New processing to improve timber strength grading with a vibration method

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Abstract
Strength grading of timber structures is required in a new European directive (EN 14081-2). Common grades are the following: C18, C24 and C30. It is difficult to predict strength of timber with non-destructive techniques because wood is a heterogeneous material; its strength depends on the rigidity of the wood fibre but also on the presence of singularities (nodes, fissure…). A well-known technique (so called “bing”) consists in shocking the timber at its extremity, measuring the longitudinal resonance frequencies and estimating the modulus of elasticity. The correlation between strength and modulus of elasticity is poor so that the efficiency is between 50 and 60% for the grade C30 and Douglas fir.

INNODURA has improved the processing to increase the efficiency. Two kinds of parameters are distinguished:
• Grading parameters that have to be correlated with strength for all samples; modulus of elasticity is the first one of these parameters,
• Qualitative parameters to detect timbers with singularities; these parameters indicate that the modulus of elasticity is too high by comparison with strength.

Data processing acts as a neural network; it includes the two kinds of parameters with non-linear functions. The results for Spruce and Douglas fir are given for green and dried conditions. The efficiency for Douglas fir in C30 was improved by more than 20%. A prototype, based on this method, is presented in the last paragraph of this paper.

Keywords: vibratory technique, timber grading, wood industry

1. Introduction

This paper forms part of the European directive on CE labelling of wooden boards intended for use in the construction industry. This labelling includes the strength grade. Three main grades are defined for resinous varieties: C18, C24 and C30.

It is not easy to determine the modulus of rupture of a piece of wood without breaking it as numerous parameters are involved. To simplify, we can say that two factors are involved:
• The rigidity of the wood fibre; in particular a slow-growing wood will have small rings and a statistically higher modulus of elasticity,
• Numerous singularities (nodes, fissures, etc.) may weaken the board.

Predicting mechanical strength from singularities is very difficult as has been clearly highlighted in visual sorting. This is also the case with methods using cameras and X-rays, the efficiency of which is very low.

To estimate the strength of a board, the first thing to do is to measure the rigidity of the fibre; this is the objective of the vibration method. Secondly, this estimate can be improved by introducing parameters associated with the singularities. This is the objective of the processing proposed by INNODURA.

2. Principle of the method

2.1 Principe of the vibration method [1].
The principle of the vibration method consists of shocking the board and measuring the acoustic response. The signal emitted is of relatively short duration (about 40 ms - see figure 1). A force sensor measures the impact force. Processing then initially involves
calculating the Fourier transform of the transfer function. Figure 2 shows this transfer function (function of the frequency) for 2 theoretically identical boards. These transfer functions show resonance frequencies, the first being around 600 Hz for boards 4 metres in length. The modulus of elasticity may be estimated from this frequency using the following formula: \[ \text{MOE} = 4\rho L^2 f^2. \] The modulus of elasticity varies with the square of the frequency. The accuracy of the estimate is therefore significant and non-trivial taking into account the duration of the signal. To improve this accuracy, INNODURA uses a number of microphones.

We can see that there are significant differences for theoretically identical boards: about 10% between the first resonance frequency of 2 boards in figure 2 which leads to a difference of 21% in the modulus of elasticity.

**Figure 1: acoustic signal emitted**  
**Figure 2: P/F transfer function**

### 2.2 Certification principle

The certification principle consists of performing tests with the classification system on a batch containing a certain number of boards (900 for certification of an initial variety - 450 for subsequent varieties), then carrying out destructive tests.

The correlation between the magnitudes obtained non-destructively may be compared on a diagram with that obtained using the rupture test. The correlation between the modulus of elasticity and modulus of rupture is plotted in figure 3 opposite.

Let us suppose we want to identify boards with a modulus of rupture greater than 30 MPa. The certification principle consists of determining the threshold on the non-destructive measurement (here the modulus of elasticity) allowing an error of 5%. For the measurements opposite, the threshold may be greater than 10 GPa, the samples in the blue square symbolising the 5% error. We note that the samples in the red square have a strength greater than 30 MPa, but they are classified in a lower category by the machine. By using the modulus of elasticity, around 40 to 45% of boards which actually have a strength greater than 30 MPa are classified in a lower category; the efficiency of the method is between 55 and 60%.

**Figure 3: correlation between MOR and MOE**
2.3 Principle of the high-efficiency method developed by INNODURA.
The approach proposed by INNODURA distinguishes two classes of parameter from the processing of the acoustic signal:

- "quantitative" parameters: a correlation is sought between these parameters and the modulus of rupture in a multi-parametric approach. The first of these parameters is Young's modulus.
- "qualitative" parameters: these parameters are used to detect defects in the board which could result in its modulus of rupture being less than that which the modulus of elasticity may predict.

The steps in the processing are as follows:

- calculation of quantitative parameters for all boards.
- calculation of qualitative parameters, comparison with thresholds and determination of boards to be "declassified",
- calculation of adapted quantitative parameters for these boards. The quantitative parameters are modified if the qualitative parameters exceed certain thresholds.

We describe below two examples of "qualitative" criterion:

- The first relates to peaks splitting into two (figure 4). The green curve corresponds to a board without "acoustic defects". On the red curve, we can see that the first resonance frequency is split in two. This is one of the criteria that can be used for lowering the value of the quantitative criteria in the processing. We also note that this board raises questions with regard to estimating the first resonance frequency. The splitting of the peak may occur on harmonic 1 or on harmonic 2.
- The second criterion relates to damping. We note in the figure that the 2\textsuperscript{nd} resonance frequency does not have a sharp peak, but that it is spread out. The width of this peak is related to the rate of damping. Boards with too wide a peak will also be "declassified" in the processing.

![Figure 4: FRF with double peak](image)
![Figure 5: FRF with 2\textsuperscript{nd} peak dampened](image)

Boards with signals showing these characteristics are artificially "declassified" in the processing.
3. Application to Douglas Fir

Tests were carried out to test this methodology on the mechanical characteristics of French Douglas Fir. 600 boards with 3 different cross-sections were measured. These boards came from 4 different regions.

The tests were broken down into the following sequences:

- Vibration measurements were carried out on green wood (moisture $\geq 30\%$),
- The wood was dried,
- Vibration measurements were carried out on the dried wood ($10\% \leq$ moisture $\leq 18\%)$,
- The boards were ruptured. The rupture tests were carried out by the FCBA (French technical centre for wood). The FCBA also processed the data to set the thresholds for the non-destructive characterisation method.

3.1 Prior analyses

This section compares the results from the green wood with those for the dried wood, some doubt subsisting as to the possibility of characterising the green wood.

The figure opposite shows the correlation between the modulus of elasticity measured with the green wood (x-axis) and the modulus of elasticity measured with the dried wood (y-axis). We note that the modulus measured with the dry wood is higher, but the correlation between the two values is very good; in all cases, this correlation is much better than that obtained between the modulus of rupture and the modulus of elasticity.

Tests were carried out to study exactly the change in modulus of elasticity with the moisture content. Different boards of two varieties (Spruce and Douglas fir) were measured at a number of moisture content levels during drying. These measurements have made it possible to determine the law governing the change in the modulus of elasticity as a function of the moisture content. The figure opposite shows these figures for Spruce and Douglas fir.

The following comments may be made:

- When the moisture content is greater than 30% (saturation), the modulus of elasticity remains constant,
- As the moisture content reduces, the modulus of elasticity increases. Between 10 and 18%, the change is linear (variation of 1% per percentage moisture content).

Between the green wood and dried wood conditions, two opposite effects may be noted:

- Faults due to drying are not present in green wood,
- Moisture content exactly between 10 and 18% causes a scattering of the modulus of elasticity.
For measurements carried out by INNODURA, the results of grading for green and dried wood were similar.

### 3.2 Results

The diagram below (figure 7) shows a correlation between the modulus of rupture (y-axis) and the modulus of elasticity (x-axis). The points shown in red are boards where a fault was detected in the acoustic signature.

![Figure 7: correlation between MOR and MOE for Douglas fir in dried condition](image)

We note that there is a correlation between the two magnitudes but that the scattering is relatively wide. The processing of the data made it possible to conclude that 83% were grade C30. The determination of the threshold at the 5% fractile enabled 46% of the boards to be graded C30 if we use the classical vibratory method (whether dried wood or green wood). The efficiency of the traditional vibration method is 55%. This corroborates the various publications with regard to Douglas fir.

A fault in the acoustic signature was detected for about 12% of the boards. We note that these boards are more often located on the bottom right in the diagram. In the processing, these boards were "artificially declassified" by the calculation of the modified quantitative parameters. This enables the threshold of the machine to be lowered for the 5% fractile. With this grading which the high efficiency can evaluate, the percentage of boards graded as C30 is 57%. The efficiency is 69%, i.e. an improvement of 25% relative to the traditional processing.
4. **Production of a prototype**

INNODURA TB has developed a system to carry out measurements on an industrial site without stopping the board. The whole system is shown installed on site in the photo opposite. It comprises the following components:

- A unit placed at the end of a transverse conveyor. The various functions of this unit are described below,
- Load cells arranged the length of the conveyor about every two metres to adapt to the different lengths of the beams to be measured.
- A length measuring cell (laser) placed at the other end of the conveyor system.

The control unit is shown in more detail in the photo opposite. It comprises:

- Two lateral lasers to determine the arrival of the board, control the impactor and measure the width of the board.
- Two other lasers above and below the unit measure the height of the board.
- The impactor whose rod exits from the centre,
- An acoustic antenna made up of 7 microphones for measuring the noise emitted. This device completely overcomes the noise of the sawmill.

This system has been used successfully to carry out the tests described above.

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