Using acoustic tools to improve the efficiency of the forestry wood chain in eastern Canada

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Abstract

The use of acoustic tools at an industrial scale could provide information on the average wood properties of timber supplies and thus help identify timber suitable for Machine-Stress-Rated (MSR) lumber production in Canada. However, a number of challenges remain to be faced before the technology is applied at an industrial scale. We describe the early results of a research programme which aims to address these challenges for four species of the Canadian boreal forest. The strength of the relationship between acoustic velocity in logs and static MOE on 2'x4' (38 x 89 mm) pieces varied between species. In a white spruce (*Picea glauca*) spacing trial, we found a weaker relationship between log velocity and plank stiffness than generally reported (R^2=0.41, n=94 logs). However, the strength of the relationship increased when we accounted for variations in sapwood width (*i.e.* moisture content) and wood density (R^2=0.69). This suggests that sawmills equipped with 3D scanners and scales could obtain more accurate MSR grade predictions from acoustic measurements, particularly in situations where timber supplies are heterogeneous in dimensions and growth rates. Acoustic velocity can be used to predict the likelihood of producing planks of a given MSR grade and, in turn, their expected value.

1 Introduction

As a result of low demand for construction lumber in the U.S. market, the forest industry in eastern Canada has been facing some serious financial difficulties in recent years. Sawmillers, which were largely focused on producing visually-graded lumber, now have to find ways to add value to their products. One potential way to achieve this is to produce Machine-Stress-Rated (MSR) lumber which can be used for structural applications requiring high stiffness and strength.

Operationally, most coniferous species from the boreal forest are harvested, sawn and marketed in the same "spruce-pine-fir" (SPF) group. The main species included in this group are black spruce (*Picea mariana*), white spruce (*Picea glauca*), balsam fir (*Abies balsamea*) and jack pine (*Pinus banksiana*). This implies that in addition to the normal variation in wood properties within a

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species, a significant source of variation is also attributable to differences between species. Balsam fir is the species of the SPF group which has the weakest mechanical properties (Jessome 2000). For this reason, it is generally disregarded as a species which can produce MSR lumber. The other three species can be considered for producing MSR lumber, with black spruce and white spruce generally showing the best potential due to their inherently high mechanical properties.

Despite this variation in wood properties, all species from the group can be visually graded and sold on the construction market. This situation means that the extra handling necessary to sort the trees or logs destined to an MSR production line must be justified by an increase in value. Hence, the inherent variability in wood properties added to the limited difference in value brought by the mechanical grading exercise (see methodology section) means that sawmillers generally choose to focus on visual grades only.

In this context, we hypothesise that acoustic tools, which can be used to measure the stiffness of wood on standing trees or logs, could help sort the wood resource prior to processing. Up until now, little industrial use had been made of acoustic tools in eastern Canada. Because acoustic technology has been tested in various species and areas of the world (e.g. Matheson *et al.* 2002, Carter *et al.* 2006, Wang *et al.* 2007, Mora *et al.* 2009), there is little doubt that it can help predict stiffness and strength in species from the Canadian boreal forest. However, the relationships between acoustic speed, stiffness and, in turn, MSR grades remain to be calibrated. This paper describes the early results of a research programme setup to help the industry apply the technology at an operational level. In order to do so, several challenges remain to be faced. Here we focus on two of these which are: 1. to examine the effect of the variations in wood density and moisture content in logs; 2. to identify potential thresholds above which a log is likely to produce lumber of a given MSR grade.

2 Methodology

Four species from the boreal forest were sampled for this study: black spruce, white spruce, jack pine and trembling aspen (*Populus tremuloides*). The first three were selected because of their potential to produce MSR lumber. Trembling aspen was chosen because of its omnipresence in several parts of the boreal forest and its potential to be used for Laminated-Veneer-Lumber. Fifteen trees were sampled from each of black spruce, jack pine and trembling aspen. The sampling locations were all within naturally regenerated forests in areas where each species is typically found. One 2.5 m log per tree was brought back to the *Centre de recherche sur le bois* at Laval University where logs were sawn into 2'x4' pieces (38 X 89 mm) using a portable sawmill.

Our white spruce samples came from the Petawawa research station located in eastern Ontario. Thirty-two trees were sampled from a thinning trial established in 1936. Eight trees were selected from each of four treatments designed to maintain some target basal areas through time: control, 18 m^2/ha, 25m^2/ha, 32m^2/ha. Our objective in obtaining these samples was to induce some variability in the dimensions, wood properties and moisture content of each log. Three logs were collected from each tree and processing was done at the Duchesnay sawmill near Québec city. Table 1 summarises our sampling scheme.

Table 1: Details of the samples collected

Species	n (trees)	n (logs)	n (2’x4’ pieces)	location
Black spruce	15	15	27	North Shore
Jack pine	15	15	26	Lac St-Jean
Trembling aspen	15	15	73	Montmorency forest
White spruce	32	94	290	Petawawa

Acoustic measurements on trees were made prior to felling our trees. However, we focus here on the measurements that were made on logs using Fibre-Gen’s HM200 tool (Carter *et al.* 2006). Each measurement was taken immediately after the trees were felled. After sawing, the lumber was dried in conventional kilns to a target moisture content of 12% using schedules adapted to each species. The pieces were then planed before the dimensions and mass were measured. Finally, the moduli of elasticity (MOE) and rupture (MOR) of each board were determined following the ASTM D198 standard.

Our analyses consisted firstly in examining the relationships between acoustic velocity and wood stiffness at the log level. This relationship is derived from the fact that in any solid material, the acoustic velocity can be related to stiffness and density in the following manner:

$$v^2 = \frac{E_{dyn}}{\rho}$$

Equation 1

Where v is the speed of sound in the material, ρ is its density and E_{dyn} represents a dynamic assessment of its MOE. Fresh-cut wood contains free water located in the cell lumens in addition to water that is bound to the cell wall. Only the latter has an impact on the static bending properties of the material (USDA, 1999). However, free water is known to affect acoustic velocity (Kang & Booker 2002), which implies that the linear relationship usually found between E_{dyn} and acoustic velocity is affected not only by the specific gravity of the wood itself, but also by its moisture content. This can have an important impact on the applicability of acoustic tools in the forest industry because wood density and moisture content can vary according to several factors. Wood density is known to vary according to site conditions and silviculture (Zobel & Van Buijtenen, 1989) while moisture content has been shown to vary seasonally and with site conditions (Gates 1991, Gingras & Sotomayor 1992).

Therefore, for white spruce, which had the highest number of samples, we tested an approach where E_{dyn} would be estimated on each log in order to predict the static MOE of the boards it contains. Values of ρ necessary to compute Eq. 1 were estimated from two measurements. Firstly, wood density at a moisture content of 12% was estimated by averaging the density of each board sawn from a given log. Secondly, discs were collected at each end of the logs at the felling stage. Sapwood widths were measured immediately after felling and, by assuming a moisture content of 38% in the heartwood and 144% in the sapwood (Cech & Pfaff 1980), log density could be estimated.

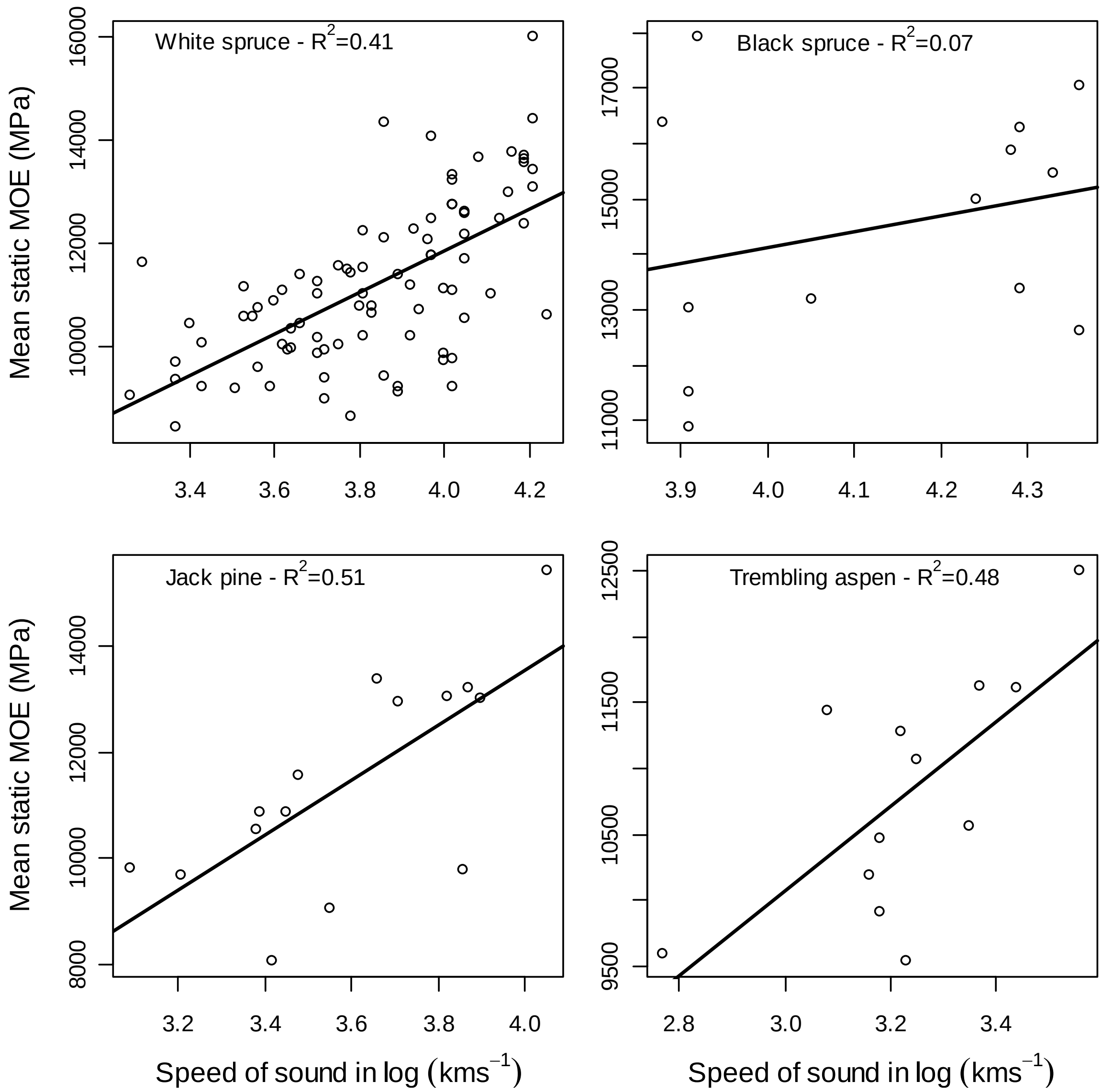

Figure 1: Relationship between the acoustic velocity of a log and the mean static MOE of the 2’x4’pieces it produced

Finally, we determined the probability of a board passing a given MSR as a function of the acoustic speed measured in a log. Probabilities were assessed using logistic regression in the R statistical package. The analysis was made at the log level and each observation was weighted according to the number of pieces it produced. Two MSR grades commonly traded in north-eastern North-America were retained for our analysis, *i.e.* '1650' (1650Fb-1.5E) and '2100' (2100Fb-1.8E).

Recent statistics show that the value of 1000 board-feet (2.4 m^3 - hereafter referred to as *tbf*) of 2'x4's 8-feet (2.5 m) in length delivered to the Great Lakes reached C$380 for the '2100' grade (Random Lengths, 2010). The '1650' grade has a value of C$375/tbf, whilst the visually graded construction lumber (No. 2 & better) is worth C$353/tbf. The probabilities calculated in our logistic regression were then used to calculate an expected value (C$/tbf) for logs of a given acoustic speed. For example, if the probability of passing the '1650' grade was 0.6, we assigned 60% of the tbf with a C$375 value and the remained (40%) with a value of C$353.

3 Results

The relationship between the acoustic velocity of a log and the average static MOE of the boards it contains differs between species (Figure 1). Based on the R^2 values, it appears that predictions for jack pine and trembling aspen are the more accurate than for other species, with black spruce showing the weakest relationship. When the dynamic MOE of the log was calculated in white spruce, the relationship with the static MOE of the boards became much stronger (R^2=0.69, Figure 2).

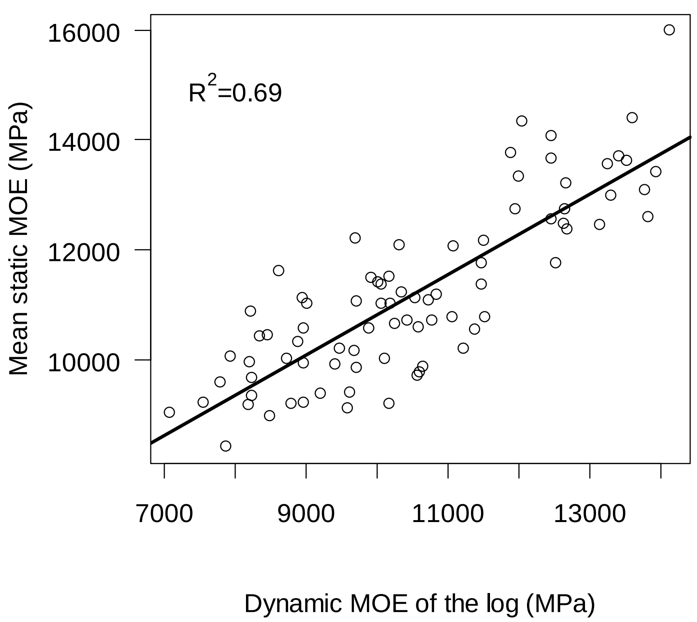

Figure 2: Relationship between the estimated dynamic MOE of a white spruce log and the mean static MOE of the 2'x4'pieces it produced

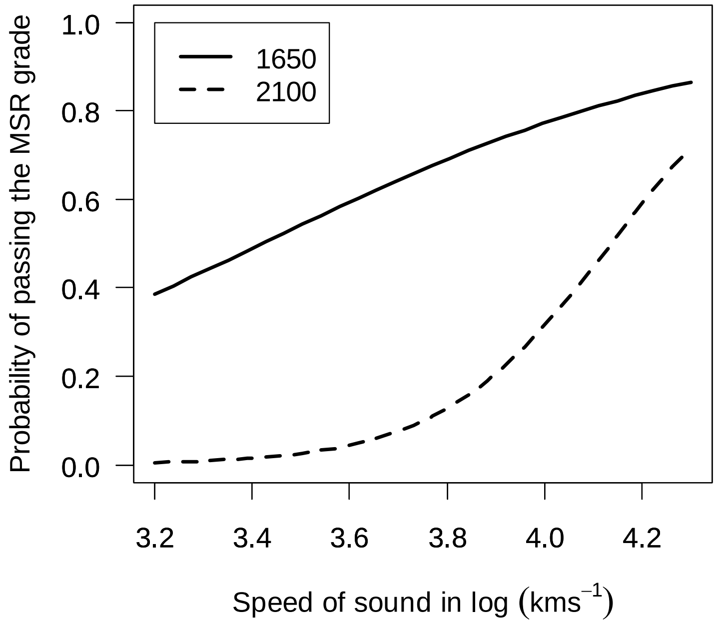

Figure 3: Probability of obtaining a 2’x’4 piece of the ‘1650’ and ‘2100’ MSR grades as a function of the speed of sound in the log (white spruce only)

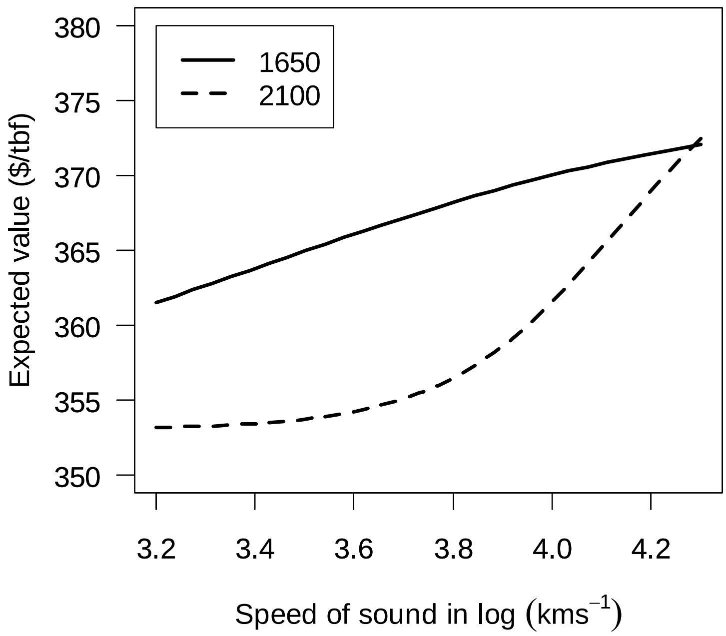

Figure 4: Expected value of one thousand board feet (tbf) of lumber as a function of the speed of sound in the log (white spruce only)

Despite the seemingly low R^2 of the relationship based on speed only in white spruce (0.41, Figure 1), the probability of obtaining a board which would qualify for the ‘1650’ and ‘2100’ MSR grades increased significantly ($p < 0.001$) as log acoustic velocity increased (Figure 3). This logistic model could be used by a sawmiller in order to calculate the expected monetary value of logs with a given acoustic speed (Figure 4). In our example, for almost the entire range of speeds, a sawmiller would have extracted more value from our white spruce logs if the production would have been set to the ‘1650’ MSR class. If this strategy is applied, a range of values of C$10 can be expected between the logs at the lower and upper ends of the range of acoustic velocities.

4 Discussion and conclusion

4.1 Accuracy of the static MOE predictions

The strength of the relationship between the acoustic velocity measured on a log and the average static MOE of the boards it contains appears to vary in the literature. For example, *Huang et al.* (2003) and Carter *et al.* (2006) reported R^2 values of 0.64 in *Pinus taeda* and *Pinus radiata*, respectively. In contrast, Matheson *et al.* (2002) found an R^2 of only 0.25 (r=0.5) in *Pinus radiata.* In our study, the strength of the relationships obtained with trembling aspen and jack pine approached those of Huang *et al.* (2003) and Cater *et al.* (2006).

Conversely, in black spruce, the relationship was much weaker than what is normally reported in the literature. This result may merit some attention as it is the most important commercial species in eastern Canada and also has a high MSR grading potential. The weakness of the relationship may be linked with a higher variation in wood density in this species (the coefficient of variation in the 2’x4’ pieces was twice as high as for any other species). Further test however need to be conducted to determine if this could have been an artefact of the small number of samples.

The slight decrease in R^2 that was observed in white spruce compared to trembling aspen and jack pine may be attributable to the fact that we tested material from a spacing trial, where the treatments induced a high variability in growth rates, and thus in moisture content and wood density. This tends to be confirmed by the fact that the accuracy of predictions was much higher when made from an estimated dynamic MOE.

A good part of the variation in log density in white spruce came from variations in sapwood width, and hence water content. Extra variation was induced by the fact that the treatments in the spacing trial induced a range of crown sizes (and sapwood widths) not normally found in a forest stand. Yet, some variability will always be present between the trees of a stand and water content is also known to vary substantially between sites or within a year (Gates 1991, Gingras & Sotomayor 1992). Because of these variations, the simple linear relationships that are often reported between acoustic velocity and static MOE can only be considered as valid for one particular part of the season or particular sites. In order to make acoustic assesments applicable at an industrial scale it is important to devise a system which accounts for variations in moisture content.

Our results suggest that a good approach to counter this problem may involve making predictions from a dynamic MOE rather than only acoustic velocity. The advantage is that predictions should remain unbiased for a wider range of conditions. However, a potential disadvantage is that it will necessitate an estimation of log density. At an operational level, one possibility would be to use a generic correction factor based on the mass-volume relationships that are available to sawmills which collect this information at their gate. Such a strategy could at least help take into account seasonal variations in moisture content.

However, sawmillers may also opt for measuring the density of each log prior to processing. Most sawmills in eastern Canada are equipped with a 3D scanner which provides a volume measurement. Installing a scale could then provide the mass measurement needed to calculate a dynamic MOE. The results from our white spruce samples suggest that the accuracy of predictions can be substantially improved if the dynamic MOE of each log is calculated.

4.2 Potential for adding value

The C$10/tbf difference in value that was found between the logs with the lowest and highest velocities may appear insignificant. However, considering the fact that production costs are currently estimated at C$350/tbf, *i.e.* very close to the value of visually graded construction lumber, an added-value of C$10 may represent the difference between losses and profits.

The information provided by this part of our analysis could be used in different ways in practice. For example, a sawmiller could set a threshold acoustic speed, or dynamic MOE, at which the extra effort needed to produce MSR lumber would be matched by the increase in expected value. This would normally require testing all logs entering the sawmill with an automated acoustic tool.

Alternatively, a sawmiller may test a sample of logs coming from a given source with a hand tool in order to predetermine its potential for producing lumber of a given MSR class. Our study provided a good example of this possibility as it appeared that the highest value would be obtained from our white spruce logs if the sawmill were set to produce the '1650' grade. Due to lower probabilities of obtaining the desired stiffness, focusing on the '2100' MSR grade would have resulted in losses in value. Conversely, focusing only on visually graded lumber at C$353/tbf would not have extracted the best potential value from the resource. In our example, the white spruce samples were of a plantation origin, a relatively rare occurrence in current wood supplies in eastern Canada. Information on the likelihood of meeting the MOE thresholds of different MSR grades would not have been available prior to processing in a normal industrial setup. Acoustic technology may therefore be very useful in the current economical context and in situations where the variability in the properties of the wood supplies can represent an issue.

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