INFLUENCE OF ACOUSTIC VELOCITY, DENSITY, AND KNOTS ON THE STIFFNESS GRADE OUTTURN OF RADIATA PINE LOGS

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Abstract. The prediction of log-average lumber modulus of elasticity (MOE) from log measurements of acoustic velocity, green density, heartwood content, and branch and whorl variables was evaluated for green and kiln-dried boards of unpruned second and third logs of mature radiata pine. The use of principal component analysis showed there were strong associations between the log acoustic velocity and branch size variables, the number of branches and whorls and mean internode length, and the green density and heartwood content. These relationships were reflected in the regression models that showed good predictions of log-average green and kiln-dried board MOE from log acoustic velocity and green density or heartwood content with only a small contribution from branch and whorl variables.

Keywords: Acoustic velocity, density, knots, modulus of elasticity, radiata pine.

INTRODUCTION

Stiffness is perhaps the most critical parameter for a significant portion of the forest resource, and in recent years, several acoustic tools have been developed to estimate the stiffness grade yield of logs. These have segregated logs on the basis of acoustic velocity, but acoustic velocity is only a moderate predictor of the average lumber stiffness of individual radiata pine logs (Tsehaye et al 2000; Dickson et al 2004). Other factors such as the green density and the presence of knots are known to affect the stiffness of lumber (Cown et al 1995) and might be useful in improving the predictions of average lumber stiffness.

The stiffness or modulus of elasticity (MOE) is calculated from the acoustic velocity (v) and the mass density (ρ) and in the direction of the axis of a rod-like object such as a very slender log is given by the equation:

$$\mathrm{MOE} = v^2\rho \qquad (1)$$

The relationship in Eq 1 assumes the acoustic wave of interest is a quasi-longitudinal wave propagating along the length of the object, and although this is accurate for rod-like objects with isotropic and uniform material properties, the assumptions do not necessarily apply to logs. The presence of knots and associated grain deviations in the logs is expected to result in deviations from the relationship.

Qualitatively we expect the material properties of stiffness and density to change around knots. If the grain deviates from being along the length of the log, we would expect the changes in stiffness parallel to the log axis to affect both the acoustic velocity and the MOE such that Eq 1 is still valid. In other words, the acoustic velocity and the green density will tell us about these stiffness changes. However, the assumption that the log is very slender is not exactly true, and we expect some deviation from Eq 1.

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In the extreme case, when the acoustic wavelength is much shorter than the diameter of the log, we find for uniform material properties that the acoustic velocity is given by the equation:

$$C = v^2 \rho \tag{2}$$

where the term C is the elastic stiffness in the direction of the log axis (Bucur 1995). The difference between the MOE and C is from the influence of the other engineering elastic parameters of the wood. Because wood is anisotropic and has many other elastic parameters that characterize it, the difference between the MOE and C can range from a few to over 20% depending on the grain direction. Using the elastic parameters for softwood with a MOE along the grain of 10 GPa, as given by Bodig and Goodman (1973), we find that C/MOE along the grain is 1.05 and that C/MOE perpendicular to the grain is 1.25.

Therefore, for a real log, we expect the relationship among the MOE, the acoustic velocity, and the density of the lumber to be given by the equation:

$$\text{MOE} = \alpha\, v^2 \rho \tag{3}$$

where α is a correction factor that depends on other factors not accounted for in Eq 1 such as the presence of knots and associated grain deviations.

In this study, the branching characteristics of the logs as well as the acoustic velocity, green density, and heartwood content were evaluated as predictors of the average lumber MOE of the logs. Unpruned second and third logs of 36 mature radiata pine trees were measured and then processed into kiln-dried structural lumber. The relationships among the log variables were evaluated and regression models developed to determine the contribution of the log variables to the prediction of green and kiln-dried board MOE.

MATERIALS AND METHODS

Wood Source

Thirty-six trees from Crater Block forest and Tarawera forest in central North Island, New Zealand (Table 1) were selected to provide a wide range of standing tree acoustic velocity, branch index and internode length, and heartwood content. The standing tree acoustic velocity was measured using the Director ST300 (Fiber-gen), the branch index and internode length were visually assessed, and the heartwood content and the outer wood basic density were measured from 5-mm increment cores at breast height (1.4 m).

The trees were felled and the second and third logs (length 5 m) were cut above the pruned butt log. The second and third logs were measured immediately after felling for acoustic velocity using the Director HM200 (Fiber-gen), and 50-mm-thick discs were cut from the log ends for the measurement of green density and heartwood content. The branch diameters, internode lengths, and whorl lengths of the second and third logs were measured and used to calculate the branch and whorl variables listed in Table 2.

Table 1. *Stand location and history.*

Forest	Year planted	Final stocking (stems/ha)	Pruning height (m)	Seed lot
Crater Block	1979	158	4.0	Climbing select GF 7
Tarawera	1981	268	6.9	850 mixed GF 14

Table 2. *Branch and whorl variables used to describe the log branching patterns.*

Variable	Definition
Branch variables	
Number of branches	Number of branches in log
Number of branches per whorl	Average number of branches per whorl in log
Mean branch diameter	Average branch diameter in log
Maximum branch diameter	Maximum branch diameter in log
Branch index	Average of the largest branch in each log quadrant
Branch basal area	Sum of basal area of branches in log
Branch basal area index	Sum of basal area of largest branch in each whorl
Branch area ratio	Branch basal area divided by surface area of log
Whorl variables	
Number of whorls	Number of whorls in log
Mean whorl depth	Average whorl depth in log
Mean internode length	Average internode length in log

Log Processing

The second and third logs were cut into lumber of 100 × 50 mm cross-section and 5 m length. The larger logs were cut using a sawing-around pattern, and the smaller logs were cut using a cant-sawing pattern.

The lumber was kiln-dried to 12% MC using a standard 90/60°C ACT kiln schedule with the normal 4-h final steaming at 100°C/100% RH. The kiln-dried lumber was dressed to cross-section dimensions of 90 × 45 mm.

Lumber Measurements

The MOE for each board was measured using acoustic resonance techniques and a third-point-bending machine stress grader.

For the green boards, the acoustic resonance frequencies were measured by placing the boards on two crosswise supporting beams, hitting one end of the boards with a hammer, and measuring the resulting longitudinal vibrations using the Director HM200. The measured resonance frequencies and the length of the board were used by the Director HM200 to determine the acoustic velocity of the board. Each board was weighed and dimensions taken to calculate the green density of the board. The acoustic velocity and green density were used to calculate the acoustic MOE of the board.

For the kiln-dried and dressed boards, the acoustic resonance frequencies were determined in the same way, except that the vibrations of the boards were measured by placing a microphone near the end of the board to record the sound made by the board vibration. The acoustic velocity was determined by transforming the microphone time-domain signal to the frequency domain using a Digital Fourier Transform, locating the frequency of the fundamental longitudinal resonance, and factoring in the length of the board. Like with the green state, the density was determined from the weight and dimensions of the kiln-dried boards, enabling the acoustic MOE to be calculated.

The kiln-dried and dressed boards were machine stress graded (MSG) using a Plessey Computermatic machine stress grader. The MOE of the boards was measured as a plank over a span of about 90 cm using a third-point-bending method. The boards were linearly fed through the machine and the MOE measured at 15-cm intervals. The first and last 70 cm of the boards were not measured. The MOE measurements are averaged to obtain the board average MOE.

Statistical Analysis

The log variables were compared for the second and third logs from the forest sites using the SAS procedure PROC GLM (SAS Institute Inc 2000) with pairwise t-tests equivalent to Fisher's least significant difference test in the case of equal cell sizes.

The sources of variation for the log variables were analyzed using the SAS procedure PROC MIXED (Littell et al 1996) with the model:

$$y_{ijk} = \mu + f_i + t_{j(i)} + e_{k(ij)} \qquad (4)$$

where y_{ijk} denotes the log variable measured on log k of tree j in forest i; μ is the overall population mean; f_i represents the effect of forest (fixed), $t_{j(i)}$ the effect of trees (random), and $e_{k(ij)}$ represents the error term for the log measurements.

The relationships among the log variables were evaluated using principal component analysis, which provided the means to simplify the data by reducing the number of log variables to a small number of principal components (linear combinations of the original log variables) using the SAS procedure PROC PRINCOMP (SAS Institute Inc 2000).

Correlations between the log variables and the log-average green and kiln-dried board MOE were calculated using the SAS procedure PROC CORR (SAS Institute Inc 2000).

Stepwise regression equations for the log-average green and kiln-dried board MOE were fitted using the log variables as potential independent variables. The SAS procedure PROC REG (SAS Institute Inc 2000) was used for this analysis. A p level of 0.05 was used for selecting variables to enter the regression or removing variables.

RESULTS AND DISCUSSION

Standing Tree Variables

The standing tree selection for a wide range of Director ST300 acoustic velocity and visual branch index (BIX) resulted in a wide range of outer wood basic density and diameter at breast height (DBH) (Table 3). Trees with higher Director ST300 acoustic velocity had higher outer wood basic density (r = 0.70, $p < 0.01$) and trees with larger visual BIX were larger in diameter (DBH) (r = 0.71, $p < 0.01$). The standing tree selection provided a wide range of heartwood content, but the distribution was skewed toward the lower end of the range (Table 3).

Log Variables

The standing tree selection provided a wide range of second and third log Director HM200 acoustic velocity, heartwood content, and BIX (Table 4).

There was a strong correlation between the Director ST300 standing tree and Director HM200 log acoustic velocity (r = 0.74, $p < 0.01$), the heartwood content of the breast height increment cores and combined second and third logs (r = 0.91), and the visual BIX of the standing tree and measured BIX of the second and third logs (r = 0.68 and 0.84, respectively, $p < 0.01$).

Table 3. *Standing tree variables: mean, standard deviation (SD), and range for the individual trees (n = 36).*

Variable	Mean	SD	Range
Diameter at breast height (mm)	610	97	422 – 797
Director ST300 velocity (km/s)	4.0	0.4	3.3 – 4.7
Visual branch index	1.9	0.8	1 – 3
Heartwood (%)	23	15	5 – 75
Outer wood basic density (kg/m^3)	433	46	350 – 527

The radiata pine seed lots and the final stockings used at the two forest sites (Table 1) provided a wider range of branch and whorl variable log values. The climbing select (GF 7) seed lot used at Crater Block had a greater number of branch whorls, longer mean whorl depth, and shorter mean internode length (MIL) in the second logs compared with the 850 mixed (GF 14) seed lot at Tarawera forest (Table 5). The Crater Block also had larger maximum branch diameter in the second logs because of the lower final stocking at this site.

The seed orchard clones of the 850 mixed (GF 14) seed lot at Tarawera forest were selected for short-internode ”multinodal” branching habit and light, wide-angled branching. The mean internode lengths of the second and third logs were therefore relatively short for radiata pine (Table 4).

The branch size of the second logs from Crater Block and Tarawera forest was typical of radiata pine from sheltered sites in New Zealand. The mean branch diameter, BIX, and maximum branch diameter were similar to mature radiata pine from sheltered sites in the Wairarapa region (Watt et al 2005).

Table 4. *Log variables: mean, standard deviation (SD), and range for the individual second and third logs (n = 71).*

Variable	Mean	SD	Range
Director HM200 velocity (km/s)	2.9	0.3	2.4 – 3.6
Green density (kg/m^3)	913	65	695 – 1012
Heartwood (%)	22	9	11 – 60
Number of branches	40	10	18 – 66
Number of branches per whorl	5	1	4 – 8
Mean branch diameter (cm)	3.1	0.9	1.5 – 5.0
Maximum branch diameter (cm)	6.6	2.5	2.5 – 12.5
Branch index (cm)	5.5	1.8	2.5 – 9.8
Branch basal area (cm^2)	386	216	70 – 1020
Branch basal area index (cm^2)	152	93	25 – 412
Branch area ratio (%)	0.3	0.1	0.1 – 0.6
Number of whorls	8	2	4 – 13
Mean whorl depth (m)	0.23	0.06	0.10 – 0.40
Mean internode length (m)	0.40	0.15	0.21 – 0.95

Table 5. *Log variables: comparison of the forest site average values for the second and third logs (n = 35 and 36, respectively).*[a]

Variable	Crater Block		Tarawera	
	Second log	Third log	Second log	Third log
Director HM200 velocity (km/s)	2.9 a	2.9 a	3.0 a	3.0 a
Green density (kg/m^3)	916 a	933 a	899 a	906 a
Heartwood (%)	20 a	20 a	25 a	25 a
Number of branches	41 a	45 a	33 b	43 a
Number of branches per whorl	5 a	5 a	5 a	5 a
Mean branch diameter (cm)	2.9 a	3.1 a	2.9 a	3.3 a
Maximum branch diameter (cm)	6.7 ab	7.3 a	5.2 b	7.1 a
Branch index (cm)	5.4 ab	6.0 a	4.5 b	5.9 a
Branch basal area (cm^2)	371 ab	445 a	258 b	472 a
Branch basal area index (cm^2)	152 a	189 a	90 b	176 a
Branch area ratio (%)	0.2 b	0.3 a	0.2 b	0.3 a
Number of whorls	8 a	9 a	6 b	8 a
Mean whorl depth (m)	0.26 a	0.25 ab	0.21 b	0.21 b
Mean internode length (m)	0.34 b	0.36 b	0.46 a	0.42 ab

[a] Values followed by the same letter do not differ significantly ($p > 0.05$).

The effect of the forest sites and seed lots on the log variables were, however, small compared with the variation among the individual trees and second and third logs. The Crater Block and Tarawera forest sites and seed lots explained less than 15% of the variation in the log variables (Table 6).

The differences among the individual trees explained more than 80% of the variation in the log Director HM200 acoustic velocity, green density, and heartwood content and between 30 – 70% of the variation in the log branch and whorl variables (Table 6). Of the log branch and whorl variables, the mean branch diameter, BIX, and MIL, were the most affected by the differences among the individual trees.

The differences between the second and third logs within the trees explained between 18 – 70% of the variation in the log branch and whorl variables (Table 6). The number of branches, whorls, and branches per whorl and the branch area ratio (BAR) were the most affected by the differences between the second and third logs.

Table 6. *Log variables: sources of variation for the individual logs (n = 71).*

Variable	Variance components (%)		
	Forest	Tree	Log
Director HM200 velocity	0	95	5
Green density	1	93	6
Heartwood	8	86	6
Number of branches	8	37	55
Number of branches per whorl	0	36	64
Mean branch diameter	0	72	28
Maximum branch diameter	1	48	51
Branch index	0	66	34
Branch basal area	0	55	45
Branch basal area index	4	53	43
Branch area ratio	0	31	69
Number of whorls	12	30	58
Mean whorl depth	14	37	49
Mean internode length	13	69	18

Relationships Among Log Variables

The relationships among the log variables were evaluated using principal component analysis (PCA). The PCA reduced the 13 log variables to 3 principal components (PC) that explained 79% of the variation. The loading plot for the first and second PCs (Fig 1) shows the log branch size variables and acoustic velocity were related in the first PC (PC1, 44% of variation) and the number of branches and whorls and the MIL were related in the second principal component (PC2, 21% of variation). The first and second PCs suggest the log acoustic velocity is influenced by the branch size rather than the whorl frequency in radiata pine second and third logs with the log acoustic velocity increasing with smaller diameter branches. This is consistent with the negative correlation observed by Sandoz (1989) between the acoustic velocity and the total diameter of visible knots in spruce beams. The loading plot of the second and third PCs (Fig 2) relates the log green density and heartwood content (PC3, 14% of variation).

The PCs show the log branch basal area variables BBA, BBAI, and BAR are similar (Fig 1) as are the maximum branch size variables: BIX and maximum branch diameter (Fig 1), and the branch and whorl count variables: number of branches and whorls (Fig 1). Of these, the BBAI, maximum branch diameter, and number of whorls are the easiest log variables to measure.

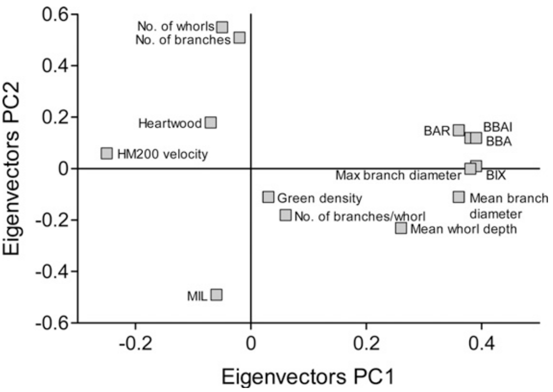

Figure 1. Loading plot of the log variables for the first and second principal components (PC1 and PC2).

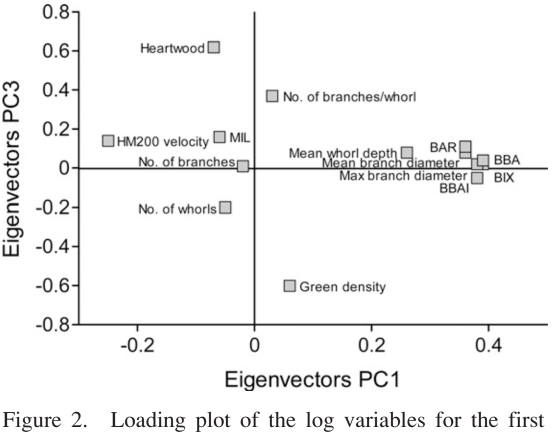

Figure 2. Loading plot of the log variables for the first and third principal components (PC1 and PC3).

Relationships between Log Variables and Board MOE

The relationships between the log variables and the log-average board MOE were evaluated using correlation and multiple linear regression analysis.

The correlations show the log-average green and kiln-dried board MOE increased with higher log acoustic velocity, green density, and smaller branch size (Table 7). The correlation of branch size with board MOE can be explained by the association of branch size with log acoustic velocity (Fig 1). Partial correlation showed that at a given log acoustic velocity, branch size had no effect on the board MOE (Table 8). However, an increase in the green density, and a reduction in the heartwood content and the number of branches and branch whorls per log, did increase the board MOE at a given log acoustic velocity (Table 8).

Multiple linear regression analysis using the log acoustic velocity, green density, heartwood content, and branch and whorl variables as independent variables gave good predictions of log-average green and kiln-dried board MOE (Tables 9 and 10). The log acoustic velocity, green density, and heartwood content were the main contributors to the regression models. The green density and heartwood content gave similar predictions of log-average green and kiln-dried board MOE when used in combination with log acoustic velocity. This means green density or heartwood content could be used in prediction models, depending on which is easier to measure. The log branch and whorl variables included in the regression models gave only a slight improvement in the model coefficients of determination (R^2) and were related to the number of branches and whorls in the logs. There was no contribution from the branch size variables to the regression models, with the log acoustic velocity accounting for the variation in the log branch size.

The relationship of acoustic velocity with MOE is a squared relationship rather than a linear relationship as shown in the regression models

Table 7. *Correlation coefficients (r) of log variables with log-average green and kiln-dried board MOE (n = 71).*

Variable	Green board acoustic MOE	Kiln-dried board acoustic MOE	Kiln-dried board MSG average-MOE
Director HM200 velocity	0.68**	0.74**	0.70**
Green density	0.30*	0.22	0.27*
Heartwood	−0.24*	−0.16	−0.18
Number of branches	−0.20	−0.13	−0.14
Number of branches per whorl	−0.15	−0.14	−0.15
Mean branch diameter	−0.37**	−0.45**	−0.40**
Maximum branch diameter	−0.33**	−0.39**	−0.33**
Branch index	−0.37**	−0.44**	−0.38**
Branch basal area	−0.43**	−0.49**	−0.44**
Branch basal area index	−0.34**	−0.40**	−0.34**
Branch area ratio	−0.43**	−0.47**	−0.43**
Number of whorls	−0.10	−0.04	−0.05
Mean whorl depth	−0.13	−0.21	−0.18
Mean internode length	0.20	0.18	0.18

* $p < 0.05$; ** $p < 0.01$.
MOE, modulus of elasticity; MSG, machine stress graded.

Table 8. *Partial correlation coefficients (r) of log variables with log-average green and kiln-dried board MOE at the same log acoustic velocity (n = 71).*

Variable	Green board acoustic MOE	Kiln-dried board acoustic MOE	Kiln-dried board MSG average-MOE
Green density	0.63**	0.60**	0.61**
Heartwood	−0.64**	−0.61**	−0.58**
Number of branches	−0.33**	−0.26*	−0.25*
Number of branches per whorl	−0.12	−0.11	−0.12
Mean branch diameter	−0.03	−0.13	−0.07
Maximum branch diameter	0.02	−0.04	0.04
Branch index	0.01	−0.06	0.01
Branch basal area	−0.10	−0.16	−0.11
Branch basal area index	0.01	−0.04	0.02
Branch area ratio	−0.24*	−0.29*	−0.23
Number of whorls	−0.26*	−0.20	−0.19
Mean whorl depth	0.23	0.16	0.17
Mean internode length	0.19	0.16	0.16

* $p < 0.05$; ** $p < 0.01$.
MOE, modulus of elasticity; MSG, machine stress graded.

Table 9. *Log variable coefficients of determination (R^2) in regression equations using log acoustic velocity, green density, and branch and whorl variables for prediction of log-average board acoustic MOE and MSG average MOE.*

Variable	Green board acoustic MOE	Kiln-dried board acoustic MOE	Kiln-dried board MSG average MOE
Model R^2	0.71	0.78	0.68
Director HM200 velocity (partial R^2)	0.47	0.55	0.49
Green density (partial R^2)	0.21	0.16	0.19
Branch basal area (partial R^2)		0.03	
Branch area ratio (partial R^2)		0.02	
Number of whorls (partial R^2)	0.03		
Mean whorl depth (partial R^2)		0.02	

MOE, modulus of elasticity; MSG, machine stress graded.

(Tables 9 and 10). Therefore, the log acoustic MOE (as given by Eq 1), branch and whorl variables were evaluated as predictors of log-average green and kiln-dried board MOE (Table 11). The similar coefficients of determination (R^2) for the regression models using the linear and squared relationships of acoustic velocity (Tables 9, 10, and 11) suggests the

Table 10. *Log variable coefficients of determination (R^2) in regression equations using log acoustic velocity, heartwood, and branch and whorl variables for prediction of log-average board acoustic MOE and MSG average MOE.*

Variable	Green board acoustic MOE	Kiln-dried board acoustic MOE	Kiln-dried board MSG average MOE
Model R^2	0.72	0.73	0.66
Director HM200 velocity (partial R^2)	0.47	0.55	0.49
Heartwood (partial R^2)	0.22	0.16	0.17
Number of whorls (partial R^2)	0.03	0.02	

MOE, modulus of elasticity; MSG, machine stress graded.

Table 11. *Log variable coefficients of determination (R^2) in regression equations using log acoustic MOE (Eq 1) and branch and whorl variables for prediction of log-average board acoustic MOE and MSG average MOE.*

Variable	Green board acoustic MOE	Kiln-dried board acoustic MOE	Kiln-dried board MSG average MOE
Model R^2	0.70	0.79	0.67
Green acoustic MOE (partial R^2)	0.67	0.71	0.67
Number of branches (partial R^2)	0.03		
Branch basal area index (partial R^2)		0.04	
Branch area ratio (partial R^2)		0.02	
Mean whorl depth (partial R^2)		0.02	

MOE, modulus of elasticity; MSG, machine stress graded.

relationship of acoustic velocity with board MOE was approximately linear over the range of green log acoustic velocity.

When the regression models were compared with other studies, the coefficients of determination (R^2) were similar to the log acoustic velocity prediction of radiata pine kiln-dried board MSG average MOE (Tsehaye et al 2000; Dickson et al 2004) and log acoustic MOE prediction of larch kiln-dried board static MOE (Jang 2000).

CONCLUSIONS

There was little benefit from including log branch and whorl variables in regression models of log-average board MOE. The log acoustic velocity and green density or heartwood content provided good predictions of log-average green and kiln-dried board MOE, but the inclusion of branch and whorl variables gave only a slight improvement in the regression model coefficients of determination (R^2 values).

The log acoustic velocity and branch size variables were strongly related, with log acoustic velocity in the regression models accounting for the variation in the log branch size variables. At a given log acoustic velocity, the branch size variables had no effect on the log-average green and kiln-dried board MOE.

The number of branches and whorls in the logs showed some independence from the acoustic velocity, having an effect on the log-average green and kiln-dried board MOE at a given log acoustic velocity. This tended to support the hypothesis that grain deviations around branches might be an important factor, but the inclusion of these variables yielded only slightly improved regression models.

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