed to be able to predict whether the highest top-logs in mature trees are undesired quality for sawn wood.

Grain angle under bark at first thinning and clear cutting.

There was a significant relation between the grain angles at different ages in individual trees. This means that there is a possibility, at the time of the thinning operation, of removing trees that will have undesired grain angles at the time of clear cutting. Since there was no relation between grain angle under bark and the mean annual ring width, there can be other external signs or characters to help decide which trees will be removed at time of thinning. There are practical instruments available on the market for measuring grain angle under bark.

The methods we normally practice in Scandinavian silviculture will probably result in Norway spruce stands with good quality concerning grain angle and risk for twist in sawn wood. If the stand is established with at least 2000 seedlings/ha, cleaning and normal thinning operations are made, this will result in a dense and even stand, ending up with 600 to 1200 stems per hectare. Stands of that structure seem to be favourable for reducing large grain angles.

Today, however, wee often mix high qualitative timber with logs that have extreme spiral grain angles. Such logs were not acceptable in earlier times (Polhem 1739 and 1740, Sjömar 1988). The timber men in earlier centuries left the trees with extreme spiral grain standing in the forest.

Tree´s diameter (DBH) and grain angle under bark is probably valuable parameters in future projects regarding wood quality.

Prediction of twist.

The level of twist was highly correlated to the degree of spiral grain and moisture content in wood. Studs were sawn from the selected logs in this study, and twist was measured at different moisture content. This study showed that 60% to 90% of twist could be explained by spiral grain in logs, when moisture content was decreased to 10%. Several recent reports are in accordance with these results (Perstorper et al. 1995 and 2001, Dahlblom et al. 1996, Forsberg 1999, Ormarsson 1999, Kliger & Säll (2000), Kliger (2001), Woxblom 1999, Johansson 2001)

In practice the best way to predict twist in logs with a top diameter over 200 mm, is to examine the rate of change of grain angle from bark to pith. This can be easily done by measuring grain angle under bark and log diameter. This has been known for a long time (Polhem 1739 and 1740) but the knowledge seem not to be applied in today's sawmills.

It is obvious that studs sawn closer than 50 mm from pith were greatly predisposed to twist, which has been shown by Mishiro & Booker (1988), Thörnqvist (1990), Perstorper et al. (1995), Danborg (1996), Ormarsson (1999), Woxblom (1999) and Johansson (2001). The core wood with high micro fibril angles in cell walls and the properties which are connected to the juvenile wood explain much of the reasons of warp in studs sawn close to pith (Thörnqvist 1990).

Based on the diameter of log and grain angle under bark, a theoretical grain angle of 3° at 15 mm from pith, the slope of grain angle was calculated. The slope of grain angle was strongly correlated with twist of sawn timber in accordance with Forsberg (1999), Kliger & Säll (2000).

Statistical models including slope of grain angle and taper on log would provide sufficient basis for decisions regarding whether a log is suitable for the purpose of sawing. Statistical models could also take into account sawing patterns, for calculation and prediction of twist. In a future project it would also be important to show why most of the sawn wood coming from the core wood area is in fact straight.

9.2 Concluding remarks

Spiral grain has been used to grade quality of softwood timber for many centuries. Today, when scaling saw timber of softwood in Sweden, spiral grain is still a quality-grading property, VMR 1/99, by The Swedish Timber Measurement Council (Anon 1999). In the quality-grading regulation (VMR/87) (Anon 1981) that were in use until July 1995 in the north of Sweden and until July 1996 in the south of Sweden, the tolerances for spiral grain are smaller that in the new ones. The reason for the increased tolerance for spiral grain is unclear. According to my opinion the regulations have not recognized the importance of spiral grain. The difference between the to grading systems (VMR /87 and VMR 1/99) is considerable, see Table 9.1. A normal taper on logs of 10 mm/m is taken into account to calculate the actual grain angle under bark in the three different log diameters measured at top under bark.

Table 9.1 *Tolerance of spiral grain in former (VMR/87) and current (VMR/1/99) grading regulations for saw timber according to The Swedish Timber Measurement Council. Revolution of spiral grain under bark per 45 dm log length (1 / part of revolution), maximal tolerance of revolution for different timber grades (VMR /87=O/S, V and VI and for VMR 1/99= 1,2,3 and 4), maximal grain angle under bark on logs corresponding to revolution per 45 dm log length for different top diameters (degrees).*

Grading regulations with quality classes		Max. revolution per 45 dm log length	Max. grain angle (deg) under bark. top diameter on log		
VMR/87	VMR 1/99		20 cm	30 cm	40 cm
Special		1/8	1.1	1.6	2.1
O/S		1/4	2.2	3.2	4.3
	1	1/2	4.5	6.5	8.5
V	2,3	1/1	9.0	13	17
VI	4	> 1/1	> 9.0	> 13	> 17

The limits of maximum allowed spiral grain in the best grades, Special and O/S in VMR/87, corresponds to the limits of tolerance for non-twisting sawn wood found in the present investigation. In the VMR/87 system, O/S represented between 50% and 80% of the volume of saw timber, and most of this volume was intended for construction wood. Grade V was the lowest quality of construction wood. The quality of grade VI was poor to use as sawn wood and the timber was therefor often paid less than pulpwood.

In the VMR 1/99 system, grades number 1 represents timber for high quality joinery. This is a minor part of the total volume of sawn timber especially in the south of Sweden. (In some price lists, grade number 1 is therefor excluded). The largest proportions of timber are found within grades number 2 and 3. Such timber are intended both for joinery and construction wood. The lowest quality, grade number 4, is proposed for low quality use such us packing-wood.

Spiral grain angles of 10° or more have not only poor shape stability but also 50% inferior modulus of elasticity and strength reduction in bending (Subsection 1.6.8). Grade 3 (VMR 1/99) is recommended for purposes where strength and shape stability is important properties, even though grain angle under bark could be 9 - 17°. Spiral grain angles over 10° are seldom found in Norway spruce timber. Studs sawn sawn from such logs will twist much more than the end-user's requirement, when they are dried.

Even if kilns with sophisticated drying schedules are used, it is probably impossible to make studs from logs with large spiral grains that will be acceptable for the end user. Investment cost for such kilns that are intended to season shape stable wood is high and can probably not be economically justified. I suggest that is more economically favourable, if logs with large spiral grain angles under bark are removed early as possible in the forest stands and used for e.g. pulp wood.

Logs with large spiral grain have today the same price per m³ as logs of good quality timber with low spiral grain. The largest single cost item for sawmills, on average 65% (Grönlund 1992), is cost of timber. Therefor it should be an important task for sawmills to reduce quantities of logs with unacceptably low qualities, such as high spiral grain.

In Sweden the turnover for logs with spiral grain under bark > 4 degrees is more than 500 million SEK every year. After being processed in the sawmills the turnover is considerably larger. The final product is inferior sawn wood at a price that customers feel is too high.

However, on the basis of findings in this thesis and other studies on Norway spruce during recent years, it can be concluded that there are in fact a number of very useful changes that could be used in practice, to diminish the problems with distortion of wood for joineries and structural timber (Danborg 1994, Perstorper et al. 1995 and 2001, Dahlblom et al. 1996 and 2000, Forsberg 1999, Ormarsson 1999, Pape 1999 b, Kliger & Säll 2000, Kliger 2001, Woxblom 1999, Johansson 2002, Öhman 2002).

One of these is that it is of great importance to reduce tolerances regarding spiral grain in the presently used Swedish grading system.

To make it possible to remove poor quality logs methods to measure spiral grain under bark on logs, both on harvesters and at the sawmills before sawing should be developed. The data can then be used to calculate and describe shape and material properties in sawn and dried wood.

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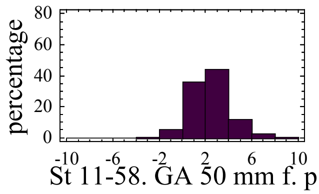
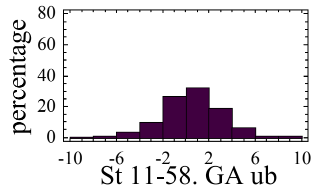
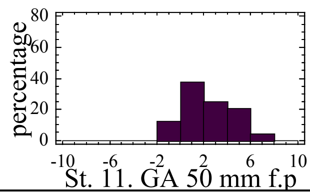
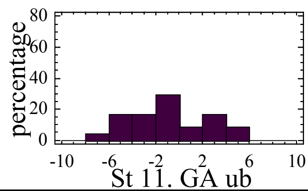
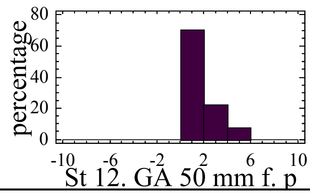
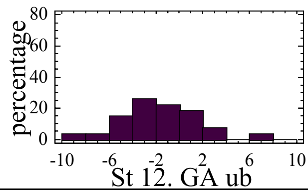
Appendix A

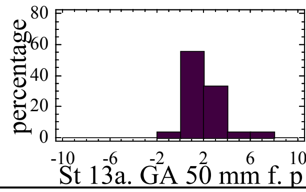
Grain angle under bark at first thinning and clear cutting

In this Appendix, results from measurements of grain angle 50 mm from pith and grain angle under bark are shown. The results are expressed in histograms showing relative frequency (%) with an interval of 2°. The histograms show the results for the total number of logs from each stand. The figures labelled with (a) show the grain angle 50 mm from pith and the figures labelled (b) shows grain angle under bark. The theory used to evaluate the measurements and the results for the material is described in Chapter 7.

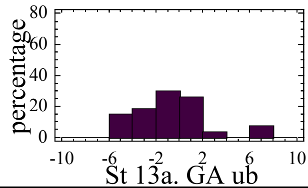
	
*(a). **Stand 11-58**. Relative frequency for GA 50 mm from pith for 390 logs.*	*(b). **Stand 11-58**. Relative frequency for GA under bark for 392 logs.*
	
*(a). **Stand 11**. Relative frequency for GA 50 mm from pith for 24 logs.*	*(b). **Stand 11.** Relative frequency for GA under bark for 24 logs.*
	
*(a). **Stand 12**. Relative frequency for GA 50 mm from pith for 27 logs.*	*(b). **Stand 12**. Relative frequency for GA under bark for 27 logs.*

(a) **(b)**

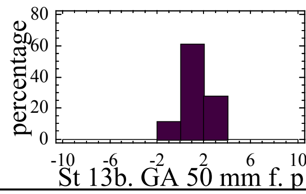
Figure A.1: Relative frequency for grain angle 50 mm from pith and grain angle under bark for butt-, middle- and top-logs in stand. **(a)** Grain angle 50 mm from pith, **(b)** Grain angle under bark.



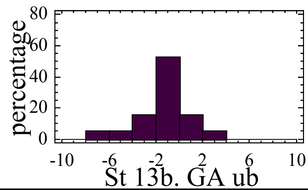
*(a). **Stand 13a**. Relative frequency for GA 50 mm from pith for 26 logs.*



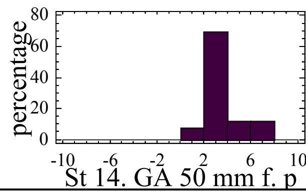
*(b). **Stand 13a**. Relative frequency for GA under bark for 27 logs.*



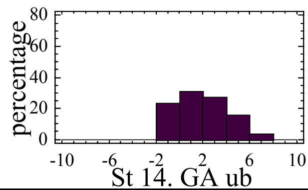
*(a). **Stand 13b.** Relative frequency for GA 50 mm from pith for 18 logs.*



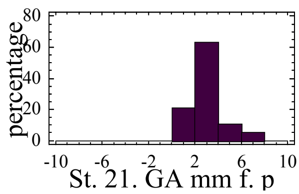
*(b). **Stand 13b**. Relative frequency for GA under bark for 19 logs.*



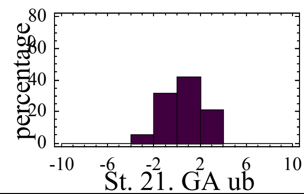
*(a). **Stand 14**. Relative frequency for GA 50 mm from pith for 26 logs.*



*(b). **Stand 14**. Relative frequency for GA under bark for 26 logs.*



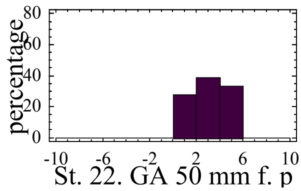
*(a). **Stand 21**. Relative frequency for GA 50 mm from pith for 19 logs.*



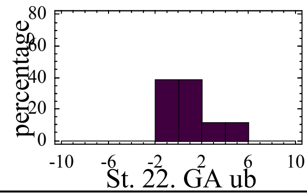
*(b). **Stand 21**. Relative frequency for GA under bark for 19 logs.*

(a) **(b)**

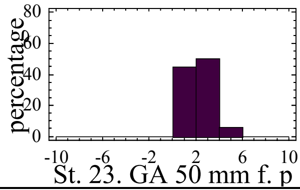
Figure A.2. Relative frequency for grain angle 50 mm from pith and grain angle under bark for butt-, middle- and top-logs in stand. **(a)** Grain angle 50 mm from pith, **(b)** Grain angle under bark.



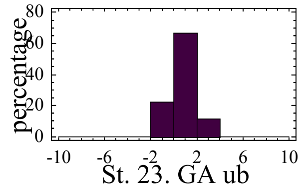
*(a). **Stand 22**. Relative frequency for GA 50 mm from pith for 18 logs.*



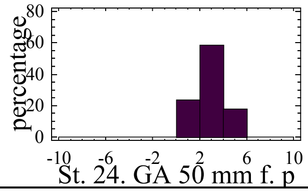
*(b). **Stand 22**. Relative frequency for GA under bark for 18 logs.*



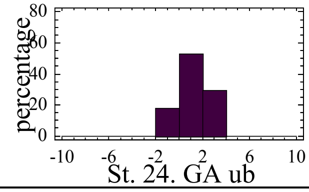
*(a). **Stand 23**. Relative frequency for GA 50 mm from pith for 18 logs.*



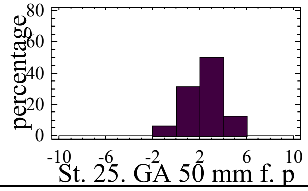
*(b). **Stand 23**. Relative frequency for GA under bark for 18 logs.*



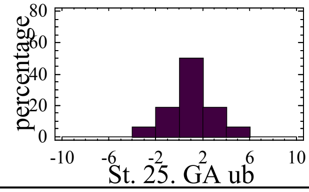
*(a). **Stand 24**. Relative frequency for GA 50 mm from pith for 17 logs.*



*(b). **Stand 24**. Relative frequency for GA under bark for 17 logs.*



*(a). **Stand 25**. Relative frequency for GA 50 mm from pith for 16 logs.*



*(b). **Stand 25**. Relative frequency for GA under bark for 16 logs.*

(a) **(b)**

Figure A.3. Relative frequency for grain angle 50 mm from pith and grain angle under bark for butt-, middle- and top-logs in stand. **(a)** Grain angle 50 mm from pith, **(b)** Grain angle under bark.

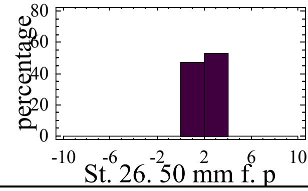
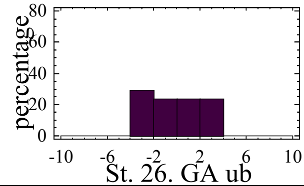
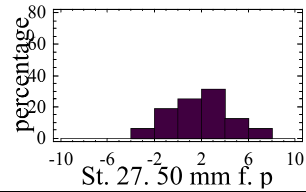
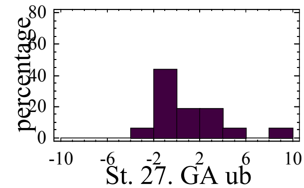
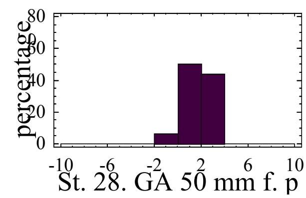
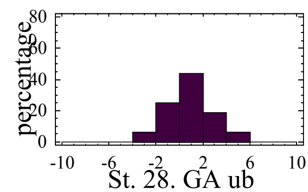
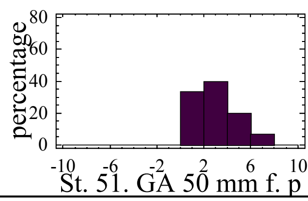
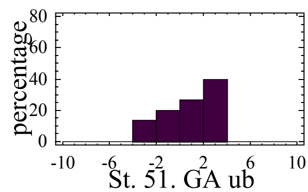
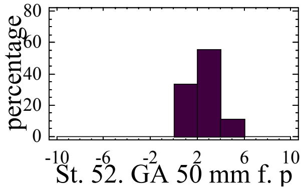
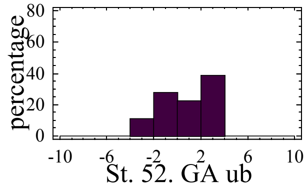
	
*(a). **Stand 26**. Relative frequency for GA 50 mm from pith for 17 logs.*	*(b). **Stand 26**. Relative frequency for GA under bark for 17 logs.*
	
*(a). **Stand 27**. Relative frequency for GA 50 mm from pith for 16 logs.*	*(b). **Stand 27**. Relative frequency for GA under bark for 16 logs.*
	
*(a). **Stand 28**. Relative frequency for GA 50 mm from pith for 16 logs.*	*(b). **Stand 28**. Relative frequency for GA under bark for 16 logs.*
	
*(a). **Stand 51**. Relative frequency for GA 50 mm from pith for 15 logs.*	*(b). **Stand 51**. Relative frequency for GA under bark for 15 logs.*
(a)	**(b)**

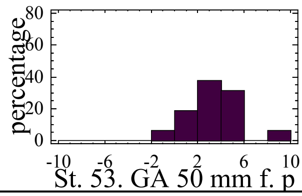
Figure A.4. Relative frequency for grain angle 50 mm from pith and grain angle under bark for butt-, middle- and top-logs in stand. **(a)** Grain angle 50 mm from pith, **(b)** Grain angle under bark.



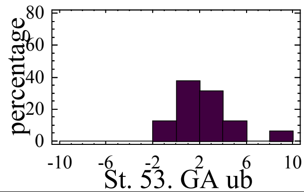
*(a). **Stand 52**. Relative frequency for GA 50 mm from pith for 18 logs.*



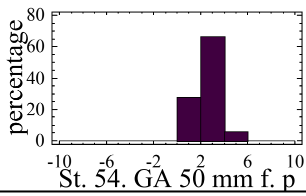
*(b). **Stand 52**. Relative frequency for GA under bark for 18 logs.*



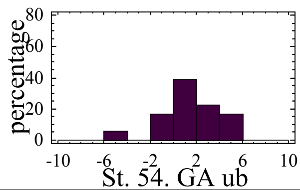
*(a). **Stand 53**. Relative frequency for GA 50 mm from pith for 16 logs.*



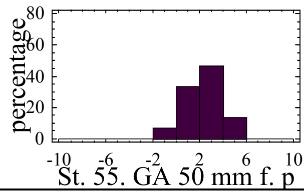
*(b). **Stand 53**. Relative frequency for GA under bark for 16 logs.*



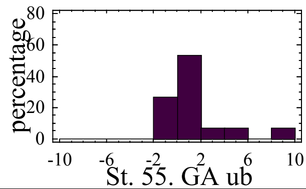
*(a). **Stand 54**. Relative frequency for GA 50 mm from pith for 18 logs.*



*(b). **Stand 54**. Relative frequency for GA under bark for 18 logs.*



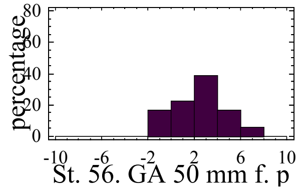
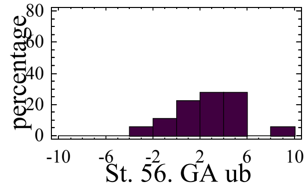
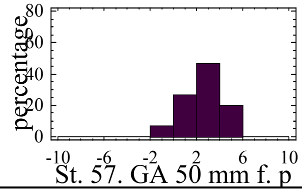
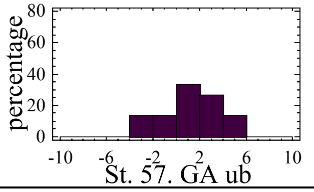
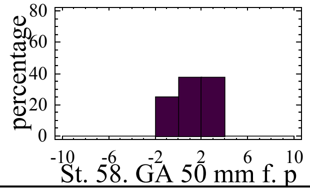
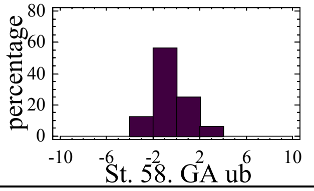
*(a). **Stand 55**. Relative frequency for GA 50 mm from pith for 15 logs.*



*(b). **Stand 55**. Relative frequency for GA under bark for 15 logs.*

(a) **(b)**

Figure A.5. Relative frequency for grain angle 50 mm from pith and grain angle under bark for butt-, middle- and top-logs in stand. **(a)** Grain angle 50 mm from pith, **(b)** Grain angle under bark.

	
*(a). **Stand 56**. Relative frequency for GA 50 mm from pith for 18 logs.*	*(b). **Stand 56.** Relative frequency for GA under bark for 18 logs.*
	
*(a). **Stand 57**. Relative frequency for GA 50 mm from pith for 15 logs.*	*(b). **Stand 57.** Relative frequency for GA under bark for 15 logs.*
	
*(a). **Stand 58**. Relative frequency for GA 50 mm from pith for 16 logs.*	*(b). **Stand 58**. Relative frequency for GA under bark for 16 logs.*

(a) **(b)**

Figure A.6. Relative frequency for grain angle 50 mm from pith and grain angle under bark for butt-, middle- and top-logs in stand. **(a)** Grain angle 50 mm from pith, **(b)** Grain angle under bark.

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