# Analysis and modeling of green wood milling: Chip production by slabber.

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## Résumé :

*En scierie, les grumes sont surfacées à l'aide de têtes de fraisage (slabbers). Les copeaux fragmentés issus de cette opération sont valorisés principalement dans les industries de pâte à papier et de panneaux de particules. Le rendement de ces industries dépend en partie de la dispersion de la granulométrie des copeaux. La maîtrise de cette dispersion n'est pas une chose aisée car elle est fortement dépendante des conditions de coupe et de la variabilité du matériau. Cette étude vise à mieux comprendre et prédire la fragmentation des copeaux. Elle débute par une description détaillée de la cinématique de coupe ainsi que l'interaction outil-matière. Ensuite, le phénomène de formation du copeau a pu être étudié à l'aide d'essais expérimentaux en conditions dynamiques. Ces essais ont été réalisés sur un pendule ($V_c = 400$ m/min), instrumenté avec une platine piézo-électrique et une caméra rapide. Les résultats ont permis de valider un grand nombre de phénomènes observés en quasi-statique.*

## Abstract :

*During the primary transformation of wood, logs are faced with slabber heads. Chips produced are raw materials for pulp paper and particleboard industries. Efficiency of these industries is partly due to particle size distribution. Command of this distribution is no easy matter because of great dependence on cutting conditions and variability in material. This study aimed a better understanding and prediction of chip fragmentation. It starts with a detailed description of cutting kinematic and interaction between knife and log. This leads to the numerical development of a generic slabber head. Chip fragmentation phenomena were studied through experiments in dynamic conditions. These experiments were carried out thanks to a pendulum ($V_c = 400$ m/min). It was instrumented with piezoelectric force sensors and high speed camera. Obtained results agreed very well with previous quasi-static experiments.*

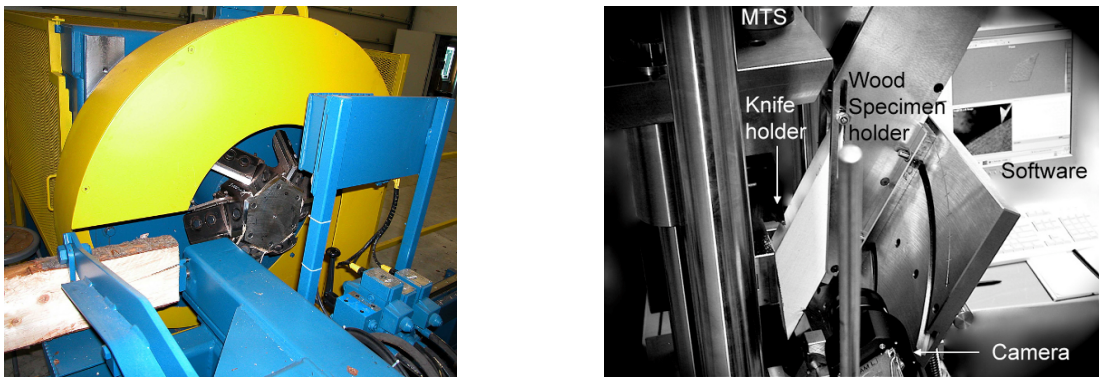
## Mots clefs : **Green wood ; wood chip ; slabber**

## 1 Introduction

The aim of sawmills consists in promoting the maximal wood volume from logs in primary transformation. After cross cutting and debarking, logs are squared by slabber heads. During this operation, up to 30% of logs initial volume is reduced in chips. Produced chips are mainly used as raw materials in pulp industries for paper and fiberboards. But using these chips as energy source is another important outlet. Defibration process represents the heart of pulp industry. It can be mechanical, chemical or both. Chip size distribution affects directly the efficiency of this process [6]. For example, in chemical defibration, cooking time depends on lignin percentage in wood. Lignin is decomposed by liquor. In alkaline conditions, liquor uniformly penetrates the chip. So chip thickness will determine the cooking time [13]. However, unlike chip thickness, chip length and width can be controlled by slabber kinematic parameters. That is why determining the influent parameters on chip thickness is required.

This issue can be studied with two points of view. The first one is built on macroscopic considerations. In order to reproduce real conditions, industrial material is used for chipping experiments with full

logs at high cutting speed ($V_c \simeq 3600$ m/min). Tested parameters are cut kinematic, tool geometry, log positioning and log parameters. Chips produced are screened and observations are done on size distribution [10, 11, 12, 14] (Fig 1a). The second point of view concerns mesoscopic characteristics. Chipping experiments on wood specimens are carried out on specific apparatus in quasi static conditions ($V_c \simeq 60$ mm/min). Tested parameters are the same as in the macroscopic process. Close attention is paid on area near cutting edge. Chip size distribution, cutting forces, failure modes, strain and stress fields are analyzed in order to understand chipping phenomena. [3, 8, 16, 17] (Fig 1b).




(a) Chipping with a slabber head [12]

(b) Chipping with Instron testing machine [8]

FIGURE 1 – Experimental devices

Our chip fragmentation analysis starts with a better understanding of cutting kinematic of a slabber head and of the interactions between knifes and log. Fragmentation phenomena are studied experimentally in a second step in dynamic conditions ($V_c = 400$ m/min). Influent parameters must be identified in regards to material variability and dynamic behavior of cellular materials [4].

This paper will focus only on chip fragmentation analysis.

## 2 Material and method

In order to get a better physical understanding of the chipping process, we have explored two axis :
- **Geometric and kinematic studies** to correctly define the working context and size of the experimental assembly.
- **Chip fragmentation experiments** in dynamic conditions.

### 2.1 Geometric and kinematic study

A slabber head is a conical milling cutter with special device for finishing (saw blade or finishing knifes). Slabber heads with split knifes like CT700 (Fig 2a) are simple and highly distributed. They were used to develop a generic and parameterizable slabber head on Mathematica® software. Program outputs consist in animation of cutting kinematic, cutting load, working angles and grain direction ($GD$) variation during cutting.

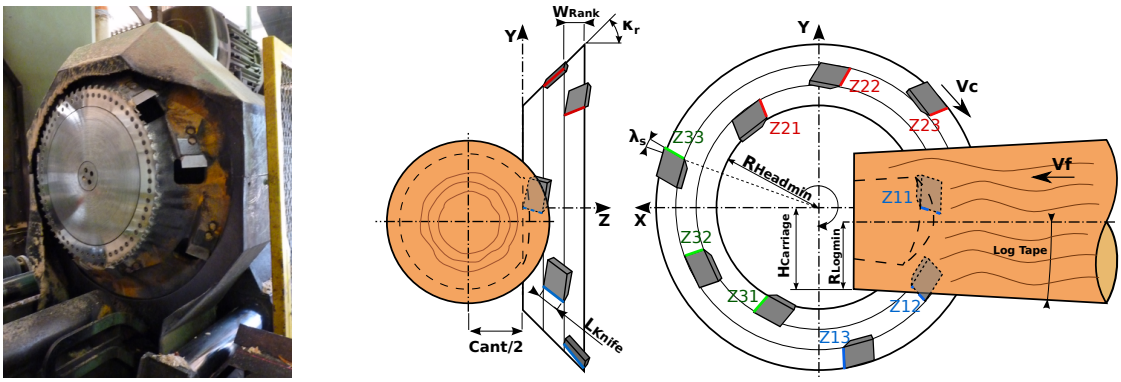
In order to agree with machining lexicon and to draw easy parallels with experimental devices, tool angles were normalized [1]. The following parameters were introduced (Fig 2b) :

**Kinematic :** Cutting speed $V_c$, feed $f_z$ and *cant*.

**Log :** Minimal log radius $R_{logmin}$, log tape $LogTape$, vertical distance between the carriage and the slabber head axis $H_{carriage}$.

**Slabber head :** Head diameter $R_{Headmin}$, number of knifes, number of splits, knife length $L_{knife}$, tool cutting edge angle $\kappa_r$, tool cutting edge inclination $\lambda_s$, normal rake angle $\gamma_n$, normal wedge angle $\beta_n$, normal clearance angle $\alpha_n$.

An example of result obtained by this geometric approach is given in section 3.1.




(a) Slabber CT700 (LBL)

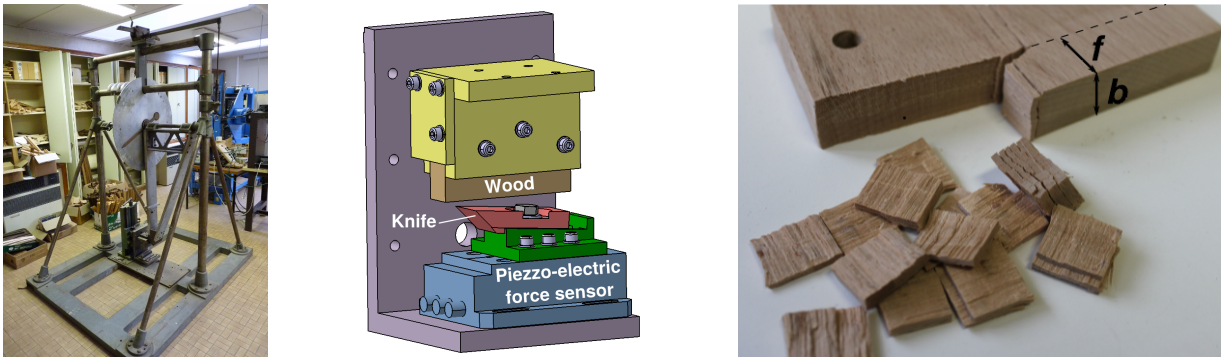
(b) Slabber scheme with parameters used in the program

FIGURE 2 – Exemple of a slabber head

## 2.2 Chip fragmentation experiments

Chipping experiments were carried out on a Chardin's pendulum (Fig 3a). It was used to obtain instrumented orthogonal cutting experiments to characterize cutting forces for dry wood [5]. The pendulum's arm is 1.2 m long and has a weight of 36 kg. Available kinematic energy is 756 J for a maximum cutting speed $V_c$ of 400 m/min. Specimen holder at the pendulum arm end was $140mm$ long. Lexicon of orthogonal cutting was used ($f$ the feed in mm and $b$ the cutting width in mm). According to [7], the delivered energy is high enough to cut chips with $f = 30$ mm, $b = 30$ mm on a cutting length of 140 mm.

Tool holder was designed and machined at LaBoMaP in order to use an industrial knife. Normal rake angle is set to $\gamma_n = 45^\circ$, normal clearance angle to $\alpha_n = 5^\circ$ and normal wedge angle to $\beta_n = 40^\circ$. The tool holder is fixed on a piezoelectric force transducer Kistler 9257A (Fig 3b). Amplifier Kistler 5019A, acquisition cards Kistler 9215 and 9234 and software Dasylab 11 record cutting forces. High speed camera Phantom v9.1 (Maximal resolution at 2000 frames/s, 800*1000 pixels. Exposure time : 6 $\mu s$) records cutting films.




(a) Chardin's pendulum

(b) Instrumented tool holder

(c) Preliminary results
(Beech $f = 20$ mm, $b = 20$ mm)

FIGURE 3 – Chipping experiments material

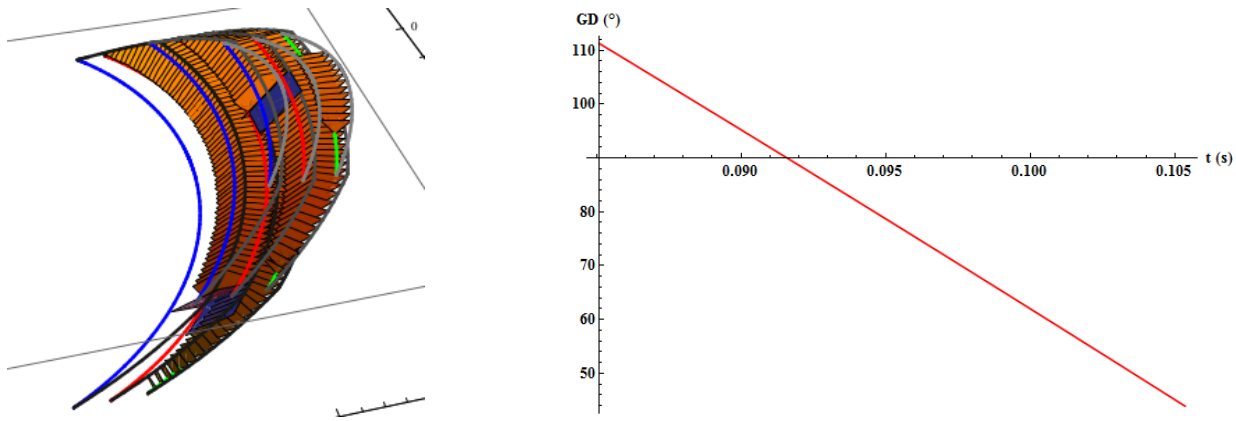
We setted an experimental design and used the following parameters : feed ($f = 6,\ 10,\ 14$ mm), cutting depth ($b = 6,\ 10,\ 14$ mm) and grain direction ($GD = 70, 90, 110^\circ$). We also selected two species : beech for its homogeneity and douglas fir known for its heterogeneity and bad machinability. Moisture Content (MC) is controlled after experiments by double weight technique. Each set of parameters was repeated 5 times. Specimens were machined from fresh beech and douglas fir slabs and put into a fridge to limit MC decrease.

Preliminary experiments showed higher energy consuming than predicted. Chardin's pendulum was not able to cut wood section of 400 $mm^2$(Fig 3c).

# 3 Results and discussion

## 3.1 Geometrical results

The following parameters were implemented into the program : $R_{Headmin} = 320$ mm, $L_{knife} = 60$ mm, $\kappa_R = 45^\circ$, $\lambda_S = 0^\circ$, $H_{carriage} = 300$ mm, $R_{logmin} = 350$ mm, $LogTape = 1\%$, $f_z = 28$ mm, $N = 550$ tr/min, $Cant = 50$ 0mm, $\gamma_n = 45^\circ$, $\beta_n = 40^\circ$, $\alpha_n = 5^\circ$. We were able to observe cutting kinematic as well as interaction of each knife with the material. The cutting load (section normal to knife path at cutting edge) was computed at different positions of knifes (Fig 4a). Results of cutting loads were validated with a geometrical model on Catia® software. Differences between these two models are less than 5% and are due to circular knife path on Catia® instead of cycloidal. Due to large feed, cutting and clearance normal working angles could diverge up to 4° with respect to tool angles. Grain direction was defined as the angle between cutting plane and the longitudinal fibers direction. It decreased quasi linearly during the cut (Fig 4b), starting at 110° when knife 2 rank 1 ($Z21$ on fig 2b) entered into the wood and finishing at 44°. Because of this large evolution, the grain direction was considered as a parameter during the experimental part. A lack of knowledge and relevance of specific cutting pressure $K_c$ or even cutting law depending on grain orientation prevents cutting forces computation from cutting load.




(a) Cutting kinematic (b) Grain direction functions of time for $Z21$ (Figure 2b)

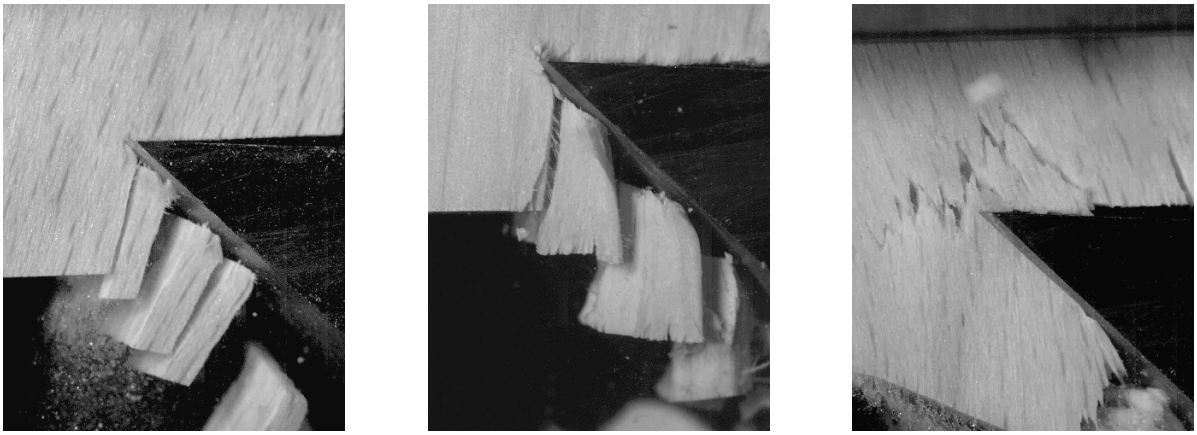
FIGURE 4 – Results of generic slabber head program

## 3.2 Experimental results

Fragmentation occurs for beech and douglas fir if grain direction is higher than 90° (Fig 5a and 5b). Chipping phenomena agree with observations published by McKenzie in [15] (Fig 6). First of all, the cutting edge bends wood fibers (Fig 6a). This bending is due to cell wall buckling. Then, when wood cell are collapsed, fibers are sliced (Fig 6b). The tool follows its cutting motion. Its face induced shear stress on the chip. When stress is higher than shear strength, shearing between fibers occurs, which ejects free water (Fig 6c). This water ejection occurs only when MC is higher than 30%. When the grain direction is lower than 90°, big wood particles are teared by tension on fibers (Fig 5c). Chip wood cells are compressed and free water is ejected. We also observed another cutting phenomenon : shearing between growing rings on douglas fir. It appears only when specimen include few growing ring. We assume that shearing between growing rings need less energy than shearing between fibers. So a limit ratio $f/b$ is needed to get a homogeneous material to produce chips.

As it could be observed in quasi-static cutting tests [3, 8, 17], average chip thickness is proportional to the feed and independent of cutting depth. With the same experimental parameters, douglas fir chips remain bigger than beech chips. This can be linked among others to the higher density of beech ($\rho_{beech} \simeq 0.7$, $\rho_{douglas} \simeq 0.45$) which induces higher rigidity.

Although specimens were machined from the same slabs at the same time and experiments carried out in consecutive days, large variations on MC appeared and could be measured only after experiments

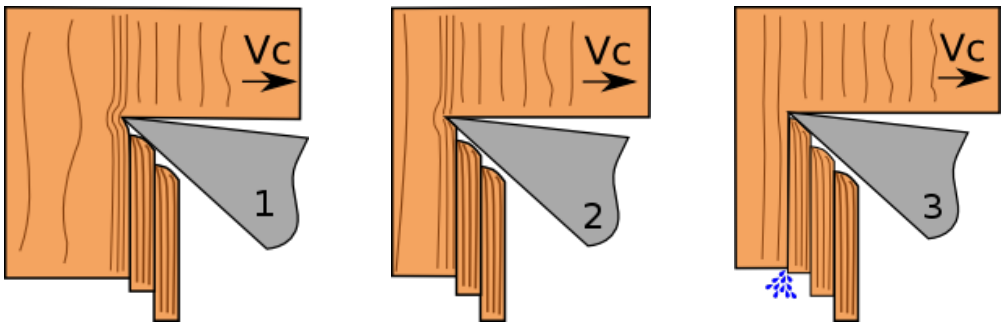


(a) Cutting of beech with $GD = 110^{\circ}$, $MC = 66\%$

(b) Cutting of douglas with $GD = 90^{\circ}$, $MC = 34\%$

(c) Cutting of beech with $GD = 70^{\circ}$, $MC = 76\%$

FIGURE 5 – High speed chipping, $V_c = 400$ m/min, Frame rate = 2 kHz, $b = 10$ mm, $f = 10$ mm.




(a) Fiber bending

(b) Fiber slicing

(c) Shearing and free water ejection

FIGURE 6 – Chip fragmentation mechanism

(20 to 60% for douglas fir and 30 to 90% for beech). This can be explained by the fast drying of the thinest specimens (a couple of hours).

Motion of Chardin's pendulum induces a grain direction variation of 7° during the cutting. Study of chip thickness evolution during the cutting on high speed film shows that grain direction evolution is negligible at this scale. As the pendulum falls freely, $V_c$ decreases about 20% during the cutting. Measurement of chip thickness variation during cutting shows no influence of speed decrease at this scale.

Average cutting forces measurements were done with piezoelectric forces transducers. However, chipping frequency was higher than transducers bandwidth. As a consequence, we could not confirm results of [15] and [17]. The obtained signals were close to results of [9] with appearance of peaks corresponding to chipping frequencies.

## 4 Conclusion and perspectives

Pulp industry needs to control chips size distribution to improve efficiency. To get a better understanding of the green wood chipping process in dynamic conditions, two axis were explored.

A generic parameterizable slabber head was developed to observe the influence of geometric and kinematic parameters on cutting load and working angles. An experimental device was sized with these results and used in dynamic chipping experiments. Results from experimental design agree with the ones from quasi-static conditions. Cutting films allow us to observe ejection of free water during chip fragmentation. Other cutting phenomena were observed like shearing between growing circles.

Following works will improve our methodology. A new experimental design must be set to find other influent parameters on chip thickness. New force transducer with higher bandwidth should be used and coupled to high speed camera. Simulate chip fragmentation with Discrete Element Method [2] will be used to predict and understand cutting phenomena.

## Acknowledgements

This work was carried out at LaBoMaP at Arts et Métiers ParisTech Cluny. We acknowledge Mathieu Martin, LE2I lecturer, for his technical support in high speed motions and LaBoMaP technicians for their availability and advice.

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