# A new grading process for structural timber based on Partial Least Squares method using acoustic vibrations spectra

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*This study highlights the possibility to develop a high performance grading process based on the analysis of acoustic vibrations in the frequency domain. The originality of the method consists in the direct use of the spectrum as predictive variables to estimate MOE and MOR. The partial least squares regression method was used to perform the calibration models. The quality of predictions obtained were compared with those of classic linear regressions performed with dynamic MOE as predictor.*

## Partial Least Squares Regression

PLS is related to both Multi Linear Regression (MLR) and Principal Component Regression (PCR) and can be thought of as occupying a middle ground between them :

- MLR seeks to find coefficients that best correlates predictors to goal variables,
- PCR finds new predictors that capture the essential information of the original experimental data set,
- PLS tries to find new predictors which both capture the essential information and achieve the best correlation with goal variables.

## Materials and Methods

A batch of 96 beams of larch (*Larix europeae* D.C.), for a structural use, was collected from French sawmills (3000 x 150 x 50 mm, MC closed to 12%). The test batch was sampled by visual observations selecting beams with a wide range of singularities like knots, splits and sapwood presence (Figure 1).
The vibration responses of the beams were recorded in the acoustic domain both in transversal and longitudinal vibrations (Figure 2).
Then, discrete Fourier transform were calculated from temporal responses recorded, and the frequency spectra constituted the predictors matrix in PLS regression.
The dynamic MOE in transversal and longitudinal vibrations were also computed using eigenfrequencies of the vibrating beams.
Standardized 4 point bending tests were performed to evaluate static MOE and MOR values (EN 408, 1995). These values constituted the reference data set to perform linear regressions, PLS and statistics analysis.

Figure 1. Example of selected beam.

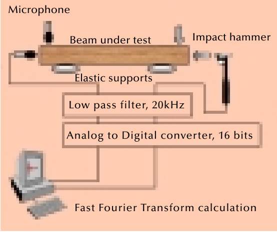

Figure 2. Experimental set up for the dynamic tests.

## Results and Discussion

### *Static tests, standardized mechanical property values*

The linear regression between static MOR and static MOE values was performed (Figure 3). A coefficient of determination $R^2$ equal to 0.43 was obtained with a 95% confidence interval of ±31 Mpa. The quality of the linear relation obtained is poor, this is due to fact that beams contain defects, mainly knots,in whole test batch.

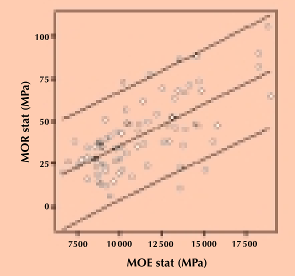

Figure 3. Static MOR as a function of static edgewise MOE ($R^2$=0.43, N=80).

### *Correlations between static and dynamic properties*

**Linear regressions**

A good correlation was found when the dependent variable was the static MOE with $R^2$≈0.7 (Table 1). The correlations between static MOR and dynamic MOE remains low, but significantly better than the one previously done with the static edgewise MOE ($R^2$≈0.5, Table 1).

Table 1. Coefficients of determination and 95% confidence intervals between the static values and the dynamic MOE.

| Regression model | N | $R^2$ | SEP (MPa) | IC95 (MPa) |
|---|---|---|---|---|
| $MOE_{Stat}$ / $MOE_{Longi}$ | 80 | 0.76 | 1407 | 2800 |
| $MOE_{Stat}$ / $MOE_{Trans}$ | 80 | 0.73 | 1483 | 2950 |
| $MOR_{Stat}$ / $MOE_{Longi}$ | 82 | 0.54 | 14.5 | 29 |
| $MOR_{Stat}$ / $MOE_{Trans}$ | 82 | 0.53 | 14.6 | 29 |

**PLS regressions**

The table 2 presents the results of PLS regressions. The best model was obtained using the longitudinal vibrations, $R^2$=0.73 for the static MOE regression (Figure 4) and $R^2$=0.83 for the static MOR (Figure 5). This is due to fact that the bandwidth on which the model was established was much more stretched in longitudinal vibrations (upper limit of 3000 Hz) than in transversal vibrations (upper limit of 1000 Hz).

Table 2. Coefficients of determination, 95% confidence interval and ratio of cross validation between the static values and the spectra using PLS regression.

| Regression model | N | $R^2$ | SEP (MPa) | IC95 (MPa) | RCV |
|---|---|---|---|---|---|
| $MOE_{Stat}$ / $Spectra_{Longi}$ | 80 | 0.73 | 1467 | 3063 | 2.8 |
| $MOE_{Stat}$ / $Spectra_{Trans}$ | 80 | 0.59 | 1811 | 3737 | 2.1 |
| $MOR_{Stat}$ / $Spectra_{Longi}$ | 82 | 0.83 | 8.6 | 18.3 | 3.4 |
| $MOR_{Stat}$ / $Spectra_{Trans}$ | 82 | 0.70 | 11.7 | 24.4 | 2.1 |

By using PLS method, the explanation of MOR variance reached 83% with the longitudinal spectra against 54% with dynamic MOE. This important jump of prediction can be explained by reminding that the impulse response of each beam is formed through whole its macroscopic structural components made of clear wood, but also knots, and others singularities.

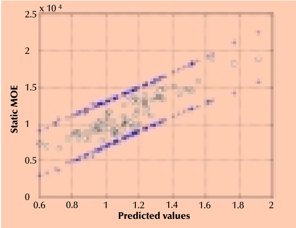

Figure 4. Relation between static MOE and predicted values by the PLS regression model in longitudinal vibrations ($R^2$=0.73, N=80).

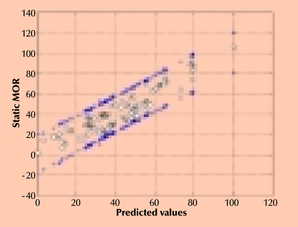

Figure 5. Relation between static MOR and predicted values by the PLS regression model in longitudinal vibrations ($R^2$=0.83, N=82).

## Conclusions

The use of PLS Regression directly on vibration spectrum allows a very good estimation of the variables of interest (MOE and MOR). When the linear model of calibration is achieved by PLS, the on line grading process is reduced to its minimum : a vibration transducer, an acquisition card, a computer performing only Fast Fourier Transform and multiplying matrices. Therefore, time of grading by piece of wood is very short, and the cost of grading is low.

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