Original scientific paper

Experimental Determination of Delimbing Forces and Deformations in Hardwood Harvesting

Benjamin Hatton, Guillaume Pot, Belhassen-Chedli Bouzgarrou, Vincent Gagnol, Grigore Gogu

Abstract

Delimbing is the process used to cut the branches off the trunk during tree processing by forest harvester. This process can be described as chipless cutting of green wood at a feed speed of 3 to 7 m s^{-1}. This work aims to identify the parameters influencing the efficiency of the delimbing process. To this end, the main parameters are defined, and different experimental tests are presented. The first experiment was conducted using a dynamometric pendulum that can reach cutting speeds of 10 m s^{-1}. A Digital Image Correlation method was used in order to compute the deformation field in the branch. The deformation fields observed are consistent with previous studies in the literature. The second experimental device was a slow speed test bench. It uses a hydraulic actuator to translate the knife through the branch while measuring force and displacement. Tests were conducted, varying the diameter of branches, to analyze its effect on the cutting force. Proportionality between branch area and cutting forces were verified, and empirical coefficients were obtained for both speeds.

Keywords: cutting force, broad-leaved tree, dynamometric pendulum, digital image correlation

1. Introduction

This paper presents a research work from the ECOMEF project (Eco-design of a mechanized equipment for hardwood harvesting), which aims to develop a harvester head more specifically designed to fell and process broad-leaved trees, in order to face the lack of motor manual workers and low rate of mechanization in hardwood logging operations (Cacot et al. 2006). This work focuses particularly on the modeling and simulation of the single-grip harvesters used in the cut-to-length method (CTL), like the Kesla 25 RH (Kesla Oyj 2013) harvester head (Fig. 1). The CTL method implies felling and processing of trees. The processing operation is composed of delimbing trunks and bucking them into logs (Ćuprić and Bajić 2009). In order to identify the models to be developed, a top-down functional analysis has been used. Four functions have been identified, associated with different phases of the CTL process: modeling the trunk gripping (function A1), feeding (function A2), delimbing (function A3) and felling and bucking (function A4). These models presented in Fig. 2, which illustrates the central place of the delimbing force, are included in a closed loop between feeding and delimbing modeling. Delimbing force is also a key parameter in designing

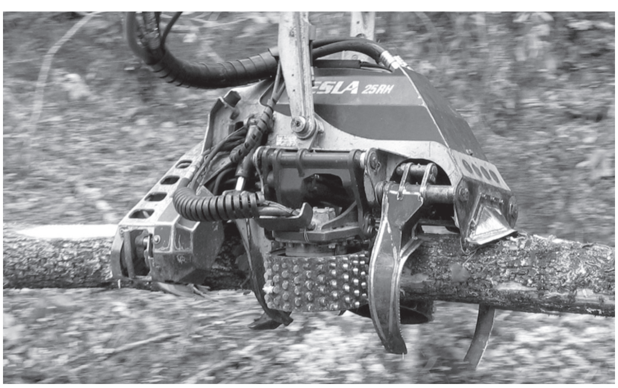

Fig. 1 A Kesla 25 RH single-grip harvester head

a harvester head and particularly in dimensioning the feeding equipment.

The specificity of the ECOMEF project is the focus on broad-leaved trees. Due to crooked trunks, bigger branches with sharper angles and hardwood (Cacot 2009), these species are indeed harder to feed and delimb than conifers, and thus require specific tools to improve the energy efficiency and productivity of the operation. For these reasons, hardwood mechanization in France only reaches 4% of the total harvest, whereas it is at approximately 55% for coniferous forests.

Previously, the European ForstINNO project emerged on similar observations, and allowed the development of the CTL-40HW harvester head (CTL Technology GmbH 2008). The absence of lower knife and the geometry of the feed rollers gripping mechanism greatly increased the compactness of the head. The hydraulic control of the fixed knife also improved the feeding of crooked trunks, but disabled momentarily the delimbing function of this knife. However, the productivity announced, compared to existing solutions, (Suchomel et al. 2012, Mederski et al. 2011) suggest that room for improvement is still possible for more innovative heads in the field of hardwood harvesting. This will probably involve a better consideration of morphological characteristics of broad-leaved trees in the design of harvester heads for hardwoods.

This work focuses on the experimental study of the delimbing process. Cutting the branches off the trunk is usually achieved by feeding the tree at 3 to 7 m s^{-1}

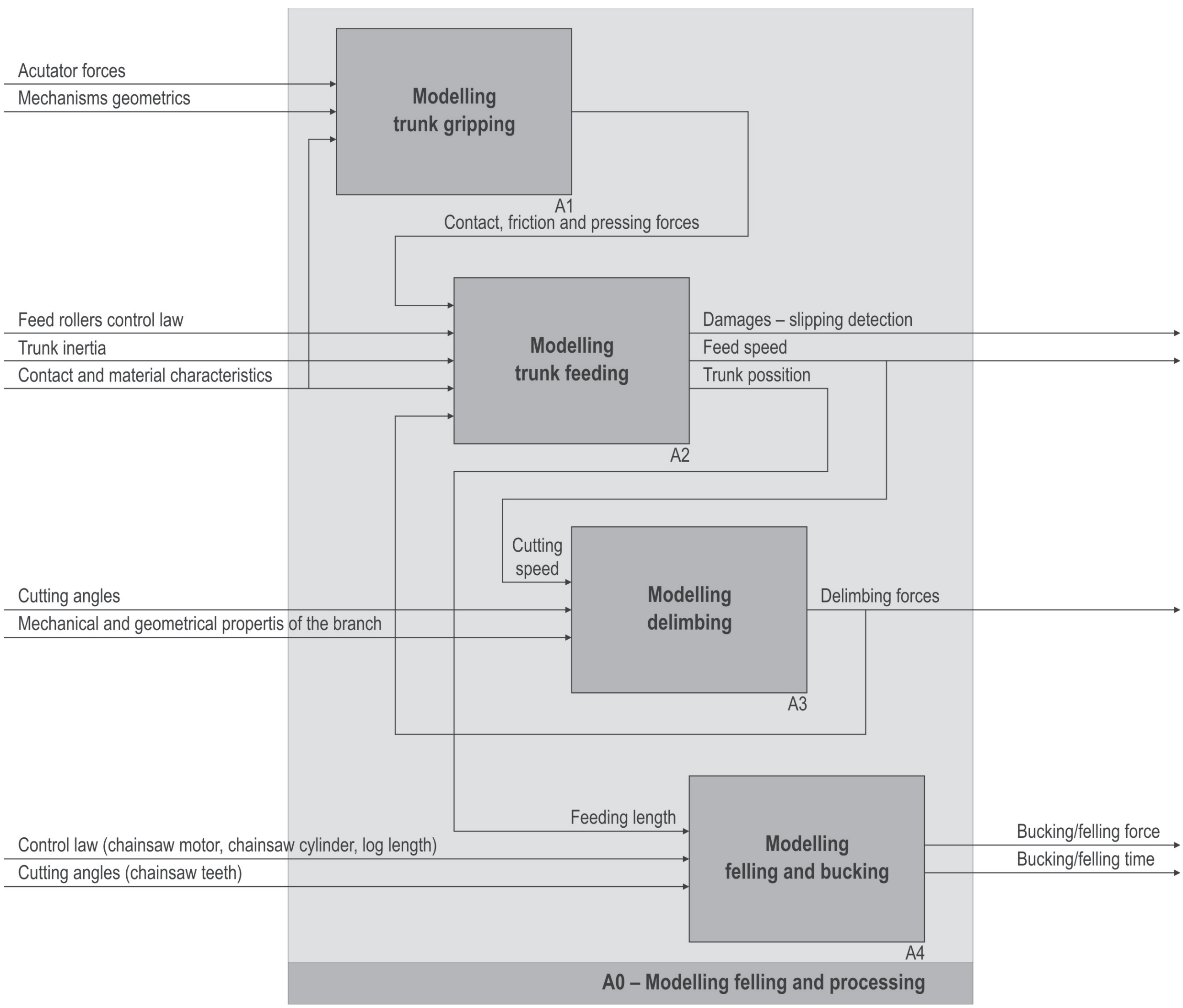

Fig. 2 Top-down function analysis of CTL modeling

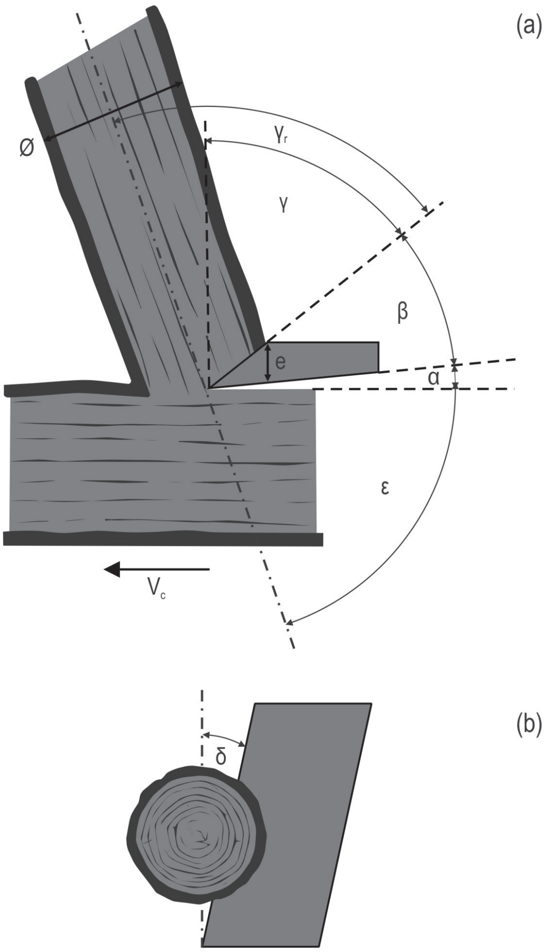

Fig. 3 Cutting angles and parameters

using feed rollers, and creating an impact of the branches against delimbing knives. Unlike many cutting studies based on the type and section of a chip (Frantz 1958) for several machining operations (Woodson 1979), it is not possible in this case to define a chip, since the »chip« is the whole branch. To identify the cutting situation process involved, the definition proposed by McKenzie (1961) can be used. In this notation, two angles are used to define the cutting process. The first one is formed by the cutting edge with the grain direction, the second one by the cutting speed direction with the grain direction. Delimbing can thus be considered as a 90°–90° orthogonal cutting process, sometimes called cross-cutting. In the same way, chipping can follow the same definition. That is why the work of Abdallah (2011) can be adapted to define the cutting situation, as presented in Fig. 3a. However, δ angle is added to the proposed description to allow considering the case of oblique cutting (Fig. 3b).

The following parameters are then defined:

α = clearance angle
β = sharpness angle
γ = rake angle
γ_r = real rake angle
ε = implantation angle (angle of the grain direction with the cutting speed direction)
e = blade thickness
δ = oblique cutting angle
V_c = cutting speed
$\varnothing$ = diameter of the branch

At the best of our knowledge, only a few, mainly experimental, studies of the delimbing process have been conducted. Johnston and St-Laurent (1974) studied the delimbing of softwood and analyzed the influence of blade thickness, bevel ratio, wood species, cutting direction, bending of the branch, position of the branch on the trunk and temperature on the cutting force. Mattson and Sturos (1996) conducted a similar study of the delimbing of sugar maple and focused on the influence of branch diameter, cutting speed, blade thickness, oblique angle and sharpness angle on cutting force. Lately, Mikleš (2013) carried out experimental tests in order to optimize the knife geometry and minimize energy consumption while delimbing softwoods, and optimal values of clearance angle, sharpness angle and blade thickness were proposed. In these studies, several experimental devices were used. Some of them were developed specifically for the purpose of the tests, whereas others rely on well-known principles and architectures. Chardin (1958) considered the dynamometric pendulum as a low-cost and simple bench, able to accurately reproduce the machining processes. Eyma et al. (2005) also used such a device in order to simulate the routing process and observed good correlation of the observed phenomena between the router and the pendulum. More recently, Pfeiffer (2012) carried out tests on a dynamometric pendulum to reproduce the chipping process. The relationship between cutting force and branch diameter has been discussed in the past. Whereas a quasi-linear regression between these two variables was first considered (Dunfield 1971), later works focused on a quadratic regression, i.e. a linear regression between the branch area and the cutting force (Pszkit and Wiesik 1985, Mikleš 2013). In a similar way, Mattson and Sturos (1996) studied the influence of several parameters on the average cutting force, i.e. the cutting force divided by the branch diameter, and still noticed a positive influence of the diameter despite the normalization.

In order to simulate the CTL process and to optimize the delimbing, a model has to be proposed, allowing to predict the cutting force needed to cut a branch for a given configuration (geometry of the system, mechanical and dynamical parameters known). The work presented here is an introduction to this study mainly based on experimental cutting tests, the first step being to understand the delimbing process in order to be able to model it.

2. Materials and methods

All the tests were carried out on fresh wood of sessile oaks (*Quercus petraea* (Mattuschka) Liebl.) between July and September. Pole-size trunks were used instead of branches implanted on stems. This choice was made for setting and sample procurement convenience, and was motivated by the study of Mattson and Sturos (1996), who compared the cutting force obtained for actual branches and saplings and concluded that similar, though not identical, values of average cutting force were obtained for both types. Because of the complex fiber implantation at the base of the branches and the eventual resulting growth stresses, working on pole-size stems also allows an easier understanding of the observed phenomena by limiting the sources of unexplained differences (knots, different moisture content, etc.). Samples were taken from each stem. Both fresh and oven dry weights were systematically measured in order to determine moisture content of the wood. During the second campaign realized with the slow speed test bench, samples were better calibrated in order to know their fresh volume. This allows to calculate the specific gravity as the oven dry mass divided by the fresh volume of the sample (Williamson and Wiemann 2010). Even if this configuration is not really representative of the hardwood morphology, the implantation angle ε was chosen as close as possible to 90° in every test except for the deformation field analysis, i.e. the branch was almost perpendicular to the knife.

For both test benches, the same cutting knife was used (Fig. 4). The knife was made of Hardox 400 wear resistant steel. The blade profile was inspired from existing cutting knives used on the Kesla 25 RH harvester head. The sharpness angle *ß* was 29°, and the rake angle 61°. The clear face was composed of three consecutive parts, the first and the last being parallel to the cutting plane, whilw the second one was oriented with a negative clearance angle of -12°, in order to keep the cutting edge away from the trunk and to avoid unexpected penetration of the knife into the trunk. For machining and fastening convenience, the decision was taken to work with a flat knife instead of a curved one as those used on real harvester heads.

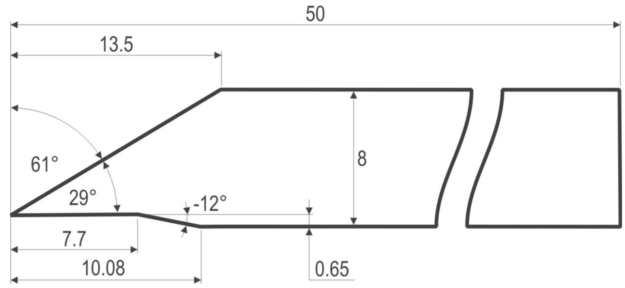

Fig. 4 Profile of the knife (units: mm, deg)

2.1 Dynamometric pendulum

To reproduce the cutting conditions met on a real harvester as accurately as possible, a dynamometric pendulum has been designed and developed as a first experimental device to study delimbing (Fig. 5). As explained by Eyma et al. (2005), this kind of bench is well known in the study of wood cutting, because of its simplicity and its ability to deal with interesting cutting speeds and impact phenomena. To be able to cut branches with diameters up to 100 mm, even at relatively low cutting speed, the pendulum had a 2.5 m and 68 kg arm, which can be equipped with up to 100 kg extra weight. The pendulum was designed as a foldable trailer in order to move it as close as possible to the fresh wood. Then, the trailer was anchored using chains and/or concrete blocks. An electric winch was used to reach the desired release position. An adjust-

Fig. 5 The dynamometric pendulum

able clamping plate allowed the positioning of the branch and the setting of the implantation angle ε. By orientating the knife support relative to the arm, it was possible to modify the couple of angles γ and α (rake and clearance angles). The sharpness angle β was changed by machining new knives.

An angle sensor measured the angular position of the arm. Due to its position on the rotation axis, this measurement was perturbed by the vibrations of the arm, and gave only information about the amplitude of oscillations. The precise position of the arm during the cut was computed using the autotracker feature of the OSP Tracker software (Brown and Christian 2011). The video used for autotracking was shot with an S-MOTION high speed camera set up at 2000 frames per second. A force transducer could be used to measure the force applied on the cutting edge (Fig. 6). This sensor returned a voltage function of the hydraulic pressure (up to 600 bar) in a cylinder chamber placed just behind the knife. An appropriate calibration allowed the conversion of pressure to force. However, in the series of tests presented below, the force was computed using the equations of dynamics and the acceleration of the arm, obtained by smoothing the tracked position using a Savitzky-Golay filter (Savitzky and Golay 1964), that directly returns the position and its first (speed) and second (acceleration) derivatives, smoothed by fitting second degree polynomials on successive periods of 4.5 ms.

A second study was performed to film the cutting of the branch with the same 8-bits camera and frame rate. Digital Image Correlation (DIC) using 7D software (Vacher et al. 1999) was used to measure full field displacements while delimbing. The DIC method consists of matching, before and after displacement, a set of Zones of Interest (ZOI) which make up a Region of Interest (ROI) on the observed surface of the object. In the present study, ROI compares with about 400 (width) × 500 (height) pixels, depending on branches widths. ZOI were 12 × 12 pixels. This size of ZOI gives the best compromise between spatial resolution and resolution of the DIC method.

Since the measured surface must be planar for DIC, branches were sawed longitudinally to obtain two half branches. Then, a small part was removed by a new longitudinal cut to obtain a tangential flat face, which helps maintaining the branch on the clamping plate (Fig. 7). It was the flat inside face of the branches that was observed with the camera, avoiding any out of plane effect. Black paint was sprayed on the sample surface before testing to obtain a speckle pattern and improve contrast. An image, taken before the knife begins to cut the branch, was referred to as the reference image, and the following images were correlated with this reference image using the DIC method. Displacements in longitudinal and radial direction were then computed using 7D software. These displacements can be noisy. Therefore, before their differentiation to obtain strains, displacements were smoothed by a moving average over adjacent ZOI. Then, planar deformations were calculated.

2.2 Slow speed test bench

The second device was a linear test bench (Fig. 8). The knife was guided on two shafts using linear bear-

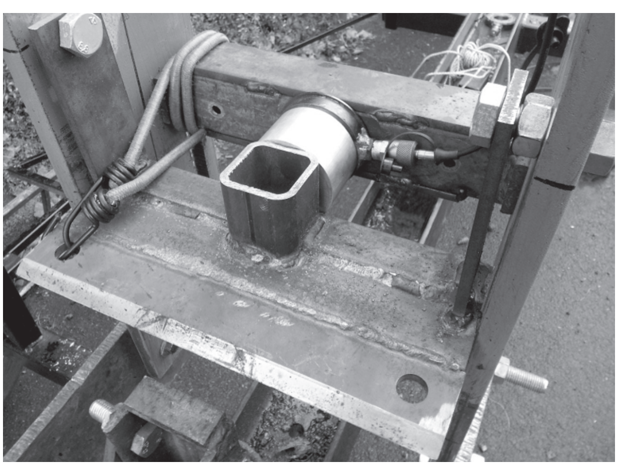

Fig. 6 The force transducer behind the knife

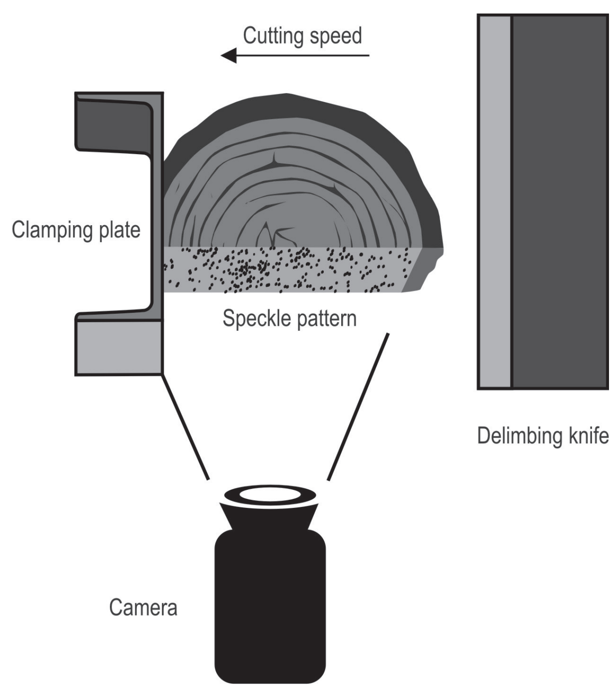

Fig. 7 Setting for Digital Image Correlation study

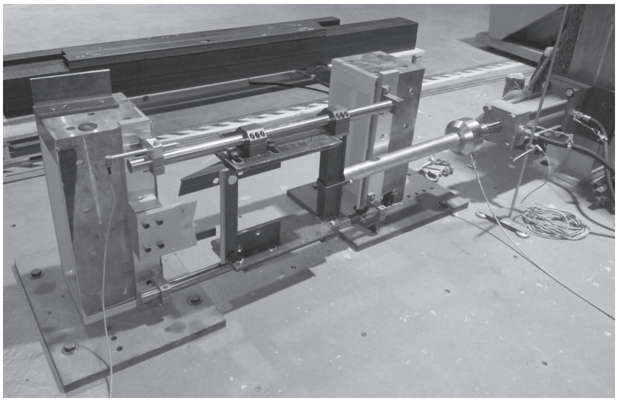

Fig. 8 The slow speed test bench

ings. The translation of the blade through the branch was actuated by a hydraulic ram without controlling displacement, force or pressure.

The branch support allowed the modification of the implantation angle ε, and the translating support was designed to allow the modification of both oblique cutting angle δ and couple of angles (γ, α). A 0–125 kN range force sensor and an inductive displacement transducer were used to measure cutting force and penetration of the knife through the branch. Using this bench, the cutting speed was reduced (up to 20 mm s^{-1}). This slow speed and the stiffness of the test bench ensured minimum vibrations and precise measures.

3. Results

This section presents some experimental results on deformation fields and cutting force measured at various cutting speeds.

3.1 Deformation field

The evolution of strains during the whole cutting process was measured by DIC. These measurements enabled a quantitative study of the cutting process. Fig. 9 presents the planar deformations obtained with DIC on a branch with an 81° implantation angle and plotted on the corresponding picture. The chosen image is representative of the behavior mostly observed during the delimbing process. DIC did not give results in zones very close to the knife because of very high deformation of wood: pattern recognition was thus impossible for the software. However, it shows, interestingly, that deformation up to 2% occurred in zones distant from the knife. Indeed, in the direction of cutting (x direction Fig. 9a), a large zone of compression between the knife and the clamping plate appeared. It is due to the force of the knife in the x direction. There was also a localized strip of tensile deformations in x-direction above the knife, which follow the direction of the grain. This phenomenon is actually due to the growth of a crack parallel to the grain: the crack starts from the knife and propagates along the grain. These cracks appeared also below the knife, but their opening is less important. It can be seen in Fig. 9c that there were also strips of high shear strains. In the direction perpendicular to cutting (y direction Fig. 9b), strains are lower than in x direction. However, two zones can be distinguished: the zone in front of the cutting edge, which is principally in tension (about +0.5%, with higher values close to the tip), and the zone behind the cutting edge, which is mostly in compression (about –0.5%).

Fig. 10 depicts what happens at the end of the cut. Another stage was reached, during which wood fiber failure below and ahead of the cutting plane can be observed. During this phenomenon, DIC was unable to compute matching of ZOIs because of huge displacements.

3.2 Cutting force

Both test benches were used to measure cutting force and displacement of the knife through the branch during the cut. Fig. 11 and 12 present the force as a func-

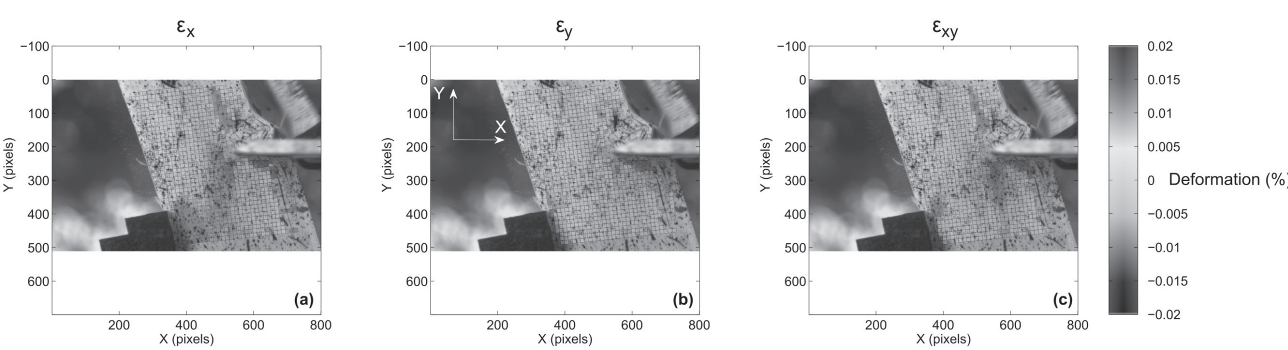

Fig. 9 Deformation in direction x (a), y (b) and shear (c)

Fig. 10 Wood fiber failure during the second stage

tion of dimensionless displacement for some tests of the two series that have been carried out, respectively, using the slow speed test bench and the dynamometric pendulum. The dimensionless displacement or unit displacement was calculated by dividing the displacement by the branch diameter in the direction of cutting, and was defined in order to be able to compare test results.

The maximum force was reached for a displacement between 50% and 65% of the branch diameter (Fig. 11). This range was larger for the series of tests carried out with the pendulum (Fig. 12). Quickly after (or before) the maximum force, a more erratic behavior was observed, corresponding to the second stage shown in Fig. 10. During this stage, the fracture frequently occurred very suddenly for the whole remaining part of the branch, which explains the fluctuation of the cutting force. The observation of the high-speed camera picture (Fig. 10), taken during the cuts with the pendulum, clearly showed that the fracture of the whole remaining part of the branch occurs almost instantaneously (at least really faster than the knife travel through the branch). Furthermore, this fracture takes place below the cutting plane and leads to the appearance of a stump on the branch. This phenomenon is not visible in Fig. 12 because of the smoothing realized on the raw data to compute the force for the dynamometric pendulum.

Fig. 13 illustrates the proportionality obtained between maximum cutting force and branch area, mentioned in the literature about chipless cutting (Pszkit and Wiesik 1985, Mikleš 2013). Linear regressions for both data sets were computed. Maximum force F_{max} as a function of branch area A can then be expressed for pendulum and slow speed as follows:

Dynamometric pendulum:

$$F_{\max} = 520 \times A + 1367 \tag{1}$$

Slow speed test bench:

$$F_{\max} = 638 \times A + 581 \tag{2}$$

Both linear regressions provided good determination coefficient (R^2 = 0.85 for pendulum and 0.95 for

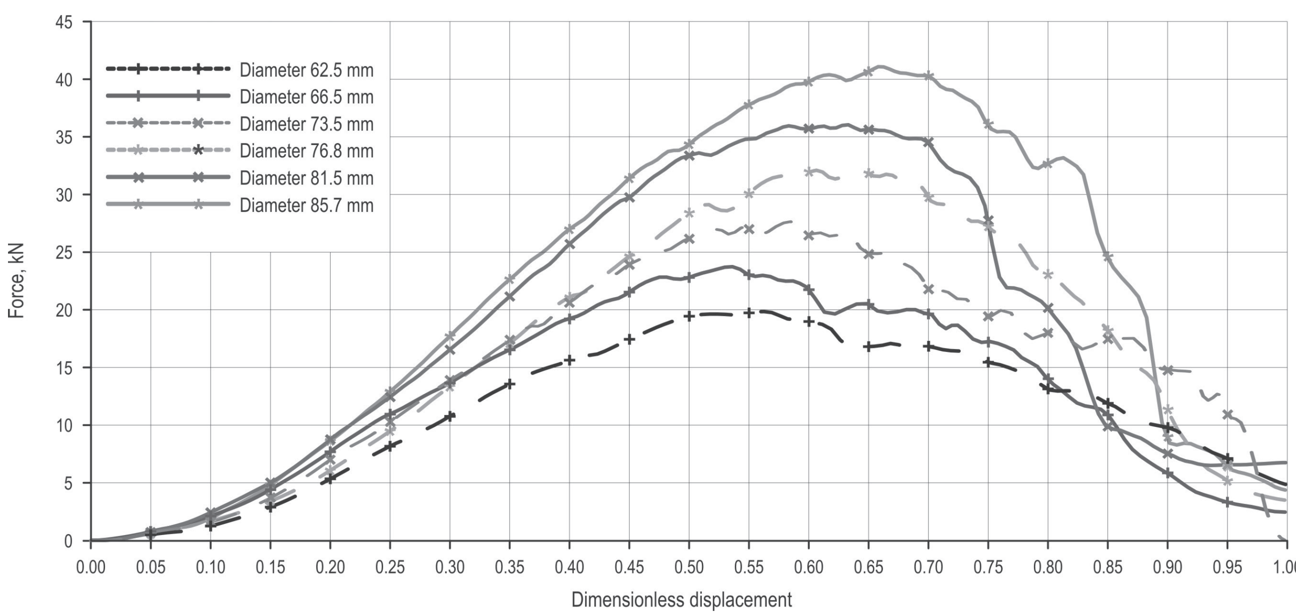

Fig. 11 Force as a function of dimensionless displacement (slow speed)

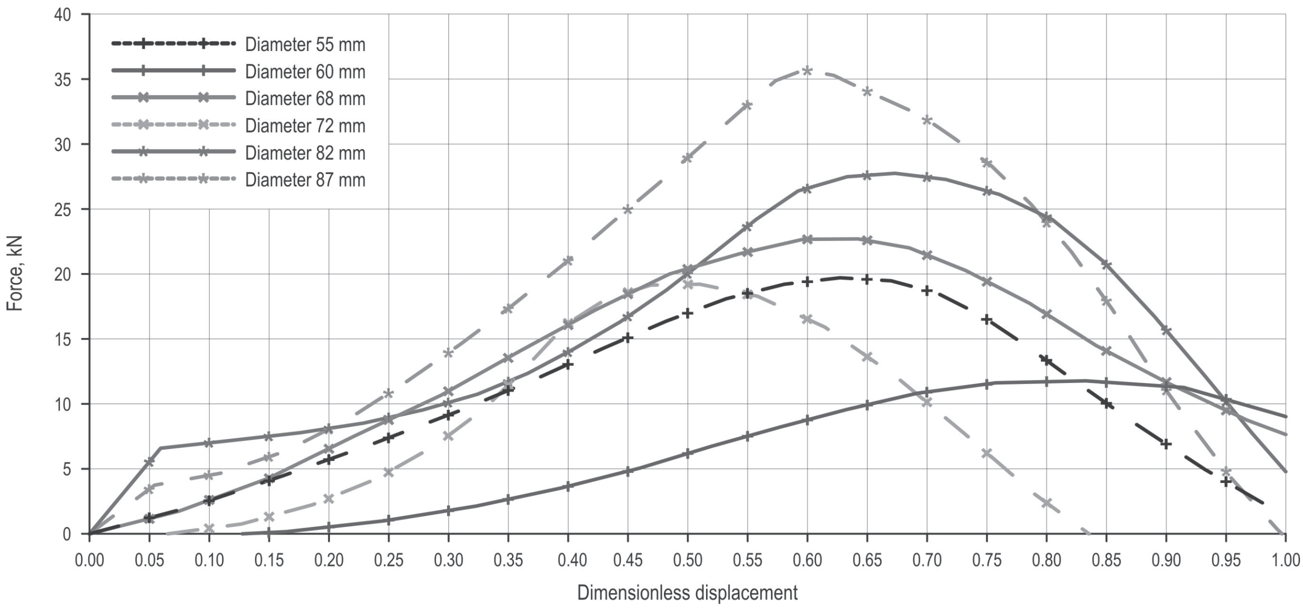

Fig. 12 Force as a function of dimensionless displacement (pendulum)

slow speed). The area considered is that of an ellipse, both the radii along and perpendicular to the cutting direction being measured and used as semi-major and semi-minor axes. In order to understand the difference between the gradients of the curves for both cutting speeds, it is important to notice that Moisture Content (MC) was not exactly similar for each series of tests. Table 1 presents the mean and standard deviation of MC for both speeds.

Table 1 Mean and standard deviation of Moisture Content for both cutting speeds

	Average MC	σ (MC)
Slow speed	46.91	4.23
Dynamometric pendulum	63.05	5.91

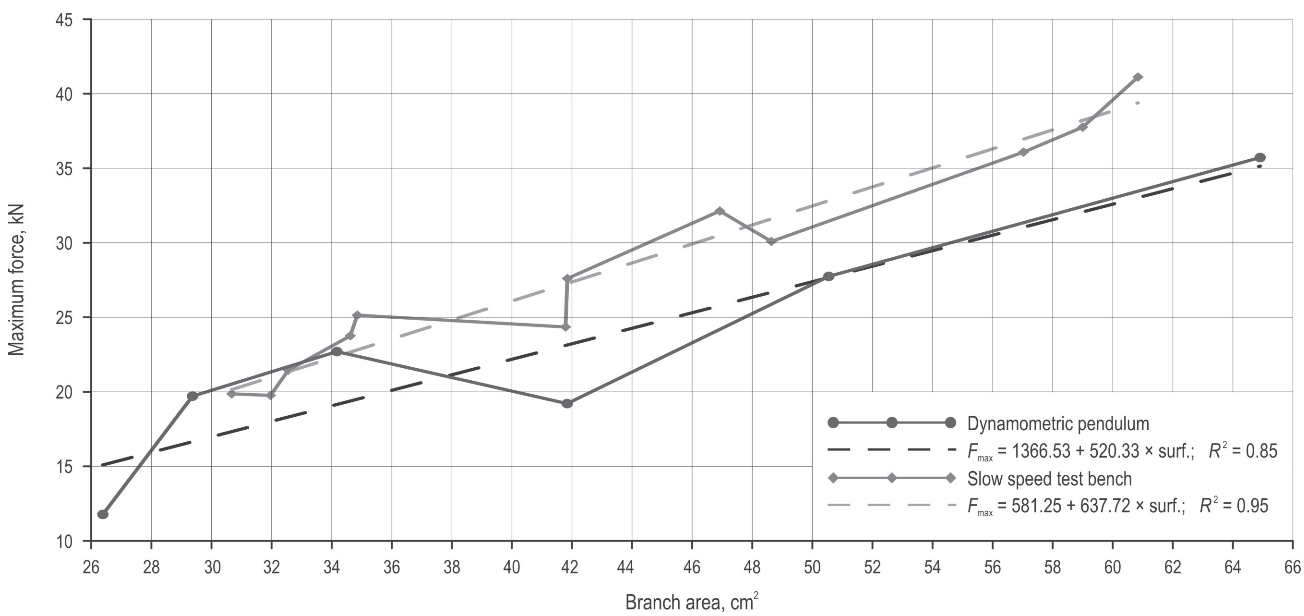

Fig. 13 Maximum force as a function of branch area and associated correlations

3.3 Cutting force

To study the influence of the speed, the scatter plot of the maximum cutting force as a function of the cutting speed is plotted in Fig. 14, and Pearson's correlation coefficient has been calculated:

$$\rho = \mathrm{cov}\left(speed, F_{\max}\right) / \left(\sigma\left(speed\right) \times \left(F_{\max}\right)\right) = -0.27 \quad (3)$$

were cov($speed$, F_{max}) is the covariance between speed and maximum cutting force.

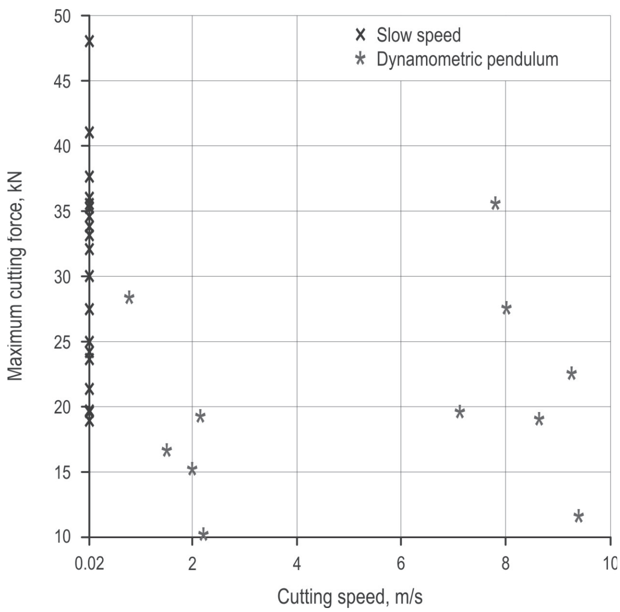

Fig. 14 Maximum cutting force as influenced by cutting speed

4. Discussion

Using DIC, the observation of strips of both shear and tensile deformations perpendicular to the grain in the zone where a crack is propagating is consistent with the interpretations of the 90°–90° cutting process: McKenzie (1961) assumed that the cracks along the grain in zones below and above the cutting edge are due to shear failure along the grain.

As assumed in the case of wood machining (McKenzie 1961), the tension perpendicular to the cutting direction in front of the knife can be the cause of failure in the cutting plane, given the fact that wood failure by shear in this plane is generally considered impossible due to the anisotropy of wood and its great strength in this direction. However, this explanation needs further elaboration, in particular by more local DIC measurements just in front of the knife to verify if tensile deformations parallel to the grain are high enough to induce wood failure in tension.

Finally, thanks to these full field measurements, it can be assumed that the theories developed by McKenzie (1961) in the frame of wood machining in 90°–90° situation can be used for the study of delimbing process.

The trend of different cutting force curves was similar for both cutting speeds, even if there was more disparity between the curves obtained with the pendulum. This can be easily explained by the dynamic nature of the test, which causes naturally more vibrations and noises than the tests carried out at slow speed, which can be considered as quasi-static experiments.

Considering the value of the Pearson correlation coefficient, it is difficult to conclude on the influence of the cutting speed on maximum cutting force. Furthermore, due to the lack of data of maximum force versus cutting speed, particularly in the range 2.5–7 m s^{-1}, it is not possible to obtain concluding results on this influence of speed on the maximum cutting force. In traditional wood cutting, this effect has been discussed in the literature as presented in McKenzie (1961), but because of the shock produced during delimbing and the high moisture content of green wood, the cutting speed may affect the cutting force more than in other types of cutting. However, for a lower speed range (from 0.64 to 1.15 m s^{-1}) than that considered in this study, the influence of the cutting speed has already been considered as non-relevant by Mattson and Sturos (1996).

5. Conclusions

Using DIC, the strains involved in the delimbing process have been analyzed and the main failure modes in the study were compared with the literature. The present study is not considered sufficient to determine if the cutting speed is relevant or not as a parameter influencing the maximum delimbing force. Comparing the strains during the cut at both low (20 cm s^{-1}) and high (5–10 m s^{-1}) cutting speeds could be an interesting step towards answering this question and ensuring that further results (i.e. optimization of the blade geometry) obtained on the slow speed test bench will be transposable on the studied system.

This first stage of understanding has been followed by a series of tests carried out on the two test benches (slow speed test bench and dynamometric pendulum). Experimental data were obtained, particularly force and displacement of the knife through the branch during the cut. The proportionality between maximum cutting force and branch area has been confirmed. This correlation will be the first step towards the modeling approach of the delimbing process. Indeed, first perspective of the work is the comparison of the area of the intersection of the knife and the branch to the force during the cut, to see if only maximum values are proportional or if a similar trend of that observed can be obtained throughout the penetration of the knife.

Based on the collected data, no clear-cut conclusions could be drawn about the relevance of the cutting speed as a parameter influencing the maximum cutting force. Further investigations on this topic, but also on other parameters such as MC or SG, are needed to explain the different gradients observed between the two curves of maximum cutting force as influenced by the branch area. The influence of tree species should also be further investigated.

Acknowledgements

This research work is part of ECOMEF project funded by Conseil Regional Auvergne and by the program Regional competitiveness and employment 2007–2013 (European Regional Development Fund – Auvergne region). These organizations are acknowledged for their financial support.

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Received: January 13, 2014
Accepted: May 6, 2014

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